CALIFORNIA ENERGY COMMISSION

CALIFORNIA NATURAL RESOURCES AGENCY

ENERGY RESEARCH AND DEVELOPMENT DIVISION

FINAL PROJECT REPORT

The Nexus of Clean Energy, Healthy Forests, and a Stable Climate

Innovative Biomass Gasification for Sustainable Forest Management

March 2024| CEC-500-2024-023

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ACKNOWLEDGEMENTS

The authors thank the project partners and the persons at All Power Labs who contributed to this project. Our helpful hosts at the Hopland Research Extension Center and the additional project partners in Mendocino were invaluable to this project's success. The efforts of site partners at Anderson Biomass Complex are also greatly appreciated. Our technical partners at the Schatz Energy Research Center and RadKEM provided excellent and thorough work that was critical. Our Technical Advisory Committee gave the project team valuable insight, and we wish to acknowledge Ray Kapahi, Tom Miles, and Farshid Zabihian for their expertise.

Lastly, over the course of this project, in addition to the authors of this report, many individuals from All Power Lab contributed to this project including: Alejandro Abalos, Brigitte Abalos, Giulio Allesina, Joel Armin-Hoiland, Bill Bayer, Nick Bindbeutel, John Collantes, Chuck Encarnacion, Ariel Fisk-Vittori, Alex Gorospe, Jacob Harris, Isolde Honoré, Sam Kaufman-Martin, Abinashi Khalsa, Ellora Larson, Austin Liu, Adrienne Lemberger, Noah Levine, Juan Martinez, Jim Mason, Nicolo Morselli, Andrew North, John Mortera, Simone Pedrazzi, Marco Puglia, Brendan Quinlan, Randy Reali, Christine Salamante, Sarah Schubert, Taran Smith, Ferdinand Vinoya, Herman Vinoya, Baylis Weaver, Tristan Wells, and Eli Whipple. Any omissions or errors are strictly unintentional and regretted.

PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission, and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation, and bring ideas from the lab to the marketplace. The EPIC Program is funded by California utility customers under the auspices of the California Public Utilities Commission. The CEC and the state's three largest investor-owned utilities—Pacific Gas and Electric Company, San Diego Gas and Electric Company, and Southern California Edison Company—were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The CEC is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

The Nexus of Clean Energy, Healthy Forests, and a Stable Climate: Innovative Biomass Gasification for Sustainable Forest Management is the final report for the project EPC-17-017 conducted by All Power Labs. The information from this project contributes to the Energy Research and Development Division's EPIC Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the Energy Research and Development Division at ERDD@energy.ca.gov.

ABSTRACT

All Power Labs (APL) developed two related technologies to manage wood waste in California. The first is a combined heat and power microgrid solution that provides 50 kW of on-demand, renewable energy. The second is the Chartainer, a high-throughput waste processing solution that produces combined heat and biochar at commercial scales.

These two technologies were developed in parallel during the five-year agreement term, processing forestry waste with a goal of reducing wildfire risk related to the dead tree crisis, based on a model for funding and scaling proactive forestry management and wildfire remediation. APL improved the efficiency of its existing technology, designed a remote monitoring system, created certified high-quality biochar, and created a new derivative product line that meets the needs of larger-scale customers and forestry agencies.

Keywords: renewable energy, waste management, biochar, biomass, wildfire mitigation

Please use the following citation for this report:

Booth, Nesdon, Bear Kaufmann, and Justin Anthony Knapp. 2023. *The Nexus of Clean Energy, Healthy Forests, and a Stable Climate: Innovative Biomass Gasification for Sustainable Forest Management*. California Energy Commission. Publication Number: CEC-500-2024-023.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Executive Summary

Introduction

California has prioritized renewable energy as an important source of energy for the state and, as a result, its related policies and initiatives on this matter are supported by academia, industry, and other institutions. To further the state's renewable energy goals, more resources must be provided to investigate all technological solutions to the large-scale and systemic needs of energy policy. One underappreciated renewable energy technology is biomass as a waste-to-energy and carbon sequestration pathway, which can meaningfully complement other renewable energies such as solar, wind, hydro, and geothermal. Public funding and private adoption of other renewables has far outpaced biomass energy in the early 21st century. Meanwhile, California has experienced historic droughts and a beetle infestation that has left over 150 million dead and dying trees. Public entities such as forestry and disaster relief agencies, have a mandate to responsibly manage this biomass to avoid wildfires which have been catastrophic in many communities. Additionally, private entities, such as green waste recycling yards and agricultural producers, must process significant amounts of material to be profitable.

