REMOTE POWER GENERATION

Part 1: Technology Selection

Waste to Wisdom: Subtask 2.7

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1 INTRODUCTION

The Schatz Energy Research Center (SERC) has completed the first phase of work under Subtask 2.7 to determine the most appropriate method to meet the energy input needs of biomass conversion technologies (BCTs) at forest landing sites. The objectives of Subtask 2.7, as written in the Statement of Project Objectives, were to

1) measure the waste heat characteristics of each BCT,
2) assess the abilities of this waste heat resource to meet the BCT's energy needs, and then
3) test the performance of a heat-to-power device under laboratory conditions.

The purpose of this report is to present the results from objectives 1) and 2) listed above.

The findings indicate that:

- The waste heat that is potentially available at a typical forest operations site is neither a reliable or economical solution to meeting the highly variable electrical demand of the BCTs. The waste-heat-to-power generators would require a supplementary fuel source to power the machines during startup and shutdown.
- The recommended alternative remote power generation technology is a biomass gasification generator set, which is expected to be more economical, mobile, and reliable than using a waste-heat-to-power conversion device at a remote field site.
- Waste heat is better utilized for moisture management of BCT feedstock, which is critical to maintaining high production efficiency and product quality from the BCTs.

Based on these results SERC procured a 20 kilowatt (kW_e) biomass gasifier to test during 2016. The second part of this report, which will be distributed in mid-2016, will detail the results from testing and analysis of this technology to address objective 3) of this Subtask as outlined above.

The following report characterizes the waste heat resource from the different BCTs and provides background about the potential remote power technologies in Section 2. The methods used to evaluate these technologies are described in Section 3. Next, results from this evaluation are presented in Section 4 and discussed in Section 5. Lastly, conclusions are presented in Section 6 before describing the future work and test plan in Section 7.

2 BACKGROUND

Waste heat from the BCTs can potentially be converted into electricity to power the machines. This section characterizes that waste heat resource from BCTs and associated equipment and then provides a list of technologies that were evaluated as potential power sources at remote forest locations.

2.1 Waste Heat Characterization

Producing electricity from waste heat is one potential alternative to power the BCTs in remote locations. Each BCT considered in this project (i.e., biochar production, torrefaction, and densification) has distinct waste heat characteristics. In addition, the exhaust gases from diesel-powered engines on the chipper and/or grinder at the forest landings provide additional sources of waste heat. The average waste heat resource from each machine is characterized in Table 1. At the time of conducting this analysis in February 2015, only the waste heat from the biochar machine has been measured directly through this project; the other values are estimated with data supplied by the manufacturers.

Table 1. Average waste heat characteristics of BCTs and forest landing equipment.

Machine	*Product Output, kg/hr*	*Exhaust Temperature, °C*	*Waste Heat (recovered to 100 °C), kW*	*Estimated Electrical Generation with ORC*, kW*	*Average Electrical Demand, kW*
Biochar Machine, As tested in 2014	50	750	400	20	12†
Torrefier, NTT Pilot Unit	25	200	20	1	8
Densifier, RUF 200	200	N/A	0	0	11
Grinder, Peterson 5710C	100,000	400	450	23	0‡
Chipper, Peterson 5900EL	70,000	450	350	18	0‡

* Estimated electrical power generation from an organic Rankine cycle (ORC) is calculated assuming a 5% conversion efficiency.
† The peak electrical load was measured to be 26 kW on the biochar machine. Electrical demand variation is shown in Appendix B Figure B.2.
‡The chipper and grinder are mechanically powered by an on-board diesel engine. Small electrical loads are met with an engine alternator.

As can be seen in Table 1, only the biochar machine, grinder, and chipper produce substantial quantities of waste heat. Note that the grinder and chipper each incorporate a diesel-powered engine, and the unit's electrical loads are met using the engine's alternator. The biochar machine appears to be the only unit that can potentially meet its electrical demand with its own waste heat. However, a supplemental electrical generator or heat source would need to be used during startup and shutdown when the machine is consuming power but not producing waste heat.

