PERFORMANCE ANALYSIS OF A BIOMASS GASIFIER GENSET AT VARYING OPERATING CONDITIONS

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

ABSTRACT. *An All Power Labs PP20 gasifier generation set (Berkeley, Calif.) was tested to evaluate its suitability for powering biomass conversion technologies (BCT) at remote forest operations sites. Feedstock of the species tanoak (*Notholithocarpus densiflorus*), coast redwood (*Sequoia sempervirens*), and Douglas fir (*Pseudotsuga menziesii*) were tested at moisture contents of 15% and 25% (wet basis). The PP20 was connected to a load bank with five different load profiles designed to simulate possible BCT loads. Two parameters of power quality, voltage variability, and frequency deviation, were determined to be within acceptable limits. The unit also successfully powered a remote biochar operation in Branscomb, California. Emissions of the PP20, when compared to diesel generator regulations, would meet non-methane hydrocarbons (NMHC) and NO_X requirements but exceed the CO emissions limits by a factor of ten. The CO emissions could be reduced by adding a catalytic converter. The results indicate that it is possible to use a PP20 unit to provide electric power for the highly variable loads of a BCT system.*

Keywords. *Bioenergy, Biomass conversion technology, Gasification, Renewable energy.*

Many promising technologies are emerging for the conversion of residual forest waste to useful products. These processes are collectively known as biomass conversion technologies (BCTs) and include processes such as torrefaction, densification, and biochar production. However, the feasibility of BCT projects is highly dependent on the transportation economics of the unprocessed waste biomass (Pan et al., 2008). From a transportation economics standpoint, it is often optimal to place a BCT operation as close to the fuel source as possible. Examples include forest landing sites, at the roadside, or in locations close to forestry operations, such as former sawmills. Although optimal for transportation costs, technological and logistical challenges arise when operating a BCT in remote locations. A key logistical factor for BCT operation is obtaining a reliable source of electricity. Many potential sites do not have access to grid electricity, and a remote power source is therefore required to provide electricity to the BCT.

BACKROUND

In a previous study by Severy et al. (2016), various remote power generation technologies were compared for their potential feasibility for providing power at a remote forest landing site. The technologies evaluated in this study were an organic Rankine cycle (ORC) waste heat recovery device, a thermoelectric generator, a biomass gasifier with an engine generator (All Power Labs Power Pallet, Berkeley, Calif.), a solar PV array with battery storage, and a shaft work power generator. The generation sources were evaluated based on their mobility, footprint, reliability, operational intensity, electrical load following ability, environmental impact, capital cost, operational cost safety, and ease of permitting. The results of the technoeconomic feasibility study concluded that a biomass gasifier was the preferred alternative technology to replace a diesel generator at a BCT site due to its mobility, small footprint, competitive lifecycle cost, and quoted load following abilities (Severy et al., 2016). To validate the results of the feasibility study and extend research on the topic, the goal of this study is to evaluate the suitability of the APL PP20 for powering biomass conversion technologies in the greater Pacific Northwest area. The objectives are to measure the power output and load following capabilities, quantify the emission rates, and provide electricity to a remote BCT that has a fluctuating load. By conducting these tests, the authors can verify whether this gasifier generator is a technically-viable alternative to a diesel generator at off-grid locations.

GASIFIER AS AN ELECTRICAL POWER SOURCE

Gasification technology has been used for decades (Ghosh et al., 2006). However, due to relatively recent technology improvements, there has been an increase in development and interest in the technology. Ahrenfeldt et al. (2013) review the state of the art of biomass gasification combined heat and power (CHP) systems that have been developed with electric power output less than 10 MW, which are being deployed primarily as distributed stationary power plants. Ahrenfeldt et al.'s review, however, does not focus

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on smaller scale, mobile gasifiers in the 20- to 200-kW electric range that would be required to operate conversion equipment at forest operations sites. Of particular interest is the development of small-scale gasification to electricity and gasification CHP systems. These small-scale biomass gasification CHP systems are still in their infant stages of development, unlike the medium- and large-scale stationary plants which are further along the commercialization process (Dong et al., 2009). Due to the high capital costs and labor requirements of gasification systems, economies of scale have made larger plants with higher throughputs more economically favorable (Ahrenfeldt et al., 2013). In certain contexts, such as a remote forest site, small-scale biomass gasifier generators can be an appropriate, clean, and economical technology selection. By using locally available fuel, gasification reduces fuel transportation cost and can simplify fuel supply logistics compared to diesel fuel (Patuzzi et al., 2016). Biomass fuel is widely available, particularly in forest harvest zones, at a substantially lower cost per unit energy than diesel fuel. However, gasification systems require more maintenance, higher operational skill, and a higher capital cost than diesel generators (National Energy Technology Laboratory, n.d.). Diesel generators are more reliable than gasifier gensets in part because they use a homogeneous liquid fuel and because of the maturity of the technology. Solid biomass fuels are, by nature, heterogeneous in size, moisture, and energy density, which requires additional preprocessing to achieve the narrow specifications of particle size and moisture content required for gasifiers to function properly (Susastriawan and Saptoadi, 2017).