All Power Labs (APL) has been a global leader in small-scale gasification and pyrolysis, chemical processes that can convert woody biomass, such as wood chips or nut shells, into electricity and heat, as well as a physical co-product of biochar. Biochar is a lightweight form of charcoal, made of carbon and ash that remain after burning biomass.

Project Purpose

This project developed a commercial-scale combined heat and power (CHP) machinery known as the Powertainer+'s (PT+) composed of gas, heat, and biochar making components called the Chartainer (PT+ Chartainer or CT), and a 50-kilowatt (kW) Microgrid-CHP Power Pallet (PP) Container. These two units are complementary biomass waste-to-energy solutions, and the 50-kW unit is designed to work as a standalone power generation option or along with other technologies in a microgrid, a localized electrical grid that can produce electricity for use onsite or to export elsewhere, including the utility grid. This solution would be larger, more efficient and fuel flexible, allowing for improved operations and maintenance and greater efficiency and biochar production. In particular, the project team had the objectives of achieving 60 percent CHP efficiency, developing remote monitoring capabilities, and introducing this revised technology in the field with real-world applications. Successful development of the Powertainer+ would result in lower costs for ratepayers by having distributed power generation, as well as safer and more resilient communities via wildfire mitigation and clean power production from the woody biomass derived from forestry, green waste recycling, and agriculture. The project team also expects commercial partners will find that this unit solves the related waste management, off-grid power generation challenges, to use biochar for agricultural soil amendment and carbon sequestration purposes.

Project Approach

The project team at APL has expertise in the domain of gasification and pyrolysis, chemical processes that convert waste biomass into the useful products mentioned earlier. This team was aided by partners from the University of California, Hopland Research Extension Center (HREC) and other project partners in Mendocino, California who hosted and operated machinery, alongside the project team, to test out a real-world application of the technology in a post-wildfire burn context. The project team also engaged with several academics from the Schatz Energy Research Center of California State Polytechnic University, Humboldt, the consulting firm RadKEM, and testing laboratories who validated the completed work and provided guidance on proper measurement and verification.

With guidance from the technical advisory committee (TAC), the project team overcame some significant challenges to build the initial Powertainer+ design, related to cost, reliability, and form factor of the product. This committee included air quality consultant Ray Kapahi, wood science and biochar expert Tom Miles, and Sacramento State professor of engineering Farshid Zabihian.

The project team initially designed the Powertainer to be a single unit housed in a shipping container. The single unit was split into two technologies, the Chartainer and the CHP Microgrid Power Pallets, that were better suited for different customer needs and use cases. The Chartainer is a large-scale biomass processing unit that focuses on higher throughput for combined heat and biochar that was derived from the earlier Powertainer design during this agreement. This unit does not generate electricity and can be used in completely remote applications where biomass cleanup at scale is the priority. Two 50 kW microgrid CHP Power Pallet units were also created and tested. These latter units took All Power Labs' existing Power Pallet platform and containerized it, pairing it with a new balance of systems, such as a revised feed system, that made it more effective and usable for partners needing off-grid power. Several rounds of engineering validation occurred that explored the characteristics of the biochar produced, the system efficiency, the remote monitoring capabilities, and emissions profile from the new 50 kW system.

Project Results

The project was successful in creating the two products and using them in some real-world and controlled environments. The project team was not able to use the Chartainer unit due to a fire at the proposed site, the Anderson Biomass Complex, and had to shift to performing all testing and demonstration on the manufacturing site. However, the team used a CHP Biomass Microgrid 50 kW unit at the HREC. The engineering validation and measurement and verification stages of the project were mostly successful, with overall power generation output, biomass throughput, and biochar and emissions characteristics meeting the research goals and, in some cases, surpassing expectations. However, the system efficiency was slightly lower than the research target because of slight variance in performance. This work was encouraging as it opened new avenues for further exploration, research, development, and commercialization. Next steps include producing the units developed, refining the remote monitoring system, and developing relationships with new project partners. The value of biochar as a co-product has resulted in a fundamental shift in outreach efforts and the company's mission for carbon sequestration, as well as opening new avenues for deployment. In particular, the Chartainer unit was more efficient at producing biochar on a per-mass basis than previous Power Pallet units, with strong implications for commercial partners and end users who may not have a need for the power generation aspect of this solution.