To produce electricity for the densifier or torrefier, waste heat would be required from another source such as the chipper or grinder because waste heat from the BCT itself cannot provide enough power to meet its own electrical demand. In this scenario, however, the equipment capacities are highly mismatched because the chipper and grinder process biomass at rates that are orders of magnitude higher than can be consumed by the densifier or torrefier. Furthermore, linking the BCT to the chipper or grinder would constrain the mobility of forest operations.

2.2 Remote Power Generation Technologies

SERC's research initially focused on waste-heat-to-power conversion devices and then expanded to other remote power generation devices with an emphasis on technologies that are powered by renewable fuels. The following technologies were considered:

- Diesel generator

  This is considered the baseline technology to provide power to off-grid locations. Diesel generators have low initial costs and are a proven, reliable technology. There are potentially significant environmental impacts associated with their use, including particulate and greenhouse gas emissions and fuel and oil spillage or mishandling.
- Organic Rankine cycle (ORC) waste heat recovery device

  An ORC uses low temperature waste heat to vaporize an organic working fluid, which produces work as it expands across a turbine. Operating an ORC-based power systems in a near-woods environment may have high initial costs, impair mobility of the BCTs, require a supplemental heat source during start up and shut down, and are unlikely to be able to follow a variable load effectively without the use of a battery.
- Thermoelectric generator

  Thermoelectric generators produce a voltage differential when exposed to a thermal gradient. They can be used for waste heat recovery but currently have high initial costs, low efficiencies, and are not commercially available in the 10 to 20 kW range
- Biomass gasifier with an engine generator

  A biomass gasifier converts biomass into syngas that can be used as fuel for an engine and generator. Gasifiers have less environmental impact and lower fuel costs than diesel generators but have higher up-front costs, require more maintenance, and have uncertain reliability.
- Solar photovoltaic array

  A solar array, battery bank, and inverter could be used to generate and store electricity for off-grid applications. Solar is a renewable, environmentally benign technology, but it is available intermittently, is expensive, and has a large footprint with limited mobility.
- Shaft work power generator

  Work can be generated from excess shaft power from other machinery at the forest operations site such as a chipper or grinder. A belt would connect between the chipper's shaft and an auxiliary generator that would power the BCTs. This device is expected to be affordable, but it would impact the mobility of the chipper or grinder because the BCT being powered would need to be relocated alongside the chipper or grinder to maintain stable operation as it is moved throughout the forest operation site.. This device would operate using diesel fuel from another engine, entailing the potential environmental impacts enumerated above for diesel generators.

3 METHODS

The technologies were ranked based on multiple criteria that attempt to quantify the performance, environmental impact, and ease of use at a forest operations site. The scores for each criterion and technology combination were determined by referencing the devices' specification sheets and talking with manufacturers. Further details on each technology and the specifications used to rate them are provided in Appendix A.

3.1 Criteria for Selecting Remote Power Device

Criteria were developed to determine which of these technologies best meets the requirements of operating at a forest landing site. The technical requirements for the generation source are to provide an electrical output of at least 20 kW_e and be able to ramp up or down at a rate of 1 kW_e/s. Each technology was scored based on its performance for each criterion. The criteria for the remote power device include:

- Mobility - easily transport between forest operations sites without impeding operation.
- Footprint – small area of the device such that it fits at a forest operations site without impeding operations.
- Reliability - proven, measured long-term performance and access to energy on demand.
- Operator intensity - low level of labor hours required to operate.
- Load following - provide power to meet the expected electrical demand and profile, including quickly ramping up and down.
- Environmental impact - Not likely to cause significant damage to the environment or human health. Examples of this include particulate and/or greenhouse gas emissions, hazardous material spills, and forest fires.
- Initial cost - low capital cost.
- Operating cost - low lifecycle costs over a 20-year lifespan including fuel, maintenance, labor, and replacement parts.
- Safety - does not have any known unmitigated safety or fire hazards.
- Permitting - relatively easy to obtain permit to operate the device in the forest.