Effects of Feedstock Quality on Small Scale Gasification

Gasifier gensets produce electrical power from biomass fuel, which would typically be available at any BCT operation site. However, there is a great deal of variation in the type, quality, and moisture content of the potential feedstock, and it is therefore important to evaluate the ability of gasifier gensets to operate effectively using a range of forest residue feedstock materials.

A key feedstock quality parameter is the moisture content, which needs to be within a fairly narrow range for use in most gasification systems. Kirsanovs et al. (2017) show that use of feedstock with higher moisture content in a gasifier creates producer gas with a lower energy content. Higher feedstock moisture content decreases the achievable processing rate and maximum gasification temperature (Perez et al., 2012). Lowering the feedstock moisture content with a dryer minimizes the cost of electricity and increases the system-wide efficiency of a gasification CHP system (Brammer and Bridgwater, 2002). Another metric of feedstock quality is particle size and consistency. Higher degrees of homogeneity of the feedstock lead to more efficient operation of the gasifier (Susastriawan and Saptoadi, 2017). Additionally, smaller feedstock particle sizes lead to higher efficiency of the entire system because they have higher surface to volume ratio, thereby enabling improved heat transfer and promoting the reactivity of the biomass in the gasification process. However, if the particle size is too small, it increases the pressure drop for gases flowing through the reactor bed and prevents the gasifier from operating properly.

The moisture content of biomass delivered to a BCT site is typically in the range of 30% to 60% and usually requires drying (Fagernas et al., 2010). A common passive method is to solar-dry the feedstock by spreading it out and exposing it to the sun. This has several drawbacks, including weather dependency, high labor cost, slow drying times, the requirement of open flat area, and the potential introduction of contaminments (e.g., sand and gravel). Feedstock can also be actively dried using biomass dryer such as a rotary drum or a belt dryer, which has drawbacks of added cost, complexity, labor, and electrical and heat requirements.

Objective

The objective of this study was to evaluate the suitability of an All Power Labs PP20 gasifier genset for powering remote BCT operations. These commercially-available gasifier systems have been previously studied by Madadian et al. (2016) to assess the gasification process of converting pelletized woody biomass into an energy-dense producer gas. Their study, however, did not assess the electricity generating capabilities of the gasifier. Patuzzi et al. (2016) measured the mass and energy fluxes of four small scale biomass gasifiers deployed in Italy with electric nameplate ratings ranging from 45 to 300 kW. Their study monitored the power plants under 5 to 6 h of normal operation, which may not include quickly varying load profiles that have been observed in field deployable BCTs. In order to confidently deploy these gasifiers to operate equipment in off-grid locations as an alternative to diesel generators, the work of these previous studies needs to be expanded to monitor the performance of the generator under conditions of changing electrical load.

Four criteria were used to investigate suitability in this study:

- The ability to maintain the power quality parameters of frequency-stability and voltage regulation under loads simulating those from BCT machines;
- The amount of electrical energy produced per unit of biomass (i.e., efficacy);
- The ability to use different types of feedstock available to a BCT site;
- The emissions produced by the gasifier during operation.

Methods and Materials

The test was designed to simulate in a laboratory setting the operating conditions of a gasifier genset at a remote BCT site. The All Power Labs Power Pallet PP20 was operated using three different species of feedstock at two levels of moisture content. An electronically controlled load was programmed to simulate anticipated BCT load profiles. Data were collected on the properties of the feedstock, feedstock mass consumed, electrical energy production, power quality, and genset emissions. The unit was subsequently taken to a field site in Branscomb, California and tested with an integrated biochar system (Eggink et al., 2018).

FEEDSTOCK

Three species were chosen to match those feedstocks expected to be available at a remote BCT site in northern California and the Pacific Northwest region. Each species was prepared at a high (25%) and a low (15%) moisture content (wet basis) to simulate feedstocks that were passively vs. actively dried (table 1).

Samples of each of the feedstock types were analyzed to determine selected physical and chemical properties. The procedure for each test is summarized below.

- Moisture content – The average wet basis moisture content of three measurements made with a moisture analyzer balance (BEL Engineering, i-Thermo 163L, Monza, Italy). Three samples were taken for each feedstock type and averaged.
- Proximate analysis – Measured using a thermogravimetric analyzer (Q50, TA Instruments, New Castle, Neb.) 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; 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; switch the purge gas to air and hold at 700°C for 10 min. Single tests were conducted for each feedstock type.
- Higher heating value – Measured in a bomb calorimeter (Model 1241, Parr Instruments, Moline, Ill.). Duplicate tests were conducted for each feedstock type using standard operating protocols described by Parr Instruments (2017).
- Bulk density – Measured by modifying CEN/TS 15103 (CEN, 2005) to use a one cubic foot box (12 in. × 12 in. × 12 in.). Three sample were taken for each feedstock type and averaged.