The unexpected necessity of splitting the Powertainer into two derived systems proved key to these insights. For instance, agricultural partners who may have seasonal biomass cleanup needs will benefit from Chartainer by applying biochar to soil for improved water retention, heartier crop growth, and reduced need for fertilizer and other amendments. The implications of this new market for co-products from the technology solution are still being explored by the project team. For customers requiring off-grid power, the 50 kW CHP system is perfect for its design and implementation of feed systems and remote monitoring capabilities that will greatly reduce its operations and maintenance costs, making this technology far more viable in the market.

The total addressable markets for waste management, renewable energy production, and biochar for agricultural purposes are significant. More biochar applications, like water filtration or industrial materials like concrete, will be explored.

The project team has several recommendations for fostering market adoption of this solution including:

- Catalytic funding opportunities which encourage public–private partnerships and grants that can complement these.
- Reduced regulatory overhead for short-term grant-funded projects so deployment during the agreement project period is realistic.
- Greater development of carbon sequestration markets.
- Funding for research and development and deployment of these solutions.

APL's future research may include creating an even more fuel flexible and modular solution that incorporates the core technology developed for different use cases, new applications of biochar in fields as diverse as building materials or industrial filtration, and refinement of the remote monitoring system to allow for real-time intervention.

Technology/Knowledge Transfer/Market Adoption (Advancing the Research to Market)

The project team explored new potential customers, on a larger scale than the previous Power Pallet technology at facilities with higher demand and including new kinds of markets, such as creating and using biochar as a soil amendment. Project team staff engaged with information stakeholders by hosting open houses and demonstrations onsite, attending industry events, participating in a marketing campaign, and publishing outreach materials. Target audiences included students, investors, and potential adopters of the technology in private and public sectors.

Benefits to California

APL’s biomass conversion technology is crucial for California ratepayers who have experienced high electricity costs and intermittent power from public safety power shutoffs and the devastation of wildfires. If adopted at scale, the technology developed in this project will not only reduce the cost of power generation by introducing more clean, local power production, but also fit into wildfire mitigation schemes, thereby increasing community resiliency. These benefits will be particularly pronounced for frontline and underserved communities, which are most vulnerable to the effects of climate change, as well as rural communities which rely most heavily on maximizing precious resources and being self-sufficient.

Economic savings come from the unique combination of benefits that biomass waste-to-energy conversion provides, from diverting waste streams of little or no value at processing sites, to avoiding costs associated with hauling material, to the multiple co-products from biomass processing. The electrical power, heat, and biochar can all be monetized to offset costs and realize economic gains for end users. As a supplement to the utility grid, this technology could avoid the great costs associated with shutoff events. If deployed at scale and used as part of a comprehensive wildfire mitigation and forestry maintenance strategy, this technology could be key to avoiding the costs of wildfires.

CHAPTER 1: Introduction

This project developed a commercial-scale combined heat and power (CHP) machinery known as the Powertainer+'s (PT+) composed of gas, heat, and biochar making components called the Chartainer (PT+ Chartainer or CT), and a 50-kilowatt (kW) Microgrid-CHP Power Pallet (PP) Container. These two products are independently operating multimodal power platforms that will generate low-cost renewable energy, process thousands of tons of forestry waste derived from California's unprecedented tree die-off and sequester massive amounts of carbon. The Chartainer went through design, testing, and demonstration at the All Power Labs (APL)'s Berkeley, California headquarters, while the 50 kW CHP PP Container was installed at a university research site in Hopland, California where it generated power off-grid. A second unit was built to demonstrate to the California Energy Commission and to gather testing data at APL headquarters. As California transitions to renewable energy, biomass power is one of several complementary technologies that has the potential to replace fossil fuels. Biomass provides dispatchable generation capability, which can be used on-demand and can complement non-intermittent technologies such as wind or solar.

The project team attempted to overcome technical hurdles related to previous work on the PT+ platform and to advance market adoption of these waste-to-energy solutions. Initial iterations of the PT+ were built into a single shipping container, generating CHP and biochar from woody biomass waste and this project originally sought to substantially upgrade the power output from this unit as well as increase overall system efficiency. During this project, this integrated design shifted to being a two-container solution and eventually, the two independent derived technologies mentioned above. The project team found that the combined PT+ platform was difficult to engineer with engines and electrical output at commercial scales that required substantially more design and development than could be achieved in the life of this grant agreement. Consequently, the team shifted to the two resulting units: Chartainer and the CHP PP container. Additionally, the original PT+ design was not sufficient to meet market needs: the project team found that customers rarely had the exact use case required for the substantial power output of the PT+.