4 RESULTS

Table 2 shows the scores of each technology evaluated for the potential to provide power for the BCTs at a forest operations site. The total weighted score is calculated as the sum of the product of each criterion weight and the raw criterion score of each technology. Higher raw criterion scores indicate better performance across all criteria. Details for the specifications used to determine the raw criterion scores for each technology are summarized in Appendix A. Criterion weights were determined by qualitatively assessing the relative importance of each criterion for successful operation at a forest landing site and meeting the goals of the Waste-to-Wisdom project. Criteria with higher weights are more important to successful implementation of a remote power source.

Table 2. Scoring matrix for remote power generation devices.

Criterion	Criterion Weight	Raw Scores Diesel	ORC	Thermoelectric Generator	Biomass Gasifier	Solar Array	Shaft Power
Mobility	9	10	6	3	9	1	4
Footprint	6	10	9	4	10	1	9
Reliability	10	10	5	3	6	7	9
Operational Intensity	7	10	6	6	6	9	8
Load following	10	10	4	4	8	9	7
Environmental Impact	10	4	8	10	8	10	4
Capital Cost	7	10	3	4	7	1	9
Operational Cost	9	9	3	10	6	1	8
Safety	8	8	10	10	7	10	8
Ease of Permitting	5	5	10	10	8	10	10
Total Weighted Score		700	498	511	602	484	595

5 DISCUSSION

As can be seen in Table 2, the diesel generator achieves the highest score followed by the biomass gasifier and shaft power device. This indicates that these power sources would integrate better into forest operations with BCTs than a waste heat conversion device such as the ORC or thermoelectric generator. While the initial and lifecycle costs for the ORC are a setback, the poor load following abilities and reliability of the waste heat resource are the largest operational detriment. During startup and shutdown when waste heat is not available, there would have to be electrical storage or excess fuel to burn to produce heat for the waste heat conversion device. Furthermore, testing performed on the biochar machine found that, even during steady state operation, the waste heat production and electrical demand was highly variable. (See Appendix B, Figure B.1 and Figure B.2), Therefore, the machine might stall or shutdown when peaks in electrical power demand correspond to a decrease in waste heat. Lastly, the ORC can not be quickly ramped up or down if its power output is solely dependent on an inconsistent waste heat resource. An ORC may require a dump load to shed excess electricity during quick decreases in the load or a battery bank to meet sharp increases in the load. The cost of these supplemental systems are not included in the rankings above.

A biomass gasifier, which received the highest score for a renewably fuelled device, is best aligned with the overall research objective and goals of the Waste to Wisdom project because it can be fueled from a side stream of the feedstock going to the BCTs. A gasifier is expected to perform well at a forest operation site because it is mobile and has a small footprint that is comparable to a diesel generator. The only physical connection between the gasifier and the BCT is an electrical cable, thus this remote power source does not impede the mobility of the BCT because it can easily be disconnected for transportation. The load following capabilities are also a benefit of the gasifier because it varies the fuel rate to match its electrical production with the load or uses syngas stored within the system to meet small surges in load. Furthermore, the gasifier has lower initial costs than the waste heat to power devices. Lastly the gasifier is expected to have a moderate level of operational intensity, which requires refilling the feedstock hopper, emptying ash, and cleaning tar filters on a daily basis.

While the shaft power device also performed well in this assessment, it is not a commercially available product and would be difficult to test in a laboratory or coupled with a BCT because SERC does not have access to a commercial grinder or chipper that could be modified.

6 CONCLUSION

Based on the results outlined above, a biomass gasifier is the recommended alternative to a diesel generator because of its reliability and mobility at a forest landing site. Furthermore, in the current market a gasifier has lower capital and lifecycle costs than the other alternatives presented above, and the load following characteristics specified by the gasifier manufacturer are expected to meet the variable loads of the BCTs.

7 FUTURE WORK

A 20 kW Power Pallet PP20GT biomass gasifier produced by All Power Labs, Inc., as shown in Figure 1, was purchased and delivered to Schatz Energy Research Center. The gasifier has been commissioned and is currently being instrumented to measure mass and energy flows through the system. The specification sheet for this gasifier is provided in Appendix C. The testing plan is under development for a the series of laboratory and field tests to occur during spring and summer 2016.