All feedstock tested was passed through a two-stage vibratory mechanical screener. The screened material ranged in size from 13 to 38 mm (0.5 to 1.5 in.) as required by the PP20 manufacturer's specifications (All Power Labs, 2017). All the feedstock was solar dried reach moisture percentage values approximately equal to the nominal values in table 1.

GASIFIER GENSET

The All Power Labs Power Pallet PP20 is a downdraft gasifier generator set rated at 20 kW_e. The three major system components are the gasifier, the engine, and the generator as shown in the diagrams in figures 1 and 3, pictured in figure 2.

The overall efficacy can be calculated by dividing the electrical energy produced by the mass of feedstock consumed during a given time period (eq. 1).

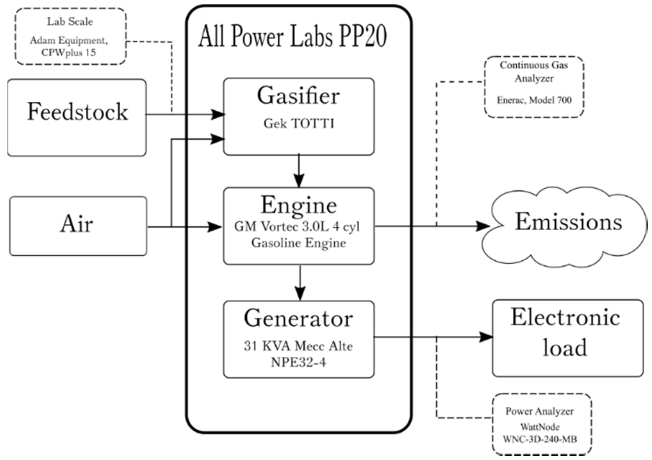


Figure 1. Simplified system diagram of the experimental set-up showing the All Power Labs PP20 gasifier genset connected to the electronic load.

Figure 2. Photograph of the experimental set-up the All Power Labs PP20 gasifier genset.

$$EF_{Overall} = \frac{E_{Electrical}}{M_{Feedstock}} \quad (1)$$

Table 1. Feedstock properties of biomass used in gasifier genset testing.

Species	Test ID	Nominal Moisture %	Feedstock Moisture (% mass, wet-basis)	Fixed Carbon (% mass, dry-basis)	Ash Content (% mass, dry-basis)	Volatile Matter (% mass, dry-basis)	Higher Heating Value (MJ/kg)	Bulk Density (kg/m^3 wet-basis)
Tanoak	TANO15	15%	17.1%	16.5%	1.4%	82.1%	18.5	204.1
Notholithocarpus densiflorus	TANO25	25%	27.5%	16.5%	1.4%	82.1%	18.5	222.2
Redwood	REDW15	15%	14.5%	17.6%	0.9%	81.5%	19.6	183.4
Sequoia sempervirens	REDW25	25%	26.3%	17.6%	0.9%	81.5%	19.6	202.4
Douglas Fir	DOUG15	15%	15.6%	17.3%	0.8%	81.9%	19.2	215.6
Pseudotsuga menziesii	DOUG25	25%	24.5%	17.3%	0.8%	81.9%	19.2	232.1

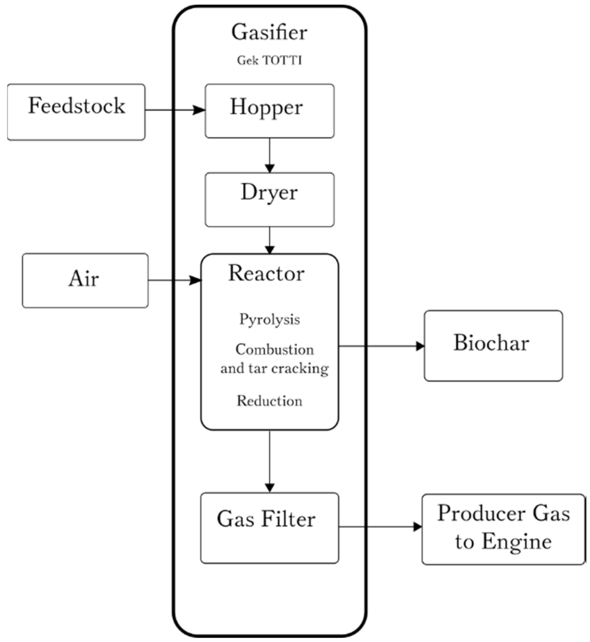


Figure 3. Simplified diagram of the gasifier subsystem on the PP20 unit.

where

$EF_{overall}$ = overall system efficacy,

$M_{Feedstock}$ = mass of feedstock consumed during test period,

$E_{Electrical}$ = electrical energy produced during test period.

The thermal efficiency of the system can be calculated by dividing the electrical energy produced during the test period by the higher heating value of the biomass as determined through bomb calorimetry. The relation is expressed as:

$$\eta_{th} = \frac{E_{Electrical}}{E_{HHVBiomass}} \quad (2)$$

where

η_{th} = thermal efficiency,

$E_{HHVBiomass}$ = total calorific value of biomass consumed during the test period.