The Chartainer met a market demand for high-throughput biomass consumption and the CHP PP container was designed to meet the needs of microgrid users, on-grid and off-grid. Different users require different outcomes from biomass processing and the Chartainer is a solution for biomass consumption without power access (such as in completely off-grid settings, clearing forestry waste), while the 50 kW CHP PP Container meets the needs of users that have power. The project team was able to identify these new markets during this project and to provide outreach to new customers who would not otherwise find the PT+ a solution.

Initially, these technologies are an appropriate waste disposal method. In the 21st century, California has experienced devastating droughts and a beetle kill that left tens of million dead and dying standing trees (Solis, 2023). There are no clear solutions nor management for this amount of biomass waste and transporting it from across the state to centrally located processing plants would be uneconomical, as well as increase emissions. Furthermore, responsibly processing this biomass is necessary to avoid the catastrophic and prolonged wildfire seasons. Providing a solution for this waste is a matter of public health and safety. The Chartainer cleared away post-burn material and could be leveraged as part of a larger biomass management strategy in the future.

The 50 kW CHP PP Container successfully generated productive power during this agreement.

Lastly, the physical co-product of biochar represents long-term carbon sequestration. The biochar that is being produced is pure, stable, and remains in soil for centuries that result in net *negative*-emissions. The benefits of biochar in soil include heartier plants, more mineral-rich land, greater water retention, and reduced run-off. In this agreement, the project team generated significant biochar and has an existing network of agricultural partners who applied it to soil.

The specific goals of this agreement were to:

- Reduce wildfire risk related to the tree mortality crisis.
- Provide a financial model for funding and scaling proactive forestry management and wildfire remediation.
- Produce renewable bioenergy to spur uptake of renewable bioenergy projects, and to meet California's other statutory energy goals.
- Create clean energy jobs throughout the state.
- Reduce energy costs by generating cheap net behind-the-meter energy.
- Accelerate the deployment of distributed biomass gasification in California.
- Mitigate climate change through the avoidance of conventional energy generation and the sequestration of fixed carbon from biomass waste.

The project team has identified several market players who can use these solutions post-award, including:

- Forestry and urban waste management agencies and companies, who need cost-effective solutions to convert waste liabilities into assets. Additionally, these entities benefit from the mobile nature of the technologies that allow for onsite conversion, rather than the costly transportation of material.
- Disaster relief agencies and rural communities that need on-demand power generation in times of crisis.
- A variety of agricultural partners, from the scale of backyard composters to community farms and gardens and industrial partners producing compost at scale who can adopt local carbon sequestration techniques.

A primary objective shared by both products was the refining of their combined heat and power/combined heat and biochar (CHP/CHAB) modules aimed at significant increases in their energy conversion efficiency. Another shared objective was developing remote monitoring capabilities with the goal of improving operability, reliability, and serviceability, cutting operator labor, thereby reducing operational expenses.

This project has successfully explored solutions for consumers who can benefit from locally manufactured technology to clear forest waste and help avoid the disastrous wildfires that devastate California communities, create clean power, and provide long-term carbon capture.

CHAPTER 2: Project Approach

The complex intersection of multiple crises in California: tree mortality, wildfire, waste management, and renewable energy demands, requires more aggressive solutions at larger and more economically viable scales.

The project team's solution was to develop innovative technology in the form of a larger combined heat and biochar (CHAB) product called the Chartainer (Chartainer, CT); and to update existing Power Pallets to increase biomass throughput and energy output by pairing two units into a containerized solution that can accept larger-scale continuous feed of waste biomass material. These two technologies are stand-alone units that can combine into a new, larger system to increase biomass throughput that meets the needs of growing waste streams from forestry, agriculture, and other green waste sources. The Chartainer and 50 kW PP30 Microgrid Container, APL's latest generation of the Power Pallet biomass gasifier, allow these systems to address a wider range of use cases and expand the climate and forest-health goals underlying the project to reduce wildfire risk related to the tree mortality crisis. A primary objective shared by both products was to significantly increase their energy conversion efficiency. Another shared objective was the development of remote monitoring capabilities with the goal of improving operability, reliability, and serviceability, cutting operator labor, thereby reducing operational expenses.