Figure 1. Biomass gasifier with engine generator rated at 20 kW_e produced by All Power Labs. Image credit: All Power Labs, 2015.

Testing will begin in a controlled, laboratory environment during March 2016. A consistent feedstock will be supplied to the gasifier to assess the reliability and performance of the generator. Performance will be evaluated by controlling the load, which will be ramped up and down on a predetermined schedule while measuring the electrical output.

Assuming positive results of laboratory testing with a controlled load, the gasifier will be connected to the biochar machine to evaluate the field performance of the gasifier. Field testing will occur in northern California in July 2016. The biomass gasifier will power the biochar machine, and waste heat from the biochar machine will be used to dry incoming feedstock with a Norris Thermal Technologies Belt-o-matic 123B belt dryer. This testing will attempt to demonstrate a stand-alone biochar production system, which dries feedstock from 30% moisture content to 18% moisture content, an acceptable moisture content for input to the biochar production machine and biomass gasifier. A preliminary flow diagram for this system is shown in Figure 2.

Results from the laboratory and field tests will be distributed in part two of this report within the following year.

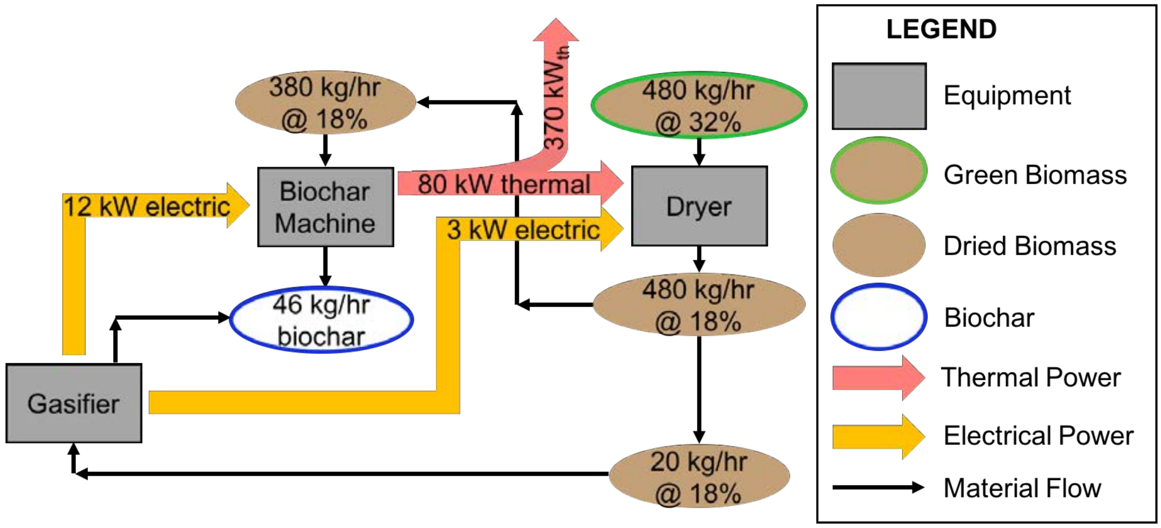

Figure 2. Preliminary flow diagram for integrated biochar system.

APPENDIX A SPECIFICATIONS FOR POWER GENERATION TECHNOLOGIES

This appendix presents the detailed specifications used to generate the raw scores in Table 2, above. The detailed specifications are shown below in Table A.1.

Table A.1. Specifications for alternative remote power technologies.