Gasifier

The gasifier is operated by manually loading the feedstock into a sealed stainless steel hopper on the top of the assembly. The feedstock is then conveyed into the top of a reaction chamber by an auger. A paddle switch located in the top of the reactor provides a signal to control the auger to keep the proper level of feedstock in the reactor chamber. The feedstock is actively dried using waste system heat as the feedstock travels to the reactor. As the biomass flows downward through the reactor by gravity, the temperature increases and the biomass is converted to charcoal by pyrolysis. Preheated air is added to the reactor to create heat through combustion. The charcoal and product gases are funneled into a restriction to concentrate heat and thermally decompose tar gases. The final step in the reactor is reduction, which is an endothermic reaction that convers charcoal, CO_2, and H_2O into a producer gas composed of H_2 and CO. Temperatures are monitored at the restriction (T_{rst}) and in the reduction zone (T_{red}) to determine if the gas can be sent to the engine.

The PP20 uses engine vacuum as the primary method to move gas through the system. The producer gas flows through a filter system which consists of a cyclone settling chamber and packed bed filter. The cyclone chamber spins, separates, and settles the larger particles of char from the producer gas stream. Producer gas is then pulled through a four-layer packed bed filter. The cylindrical filter vessel is 406 mm wide with the following layers:

- 230-mm layer of charcoal particles with longest dimension between 12 and 25 mm,
- 175-mm layer of charcoal particles with longest dimension between 3 and 6 mm,
- 175-mm layer of charcoal particles with longest dimension between 1 and 3 mm,
- 7-mm layer of raw biomass particles with longest dimension between 12 and 25 mm.

A condensation vessel is located downstream of the filter to collect any liquid condensate before the gas enters the engine system.

Before each test run, all feedstock was removed from the system above the location of the paddle switch in the reactor. This left a small, fixed amount of partially pyrolyzed material in the reactor as required for startup (All Power Labs, 2017). The hopper was then filled with a measured amount of mass of feedstock. Standard operating procedures described in the operator's guide (All Power Labs, 2017) were followed to conduct each test. For system startup, approximately 100 mL of kerosene were added to the reactor to provide initial heating energy. As the gasifier heated up to its target T_{rst} starting temperature of 800°C, the producer gas was sent to a flare for combustion. After reaching the target temperature, the producer gas was delivered to the engine, which was turned on for ignition. Once the engine was stable and idling at a low load, the electronic load profile was connected and the test could begin.

Each test lasted approximately 57 min, cycling through five different load profiles on the electronic load. After the final load profile was complete, the engine and gasifier returned back to idling mode and the operators shutdown the system. After completing a test and allowing the system to cool, the remaining feedstock in the hopper was removed and weighed to determine the amount of feedstock consumed during the test run.

Engine-Generator

The engine and generator subsystems on the PP20 are both commercially available products. All Power Labs modifies a 3-L 4-cylinder GM Vortec engine (Detroit, Mich.) to accept filtered producer gas (All Power Labs, 2017). Air is metered into the producer gas to create a combustible mixture, which is delivered to the engine. Air-fuel mixture is controlled by digital lambda meter with a nominal air-fuel ratio of 1.05. The engine drives a Mecc Alte NPE32 E/4 12-wire 4-pole generator (McHenry, Ill.) at 1800 rpm. The generator can be configured to deliver various 3-phase power output configurations. It was tested under the 3ϕ 240 V series delta configuration.

ELECTRONICALLY CONTROLLED LOAD

An electronically programmable load was designed and assembled to test how the power quality of the PP20 responds to varying load conditions. The load bank consisted of 21 water-immersion resistance heaters mounted in a 208-L thermal reservoir. The load bank was controlled by a microprocessor through a solid-state relay array, allowing individual control of each element on a one millisecond time range.

Identical load programs were run for each of the feedstock types. The 57-min load program had five load profiles that were run in series, as described in table 2. The 21 load elements were arranged into seven steps of delta configuration when connected to the PP20. Only balanced loads were created for the test runs.

EMISSIONS

Emissions from the PP20 were measured with a continuous gas analyzer (Model 700, Enerac, Holbrook, N.Y.) equipped with electrochemical sensors for O_2, NO, NO_2, SO_2, and CO (low range). It was also outfitted with non-dispersive infrared (NDIR) sensors for CO (high range), CO_2, and unburned hydrocarbons (measured as propane). The sample probe was installed approximately 100 mm (4 in.) before the exit of the engine exhaust. Emissions rates were determined from gas composition results from the continuous gas analyzer and from flow rates measured by a pitot tube (36FMS 4", Nailor, Houston, Tex.). Samples of producer gas were manually collected for each load profile into 0.5 -L Tedlar sample bags (SKC-West, 232-02, Brea, Calif.). Samples were analyzed for molar composition of N_2, O_2, H_2, CO, CO_2, CH_4, C_2H_6, and C_3H_8 using a gas chromatograph (GC) (3000A, Agilent Technologies, Santa Clara, Calif.) equipped with a MolSieve 5A column and a PoraPlot U column equipped with thermal conductivity detectors. Higher heating values of the producer gas was calculated using the higher heating value of each component.