The project team was assisted by partners at the University of California, Berkeley Hopland Research Extension Center (HREC), at Hopland, California, who helped with an in-field installation, as well as the owners of the Anderson Biomass Complex (ABC) who helped designate a site that would have had a second installation if a fire had not severely interfered with these plans. Additionally, academics with backgrounds in material science and chemical engineering doing business as RadKEM wrote the final Measurement and Verification Report, which was based on a plan designed by the Schatz Energy Research Center at California State Polytechnic University, Humboldt. Finally, the project team was given invaluable guidance by the technical advisory committee, which included air quality specialist Ray Kapahi, biochar and wood processing expert Tom Miles, and mechanical engineer Farshid Zabihian, who has an appointment at Sacramento State University.

Methods developed to achieve the technology included a scale-up of the project team's swirl hearth gasifier, a proprietary technology that allows for particularly clean biochar production from pyrolysis and gasification of woody biomass as well as the creation of a remote monitoring system to allow for simplified data gathering. Key project milestones were impacted by a scope of work change and the COVID-19 pandemic, but in the last two years of this project, the project team built and installed an in-field unit that ran for more than 500 hours of extended operation, another unit that achieved a successful demonstration of charging an electric vehicle, and a third unit that produced high-quality biochar at scale.

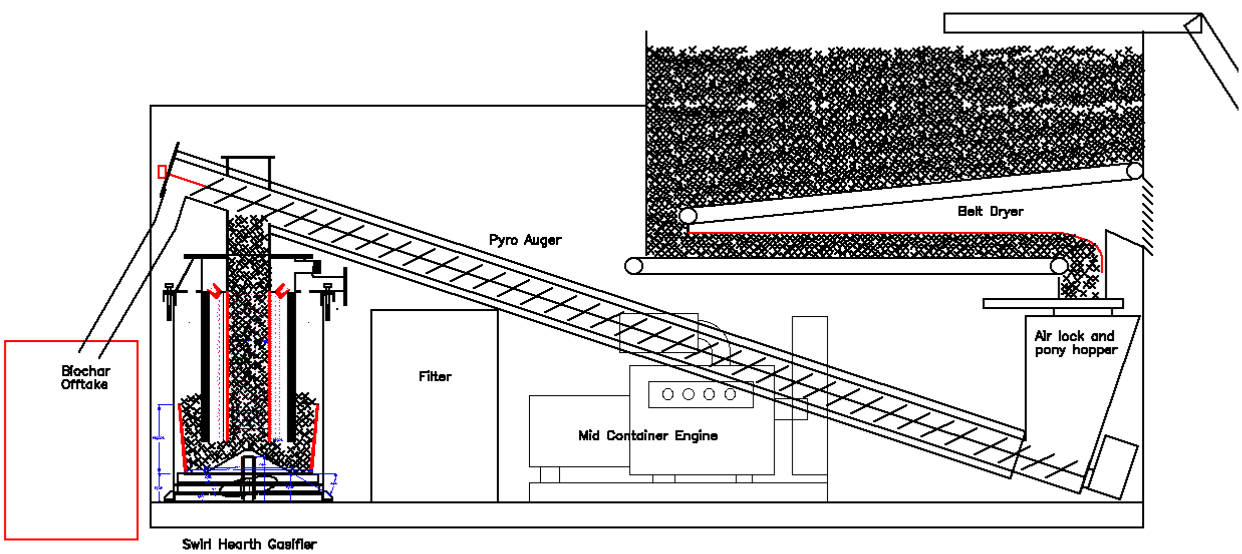
Chartainer

The focus of Chartainer development is to increase the capacity of forest-waste conversion into biochar. Specific technical objectives included the development of APL's novel "swirl hearth" gasification technology and the resolution of various engineering challenges involved in the prototype's integrated subsystems. The project team set out to produce useful and scalable thermal energy by increasing the energy conversion efficiency of the combined heat and biochar module from 20 to 60 percent by capturing heat during the biomass processing cycle. The Chartainer beta prototype demonstrated that it can be commercialized to generate significant revenue streams.

Initial development of the Chartainer happened in parallel to the original Powertainer scope of work and as the project team faced challenges with that initial plan, they shifted to refining the Chartainer's core technology solution. During this agreement, the Chartainer itself was redesigned and rebuilt multiple times, resulting in a final unit that successfully and reliably produced biochar and heat on a larger scale than previous APL technology.

A simple schematic diagram of the Chartainer is shown in Figure 1. Material is fed into the unit at the top-right, where it is dried with recirculated heat from the process. An auger pushes the material toward the gasifier at the far left, where the swirl hearth separates out gasses and biochar. Biochar falls into the offtake vessel to the right and gasses are combusted. Heat is recirculated in the system and a portion is used to dry feedstock.