	Diesel	ORC	Thermo-electric	Biomass Gasifier	Solar Array	Shaft Power
Make	Multiquip	Infinity Turbine	Hi-Z	All Power Labs	GreenTow	Mecc Alte
Model	DCA25SSIU 4F	IT50	HZ-20	PP20	GT3049	Eco-32
Power (kW)	27	25	20	20	20	20
Lifetime (yr)	20	20	20	20	20	20
Mobility	Standalone, trailer mount	Tied to BCT location, Skid-Mounted	Tied to BCT Location, Custom trailer mount	Standalone, Pallet Mounted	10 large trailers	Tied to chipper and BCT location
Footprint	24 ft^2	80 ft^2	567 ft^2	20 ft^2	6000 ft^2	Small
Reliability	Good	Low, depends on waste heat resource	Low, unproved technology at this scale	Medium, long term reliability is not proven	Medium, unreliable resource	Good, reliability depends on chipper
Operational Intensity	Low	Medium	Medium	Medium	Low	Low
Load Following	Good	Poor	Poor	Good	Good	Medium, available capacity depends on chipper use
Environmental Impacts	Diesel; SO_2, NO_x, GHGs	Working fluid is HFC	No	Should be Carbon Neutral	No	Diesel; SO_2, NO_x, GHGs
Capital Cost, total	$27,000	$160,000	$120,000	$45,000	$1,149,000	$23,000
Capital Costs, $/kW	$1,000	$6,400	$6,000	$2,250	$57,450	$1,150

Table A.1. Specifications for alternative remote power technologies. (continued)

	Diesel	ORC	Thermo-electric	Biomass Gasifier	Solar Array	Shaft Power
Operation Cost, NPV	$56,667	$168,000	$30,000	$75,200	$323,380	$52,333
Amortized Operation Cost, $/kW/year	$168	$539	$120	$302	$1,297	$210
Safety	Fire hazard, Combustion	None	None	Fire hazard, Combustion, Potential CO hazard	None	Large belt drive, Fire hazard, Combustion
Ease of Permitting	Air Quality Permit	None	None	Air Quality Permit	None	Falls under Chipper's Air Quality Permit

APPENDIX B BIOCHAR MACHINE ELECTRICITY AND HEAT OUTPUT

Testing the biochar machine showed that the waste heat production and electrical demand are highly variable during steady state operation of the machine. Figures B.1 and B.2 show the distribution of waste heat production and electrical demand, respectively, for 14 test runs performed in August 2014.