RESULTS AND DISCUSSION

The values for overall efficacy and thermal efficiency for the All Power Labs PP20 gasifier genset are provided in table 3.

PERFORMANCE

Thermal efficiency ranged from 7.5% to 11.1%. The lowest moisture content feedstock provided the highest efficiency for redwood and tanoak; however, the highest moisture content feedstock provided the highest efficiency for Douglas fir. Efficacy ($kWh_e\ kg^{-1}$ dry-basis) ranged from 0.40 to 0.61 $kWh_e\ kg^{-1}$. The lowest moisture content feedstock also provided the highest efficacy for tanoak and redwood species, while the opposite occurred for Douglas fir. The lower moisture content feedstocks were all expected to have

Table 2. Load profile description and parameters for gasifier genset testing.

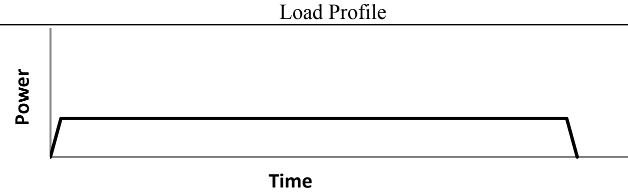
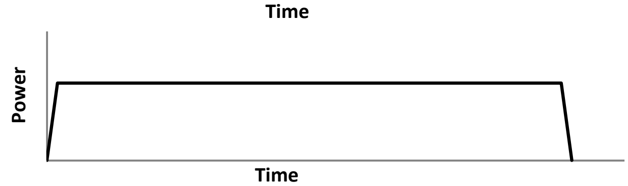
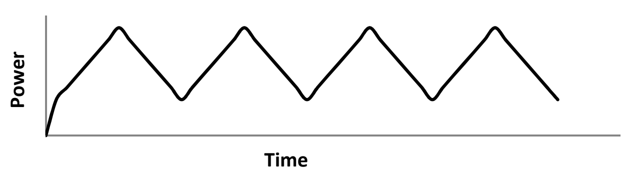
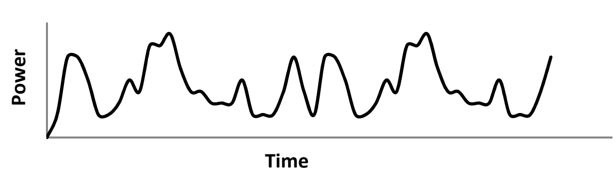
Load Profile Name	Load Profile	Maximum Power Rate of Change	Power Range (kW)	Average Power (kW)	Duration (min)
Low		-	4.7	4.7	8
Medium		-	6.5	6.5	8
High		-	12.1	12.1	8
Ramping		1 kW/s	6.8-13.4	9.9	20
Variable		4 kW/s	4.7-12.7	9.9	13

Table 3. Overall efficacy and thermal efficiency results for the gasifier genset by feedstock type.

Species	Test ID	Feedstock Moisture (% mass, wet-basis)	Efficacy (kWhe kg^{-1} Dry-basis)	Overall Efficacy (kWh Electrical Energy / kg Feedstock Wet-basis)	Thermal Efficiency
Tanoak	TANO15	17.1%	0.55	0.46	10.8%
Lithocarpus densiflorus	TANO25	27.5%	0.51	0.37	9.9%
Redwood	REDW15	14.5%	0.61	0.52	11.1%
Sequoia sempervirens	REDW25	26.3%	0.55	0.40	10.1%
Douglas Fir	DOUG15	15.6%	0.40	0.34	7.5%
Pseudotsuga P. menziesii	DOUG25	24.5%	0.58	0.43	10.8%

higher efficacy and higher thermal efficiency, but this was not the case for Douglas fir. A possible explanation is the DOUG15 feedstock had the highest reaction temperatures (table 4). High reaction temperatures have been shown to lower producer gas energy content because of a decrease in CO and alkane content in the producer gas (Karamarkovic and Karamarkovic, 2010; Yan et al., 2010).

From the perspective of fuel cost, all the feedstocks have similar results. Assuming the PP20 was powering a 10 kWe BCT load with a delivered feedstock price of $55.27 per bone-dry short ton (Pan, 2008) over an 8-h day, the difference in cost between the highest recorded efficacy (0.61 kg^{-1} dry-basis) and the lowest (0.40 kWh_e kg^{-1} dry-basis) would be $3.79 per day. These results suggest that even if the incoming moisture percentage of the feedstock is relatively high at 25%, the cost of operating the machine may not be improved significantly by reducing the moisture percentage to a lower amount.