Figure 1: Chartainer Schematic

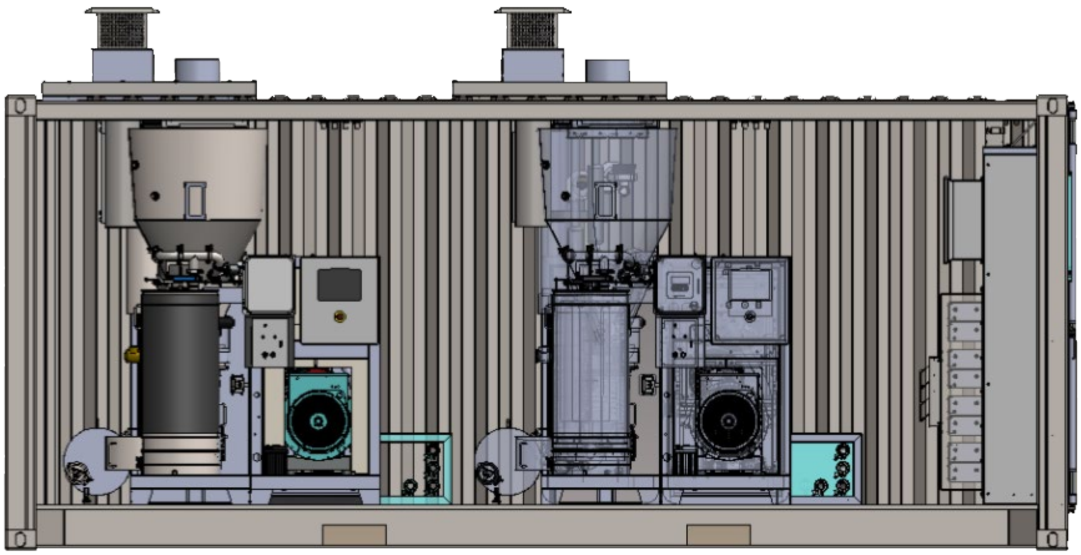


Source: All Power Labs, 2018

50 kW PP30 Microgrid Container

The Power Pallet updates involved the integration of two PP30s with additional balance of system (BOS) components and electrical storage capability into a single 20-foot shipping container envelope, thereby doubling the throughput and simplifying the logistics and value of deployment to project sites (Figure 2). BOS components can be modulated to customer needs but may include elements such as inverters for power export or batteries for power storage. The project team also developed remote monitoring capabilities to reduce operational expenses and verify the new technology's performance improvements.

Figure 2: 50 kW PP30 Microgrid Container Rendering



Source: All Power Labs, 2021

A pilot demonstration project was performed to prove the ability of these products to convert material from a green waste yard into significant revenue streams. APL addressed technical challenges through an iterative process of physical testing and refinement at their Berkeley factory. The team divided the project into various tasks and components based on subsystems grouped by timeline dependencies, required supply chains, and the expertise involved in completing them:

Gasifier Design

- Chartainer (such as combustor)
    - 50 kW Container (for example filtration)
    - Container and weldments
- Biomass feed systems
- Control Systems (such as electrical output)
- Remote Monitoring
- Testing and Validation
- Feedstock Supply

The gasification system uses instrumentation and data logs to monitor and understand system performance and dynamics. The project team performed a combination of on and off-site operations of the systems and used engineering validation testing (EVT) procedures to qualify individual components, as well as the fully integrated system and enable a feedback loop for system improvements. Final performance and emissions testing included 40 hours of full system operations.

Historically, APL had done most of the research, design, and production in-house. Increasing sales had required the development of subcontractor supply chains for various manufacturing and subsystem production. Some of these external tasks were brought back in-house, and some previously in-house activities were outsourced during the grant work due to time constraints, validation requirements, project complexity, and pandemic considerations.