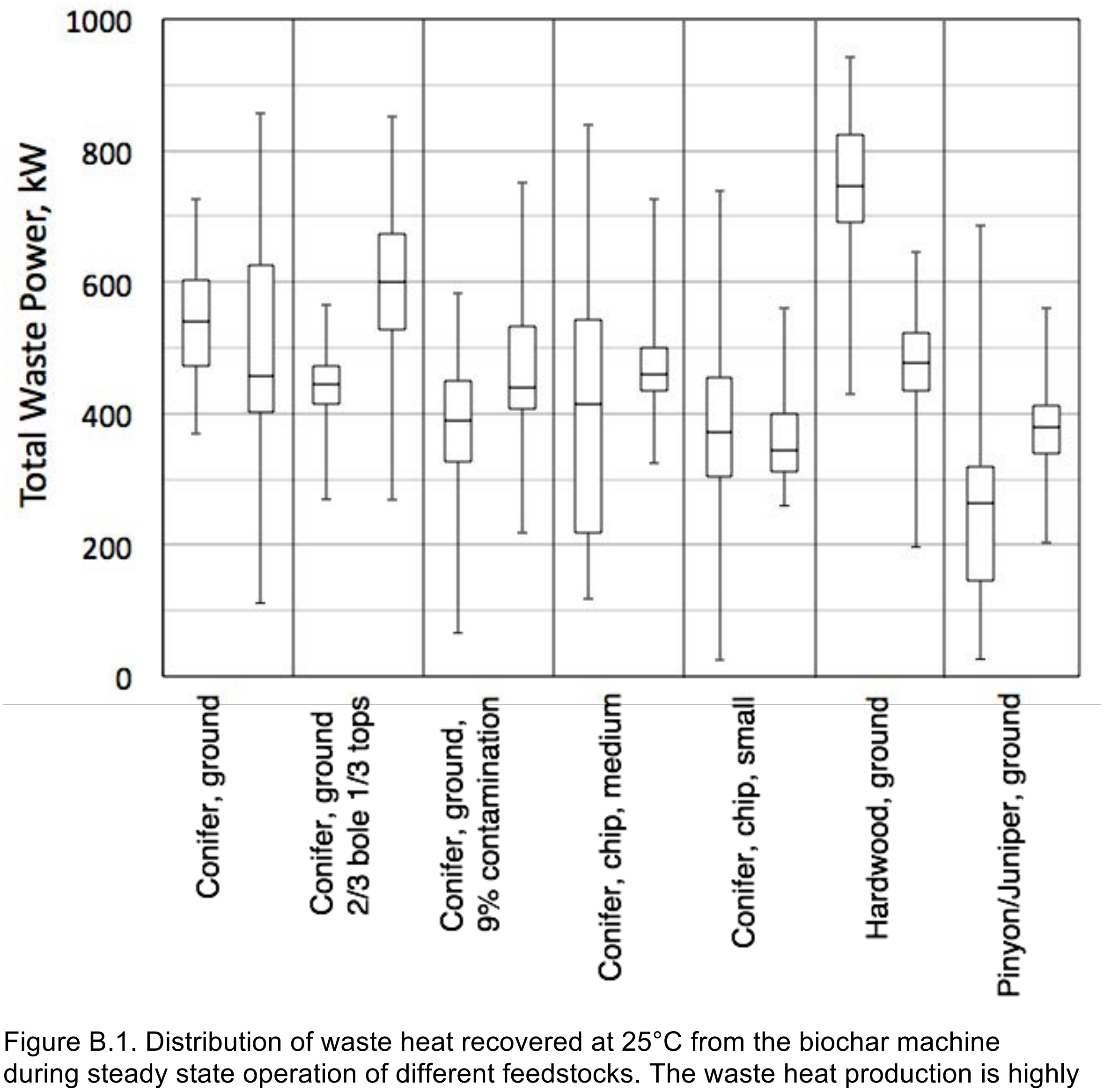

Figure B.1. Distribution of waste heat recovered at 25°C from the biochar machine during steady state operation of different feedstocks. The waste heat production is highly variable based on combustion conditions in the reactor and flare. The error bars represent the minimum and maximum values, and the boxes show the first quartile, median, and third quartile.