Power Quality

Power quality is a key consideration for analyzing the suitability of any remote electrical generation system. A generation device needs to compensate for changing variables such as varying load and fuel quality while maintaining power quality parameters. The PP20 is not equipped with fuel-gas ballast or storage, which implies the gasifier reaction rate needs to keep up with the electrical demand. The power quality parameters of focus for this study are frequency-stability and voltage regulation. Both of these parameters indicate the gasifier's ability to generate producer gas quickly enough to respond to changes in electrical load.

Power quality tolerance depends on the types of loads within a system. In general, loads with electronic components are more sensitive to power quality deviations. BCTs often have variable frequency motor drives (VFDs), programmable logic controllers (PLCs), and other electronic-based loads within the system. For a gasifier genset to be suitable for powering a remote BCT, it needs to not only be able to provide enough power. It must also provide the power at suitable power quality.

The PP20 was used to power an integrated biochar system at a remote field site in Branscomb, California. The system performance during this field testing is summarized in table 5. The system consisted of a biochar machine with a stack heat exchanger (Biochar Solutions, Inc., Carbondale, Colo.), a belt dryer (Beltomatic 123B , Norris Thermal Technologies, Tippicanoe, Ind.), and a series of automated conveyors. The PP20 was able to provide the power and power quality necessary to successfully operate the system (Eggink et al., 2018). Additional detailed power quality lab results are provided below.

Frequency

For all feedstocks under all load profiles, the frequency average deviation from nominal remained within 1 Hz (fig. 4) of the target value of 60 Hz. For the three constant load profiles, the average deviations were about 0.3 Hz. Larger deviations were observed for the ramping and the variable profiles. The ramping load profile was observed to have the most severe frequency deviations. This is because the control loop that governs the fuel to the engine was adjusting to match a load set point that was continually changing. Although the variable load program had the highest rates of change, the program also stabilized at certain load set points for periods of time.

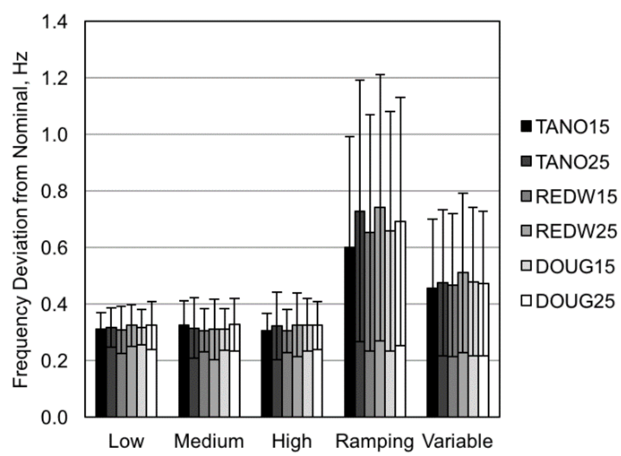


Figure 4. Average absolute value of frequency deviations for each feedstock type and load profile. Error bars represent one standard deviation.

Table 4. Average reaction temperatures at the restriction and in the reduction zone for each feedstock type.

Feedstock ID	Average T_{rst} (°C)	Average T_{red} (°C)
TANO15	810	634
TANO25	822	680
REDW15	860	675
REDW25	860	717
DOUG15	885	729
DOUG25	828	688

Table 5. Data from field testing to power biochar machine.

Description	Value
Biomass In	21 kg h^{-1}, wet basis
Moisture Content In	22%
Biochar Out	0.45 kg h^{-1}, wet basis
Avg Elec Power Out	9.3 kW
Max Elec Power Out	17 kW
Effective Labor Hours	0.28 labor-h/machine-h

Voltage

Average voltage deviation remained below 5 V, or about 2.1% of 240 V for all tests (fig. 5). Actual allowable voltage deviations depend on the specific application and the specifications of the load components within the system being powered. For reference, voltage fluctuations greater than 110% are considered a voltage swell disturbance, and voltage fluctuations below 90% are a voltage sag disturbance (Chattopadhyay, 2011), which would be equivalent to a deviation of ±24 V with the PP20 gasifier genset.

EMISSIONS

Average emissions at the exit of the engine during each test are shown in table 6. The molar heating value of the syngas on a dry basis is calculated based on the producer gas composition measurements made with the gas chromatograph.

A multiple linear regression was performed to investigate the relationship between gas emissions (independent variables) as shown in table 6 and the feedstock and load profile (dependent variables). The results from this analysis identified two relationships with p-values less than 0.05, which are:

- CO concentration is affected by load profile. CO concentrations increase as the load profile becomes more severe in the order of low load, medium load, high load, ramping load, and variable load.
- Propane concentration is affected by feedstock moisture content. Higher moisture content feedstock results in greater emissions of propane (i.e., unburned hydrocarbons).