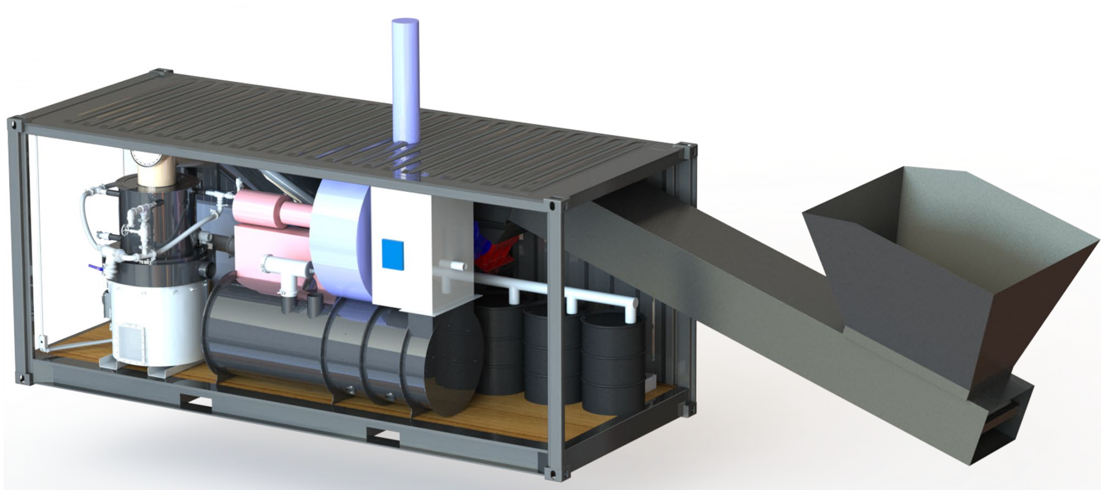
Gasifier Design

Chartainer

The Chartainer's reactor, thermal integration, and feed systems were optimized for high-temperature biochar output (added to compost and used for plant growth), which is valuable because of its monetary and ecological value as an agricultural soil amendment (Figure 3). This was achieved by forgoing electrical power generation and incorporating the proprietary swirl hearth that resulted in pure biochar appropriate for food production. The swirl hearth has an annulus that keeps combustion in a particular area, so biochar falls down a separate column. These zones allow for combustion in a larger volume with cracking of volatile organic compounds at a high temperature that produces a low-tar gas.

To increase the quantity of biochar conversion from forest waste, the project team designed an additional biochar-offtake system to produce low-temperature biochar by diverting pyrolyzed precombustion biochar into a separate collection vessel. While not as useful as a soil amendment, this biochar still stabilizes and allows for sequestration of the carbon contained in the biomass generated by forest-fire-remediation clearing. This would mitigate the potential greenhouse gas emissions if the feedstock had been burned or left on the forest floor to decompose.

Figure 3: Chartainer With Feed System Rendering



Source: All Power Labs, 2020

50 kW Microgrid Container

The historic PP30 development has been based on optimizing and tuning its gasifier to maximize electrical power output. In the context of a waste-processing priority, data and technology developed during the Chartainer's gasifier design and testing will be applied to the refinement of the PP30's gasifier design. The generation of gasifiers used for this project did not include the swirl hearth technology found in the Chartainer for practical and budgetary reasons, but future iterations of the PP30 will find it as a standard feature. APL's Imbert downdraft gasification process has a fixed bed, and the material is static with air injection leading to several zones as the material passes through the system, such as feedstock heating, combustion, and gas reduction.

The final stage of the gasifier's thermal reactions employs a reduction reaction to convert the carbon in the charcoal created during combustion into additional hydrogen and carbon monoxide fractions of the producer gas. Various solid-material handling, metallurgic, and other engineering factors have previously been balanced in such a way that approximately 5 percent of the carbon contained in the feedstock passes through the reactor and collected as high-temperature biochar. It was, therefore, a goal of the project to explore increases in the biochar output percentage that can be achieved by modifications of the control system or physical design of the reactor architecture.

Containerization

The 50 kW PP30 Microgrid Container builds upon independent development of the PP30 system by APL (which paired a PP30 unit with a custom-built material drying solution) and atmospheric water generator. Instead, the units built contain two PP30 units in a modified container. Special attention was paid to building out the containers for concerns such as depositing feedstock into the hoppers at the top of the units, including making a custom feed system and allowing clearances for the combustors on the PP30s as well as basic accessibility to maintenance and for mundane operation.

The wide variety of shipping container applications often require container customization, creating a class of vendors specializing in modification and customization of shipping containers to be used similarly to this project. Rather than purchasing dry storage containers and modifying them in house as was done with previous prototypes, the team opted to subcontract to a custom vendor. To get accurate bids and assure that the other equipment fits properly, careful design and generation of CAD drawings specify the modifications required and created in-house by the team's engineers (Figure 4).

Figure 4: Rendering 50 kW PP30 Microgrid Container With Balance of Systems

Source: All Power Labs, 2020

Installation of the actual PP30 is shown in Figure 5.