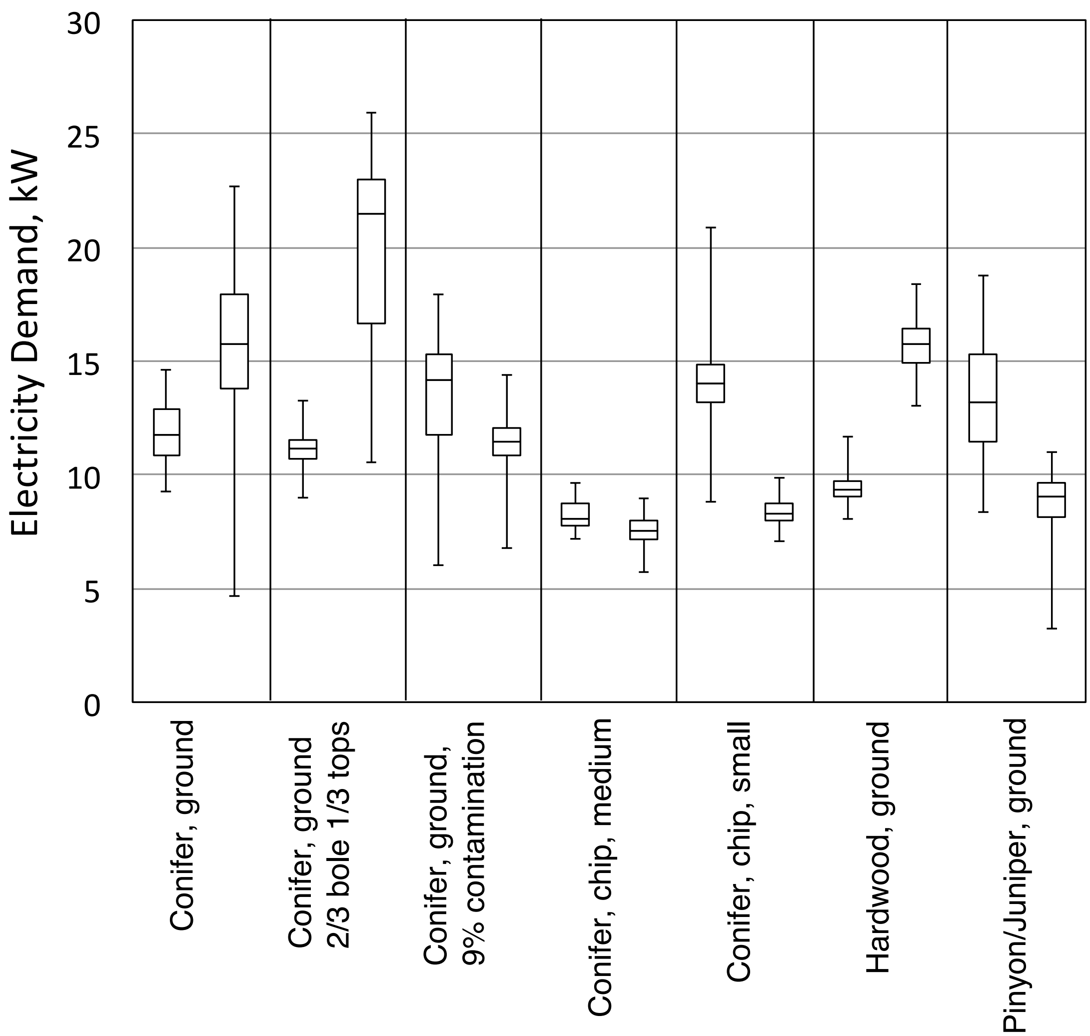

Figure B.2. Distribution of electrical demand of the biochar machine during steady state operation of different feedstocks. The electricity demand is highly variable based on reactor bed depth and motor speed. The error bars represent the minimum and maximum values, and the boxes show the first quartile, median, and third quartile.

APPENDIX C GASIFIER SPECIFICATIONS SHEET

This appendix includes the specification sheet for the biomass gasifier from All Power Labs (2015) accessed 18 May 2015 <http://www.allpowerlabs.com/wp-content/uploads/2015/05/PP20GeneratorOneSheet2_18_15Press.pdf>.

ALL POWER LABS

Personal-Scale Power

POWER PALLET - PP20

RENEWABLE
AFFORDABLE
ON-DEMAND
POWER

PP20 - Basic Configuration

The **Power Pallet** is a renewable power solution that is a sensible answer to a critical global problem. It meets the expectations for portable on-demand generators, is proudly made in California and available now at an affordable price.

APL's unique patented multi-stage gasification architecture, in combination with our innovative gasifier-engine thermal integration, our electronic control system and waste-heat recycling, gives the Power Pallet unprecedented biomass fuel flexibility and efficiency.

The Power Pallet uses agricultural and forestry waste materials that can be readily sourced very near the point of generation. It is compact and portable, easily transported in the bed of a pickup truck to where the fuel is and where the power is needed. Unlike diesel fuel or gasoline, this fuel is often available at little or no cost, and most importantly, depending on feedstock selection and use details, the Power Pallet can avoid the carbon impact of fossil fuels.

PERFORMANCE

Continuous Power Rating:	15 kW@50 Hz/18 kW@60 Hz
Sound Level @ 30 feet:	85 dB(A)
Biomass Consumption:	1.2 kg/kWh, 2.5 lbs/kWh
Run Time per Hopper Fill: approximate @ 250 kg/m^3 fuel density	5 kW: 10 hrs 10 kW: 5 hrs 15 kW: 3 hrs
Max. Continuous Operation:	>12 hours
Start Up Time:	10-20 min.