The average emission rates from the gasifier across all load profiles and feedstocks on a constituent mass per unit electric energy produced basis are shown in table 7. These results are compared to regulations for off-road diesel engines with an equivalent sized generator. The gasifier meets the regulations for non-methane hydrocarbons (NMHC) and NO_X but exceeds the CO emissions regulations by a factor of ten. The CO emissions could be reduced by adding a catalytic converter. Sulfur dioxide emissions exceed equivalent regulations for diesel generators by four orders of magnitude. Sulfur emissions, however, are a function of the sulfur content in the fuel, and diesel is highly regulated and refined to sulfur contents of less than 15 ppm (EPA, 2016b), which is not feasible with raw biomass feedstocks.

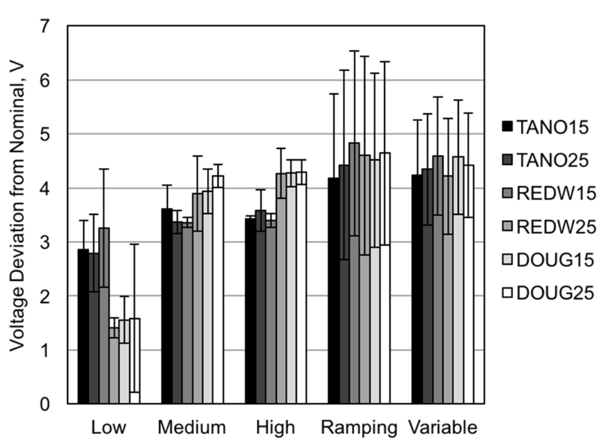


Figure 5. Average absolute value of voltage deviations for each feedstock type and load profile. Error bars represent one standard deviation.

Average CO_2 emission rates were measured to be 3,400 g kWh^{-1}. However, the feedstock is a forest residual that would have resulted in a higher level of emissions if it hadn't been used in the gasifier (Alanya-Rosenbaum and Bergman, 2017).

The average producer gas composition across all tests was measured to be 16% H_2, 21% CO, 11% CO_2, 2% CH_4, 0.06% C_2H_6, and 0.04% C_3H_8 by mole. The remainder gas fraction is presumed to be N_2 and H_2O vapor. The heating value ranged from 96 to 145 MJ mol^{-1} (table 6) and was related to feedstock moisture content at a 5% significance level based on a regression analysis. Feedstocks with higher moisture content created a producer gas with a lower molar heating value.

CONCLUSIONS

Testing has indicated that it is possible for the PP20 to provide electric power to remote biomass conversion technology systems and associated equipment. Specific conclusions are itemized below.

- The PP20 is effective at converting biomass into electrical energy. It can respond to changing load while maintaining acceptable power quality parameters.
- The PP20 was able to provide the power and power quality necessary to successfully operate a remote biochar integrated system.
- If the feedstock moisture content is between 15% and 30% as per manufacturer's specifications, the species and moisture content do not play a major role in overall efficacy and the cost of fuel to operate the machine.
- Emissions of the PP20, when compared to diesel generator regulations, would meet non-methane hydrocarbons (NMHC) and NO_X but exceed the CO emissions by a factor of ten. The CO emissions could be reduced by adding a catalytic converter.
- Future work should focus on long term reliability field testing.

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Table 6. Average emissions from the gasifier genset system during each load profile and feedstock combination.[a]

		Stack Gas Emissions								Producer gas
Feedstock	Load Profile	Temp., °C	Flow Rate, kg h^{-1}	CO_2, mol%	CO, mol%	C_3H_8, ppm	NO_x, ppm	SO_2, ppm	O_2, mol%	HHV, MJ mol^{-1}
TANO15	Low	236	109	19%	0.19%	0	170	5	1.5%	131
		(30)	(25)	(0.2%)	(0.04)	(<0)	(66)	(1)	(0.3%)	(0.4)
	Med.	314	112	19%	0.15%	0	203	4	1.3%	134
		(14)	(22)	(0.1)	(0.01)	(<0)	(21)	(1)	(<0%)	(0.5)
	High	378	149	19%	0.15%	0	207	3	1.4%	137
		(14)	(20)	(0.1%)	(0.02)	(<0)	(19)	(1)	(0.1%)	(0.3)
	Ramp	389	128	18%	0.59%	0	168	12	1.6%	145
		(1)	(37)	(0.2%)	(0.11)	(<0)	(20)	(2)	(0.1%)	(3.5)
	Variable	390	123	18%	0.74%	0	222	11	1.7%	150
		(1)	(38)	(0.1%)	(0.04)	(<0)	(14)	(1)	(0.2%)	(0.5)
TANO25	Low[b]	194	38							113
		(35)	(15)							(1.4)
	Med.[b]	290	78							105
		(19)	(47)							(0.6)
	High[b]	360	131							125
		(15)	(24)							(0.7)
	Ramp	370	86	12%	0.46%	0	39	14	1.7%	94[c]
		(3)	(32)	(0.1%)	(0.08)	(<0)	(33)	(1)	(0.1%)	(0.5)
	Variable	373	64	18%	0.65%	0	81	15	1.5%	61[c]
		(1)	(31)	(0.1%)	(0.05)	(<0)	(2)	(1)	(0.1%)	(0.2)
REDW15	Low	239	119	18%	0.17%	17	5	9	1.3%	132
		(14)	(20)	(0.1%)	(0.01)	(1)	(2)	(1)	(0.1%)	(0.8)
	Med.	304	119	18%	0.17%	20	7	9	1.2%	145
		(19)	(23)	(0.1%)	(0.01)	(3)	(1)	(1)	(0.1%)	(0.8)
	High	378	155	18%	0.16%	20	17	9	1.2%	143
		(16)	(31)	(0.1%)	(0.02)	(3)	(7)	(2)	(0.1%)	(0.8)
	Ramp	398	131	18%	0.63%	21	13	25	1.3%	140
		(2)	(44)	(0.1%)	(0.11)	(2)	(6)	(4)	(0.1%)	(0.3)
	Variable	407	132	17%	0.93%	20	11	28	2.0%	138
		(3)	(44)	(0.1%)	(0.11)	(1)	(4)	(5)	(1.7%)	(0.2)
REDW25	Low	226	36	18%	0.20%	311	40	11	1.4%	118
		(23)	(14)	(0.1%)	(0.01)	(3)	(7)	(1)	(0.1%)	(0.8)
	Med.	298	59	18%	0.20%	302	46	8	1.4%	111
		(16)	(26)	(0.1%)	(0.01)	(3)	(11)	(1)	(0.1%)	(2.5)
	High	364	100	18%	0.22%	305	55	10	1.4%	120
		(16)	(43)	(0.1%)	(0.06)	(3)	(17)	(2)	(0.1%)	(0.1)
	Ramp	380	89	18%	0.47%	304	56	15	1.6%	124
		(2)	(34)	(0.1%)	(0.07)	(4)	(23)	(1)	(0.1%)	(0.3)
	Variable	381	87	18%	0.71%	300	76	18	1.5%	127
		(3)	(32)	(0.1%)	(0.09)	(2)	(13)	(2)	(0.1%)	(0.3)
DOUG15	Low	220	87	19%	0.16%	8	158	3	1.4%	96[c]
		(35)	(50)	(0.1%)	(0.02)	(2)	(65)	(1)	(0.3%)	(0.5)
	Med.	303	116	19%	0.15%	10	212	2	1.2%	127
		(17)	(21)	(0.1%)	(0.01)	(1)	(18)	(1)	(<0.0%)	(0.2)
	High	376	156	19%	0.15%	12		2	1.2%	140
		(16)	(21)	(0.1%)	(0.02)	(1)		(1)	(0.1%)	(1.2)
	Ramp	392	134	18%	0.57%	11	220	9	1.4%	133
		(4)	(43)	(0.1%)	(0.09)	(1)	(15)	(2)	(0.1%)	(0.6)
	Variable	395	120	18%	0.83%	9	240	11	1.4%	135
		(2)	(28)	(0.1%)	(0.06)	(1)	(4)	(1)	(<0.0%)	(0.1)
DOUG25	Low	195	n/a	19%	0.21%	68	109	7	1.4%	119
		(41)		(0.1%)	(0.05)	(32)	(34)	(2)	(0.2%)	(0.8)
	Med.	294	50	19%	0.20%	38	104	4	1.3%	127
		(19)	(25)	(0.1%)	(0.01)	(29)	(22)	(1)	(0.1%)	(0.4)
	High	364	146	19%	0.20%	26	115	5	1.4%	122
		(15)	(19)	(0.1%)	(0.01)	(2)	(24)	(1)	(0.1%)	(0.6)
	Ramp	380	116	18%	0.54%	27	87	9	1.5%	124
		(2)	(37)	(0.1%)	(0.10)	(2)	(19)	(2)	(0.1%)	(0.3)
	Variable	385	98	18%	0.74%	26	100	12	1.5%	125
		(2)	(32)	(0.1%)	(0.06)	(1)	(14)	(1)	(0.1%)	(0.1)

[a] The standard deviations are shown in parentheses for each value. The sample size for stack gas emissions is equal the number of seconds in each load condition. The producer gas heating value is based on the composition measured with a gas chromatograph with a sample size of two.

[b] Stack gas emissions data unavailable.

[c] Producer gas heating value appears to be low due to higher than expected O_2 content in the producer gas sample. Oxygen may have leaked into the sample bag during the sampling procedure.

Table 7. Gas emission rates from the PP20 gasifier genset averaged across all tests compared to equivalent diesel regulations.

	Gasifier, g kWh^{-1}	Diesel Regulations, g kWh^{-1}
CO	43	4.7[a]
NMHC[b]+NO_X	2.3	5.5[a]
SO_2	0.12	0.00013[c]

[a] EPA Tier 4 (EPA, 2016a)
[b] Non-methane hydrocarbons
[c] Derived from EPA Diesel Fuel Standards (EPA, 2016b) assuming full conversion of S to SO_2 and 20% thermal efficiency of engine.

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