OPERATING CONDITIONS

Ambient Temperature:	5-40°C/40-100°F
Humidity:	5-95% RH
Installed Footprint: without ash vessel or grid tie	1.36 x 1.36 m 53.5 x 53.5 inches
Site Requirements:	Well-Ventilated protected from rain & direct sun

FEEDSTOCK BIOMASS

Size:	12-40 mm/0.5-1.5 in.
Moisture Content:	10-30% dry basis
Approved and Tested w/ normal operating procedures	Walnut Shells Softwood Chips (e.g. Fir, Pine) Hardwood Chips (e.g. Oak, Ash)
Approved and Tested w/ increased operating effort	Corn Cobs Coconut Shells Palm Kernel Shells
Not Approved dangerous & voids warranty	Coal Tires Plastic Municipal Solid Waste

SHIPPING

Dimensions:	PP20 - Crated Hopper - Crated	145 x 145 x 140 cm/57 x 57 x 54 in. 83 x 83 x 114 cm/33 x 33 x 45 in.
Weight:	PP20 - Crated Hopper - Crated	700 kg/1550 lbs. 91 kg/200 lbs.

FUEL COST COMPARISON (VARIES by REGION)

FUEL	PRICE RANGE
Diesel/LPG	\$0.40 - \$0.75/kWh
Gasoline	\$0.50 - \$1.00/kWh
Gasified Biomass	***\$0.00 - \$0.20/kWh***

All specifications are subject to change without notice

Mecc Alte NPE32 Genhead GM Vortec 3.0 I.C. Engine

ALL Power Labs

APL is the global leader in small-scale gasification technology. We make biomass-fueled power generators that are ready for everyday work, to serve real-world, distributed-energy needs. Our compact gasifiers are now at work in over thirty countries, and support research at more than fifty universities around the world.

Our APL team is an unusual combination of hands-on fabricators and university-trained scientists and engineers. The result is a powerful combination of technical ability and physical know-how for developing innovative energy solutions.

We are deeply committed to supporting and developing biomass energy conversion by curating and disseminating comprehensive information and data on gasification science and technology—online, in workshops, and free Open House events.

Our facility is in Berkeley, CA. Please contact us to arrange a visit the next time you are in the Bay Area. We'd love to show you around.

WARRANTY

ALL Power Labs products are covered by a 100% money back guarantee. If you buy something & find yourself unimpressed with the value of the product or company, we'll refund all your money (minus shipping costs) within 30 days of delivery. APL directly warrants all parts we manufacture (i.e. gasifiers, electronics, & related components) for two years or 4000 hours, & passes along the OEM warranty for parts we source & configure into our end products (e.g. engines & genheads). See **http://allpowerlabs.com** for full details.

GASIFIER

Type:	APL v5 Patented Thermally Integrated Downdraft
Materials:	304 SS/310 SS/ 321 SS/mild steel
Hearth:	Coated Ceramic
Ash Removal:	Automated 12 hour batch vessel
Fuel Feed:	Automated
Hopper Capacity:	0.33 m^3/88 gallons
Hopper Filling:	Batch - refill while operating
Min. Maintenance Cycle:	~ 12 hours
Control System:	On-Board Automation

ENGINE

Type:	GM Vortec
Displacement:	3.0 liter
Compression Ratio:	10.25:1
RPM:	1500@50 Hz 1800@60 Hz
Valve Configuration:	Overhead, Pushrod
Engine Block/Cyl. Head:	Cast Iron w/ exh. valve inserts
Ignition:	Solidstate Distributor
Spark Timing:	Fixed
Lube Oil Capacity:	5 quarts - including filter
Coolant Capacity:	11.4 L, 12 qts - incl. radiator
Auto Shutdown:	Low Oil Pressure High Coolant Temperature
Starter:	Reduction Gear PG-260L
Charging System:	Delco-Remy 7-SI (70 A)
System Voltage:	12 V DC
Recommended Battery:	75Ah, 880 CCA Marine
Battery Footprint:	250 x 300 mm/10 x 12 in.
Speed Control:	Electronic Governor Woodward L-Series
Oxygen Sensor:	Bosch Wide Band

GENERATOR

Type:	Mecc Alte NPE32-E/4 12 wire
AVR:	Mecc Alte DSR
Available Voltages:	190-277, 380-480 V AC
Available Topologies:	Series Delta/Star, Parallel Delta
Total Harmonic Distortion:	<5%
Genset Starting:	Manual Handover
Maximum Step Load:	50% of rated power

All specifications are subject to change without notice

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