Figure 5: 50 kW PP30 Microgrid Container In-Field Installation

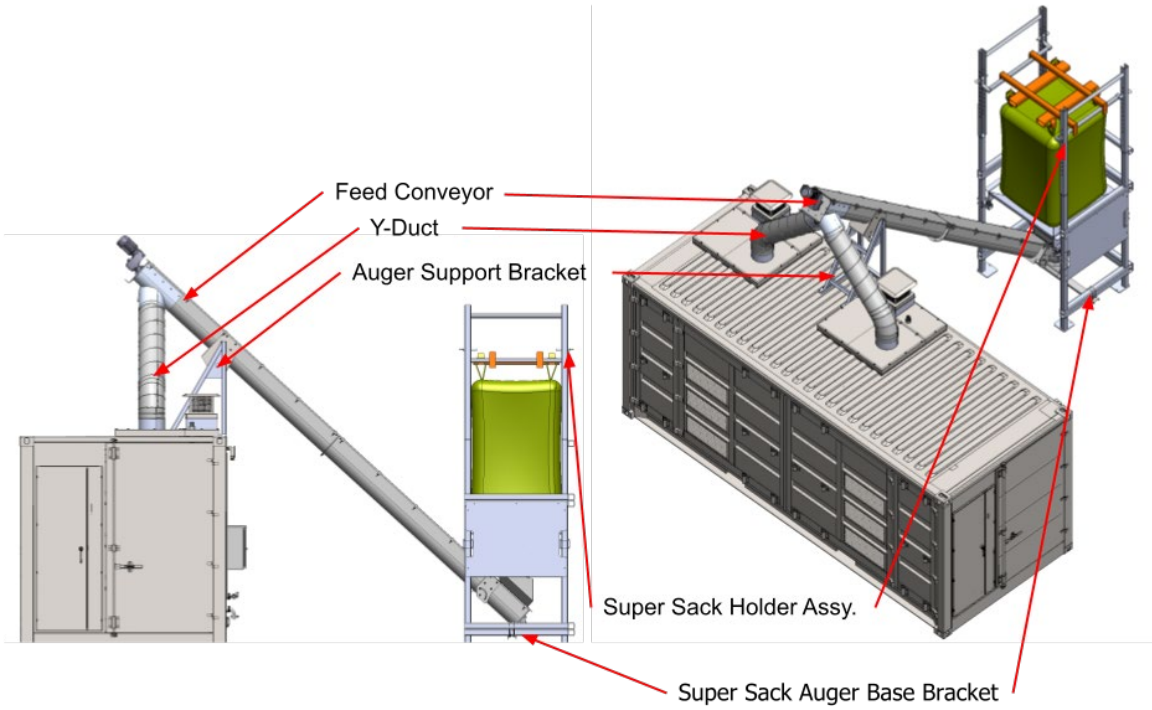
Source: All Power Labs, 2021

Biomass Feed Systems

PP30 Feed Distribution System

Four subassemblies were developed to transfer feedstock from bulk stores into the hoppers of the two PP30s as shown in Figure 6.

Figure 6: Feed Distribution System



Source: All Power Labs, 2020

These four feed components were developed with an iterative design and fabrication process using a combination of off-the-shelf components, in-house fabricated parts, and outside vendors. The goal of this process was to establish a production scheme that allowed for the most cost effective, reliable, and adaptable feed system shown in Table 1.

Table 1: Feed Distribution System

Line #	Subassemblies	Shown In
1	Y - Ducting	Figure 6
2	Feed Conveyor	Figure 6
3	Super Sack Holder Assy	Figure 6
4	Super Sack Auger Base Bracket Weldment	Figure 6

Source: All Power Labs, 2020

Control Systems

Electrical Output

Container Electrical System

The inverter interconnection for grid tied output has stringent compliance standards imposed by the utility where the unit will be installed, and each utility company may have differing requirements to connect to the grid. Electrical components cannot be specified until details of the customer's installation are known, so cabinets, raceways, and other subcomponents are designed to accommodate the maximum range of type and number of components. For the in-field unit built in this agreement, power was only exported to local batteries. A second unit at APL's headquarters was used to charge an electric vehicle.

Electrical Load Capacity

The hybrid microgrid version included a large battery bank. This requires a metal enclosure fixed inside the container. As an optional component, the size and specifications of the load bank items will be dependent on the customer needs, and as such APL sizes the enclosure and raceway to accept the largest capacity and most complex interconnection system. During this agreement, the team identified an inverter system that would have been able to export 40 kW to the utility grid, but interconnection was not completed for the 50 kW PP30 Microgrid Container.

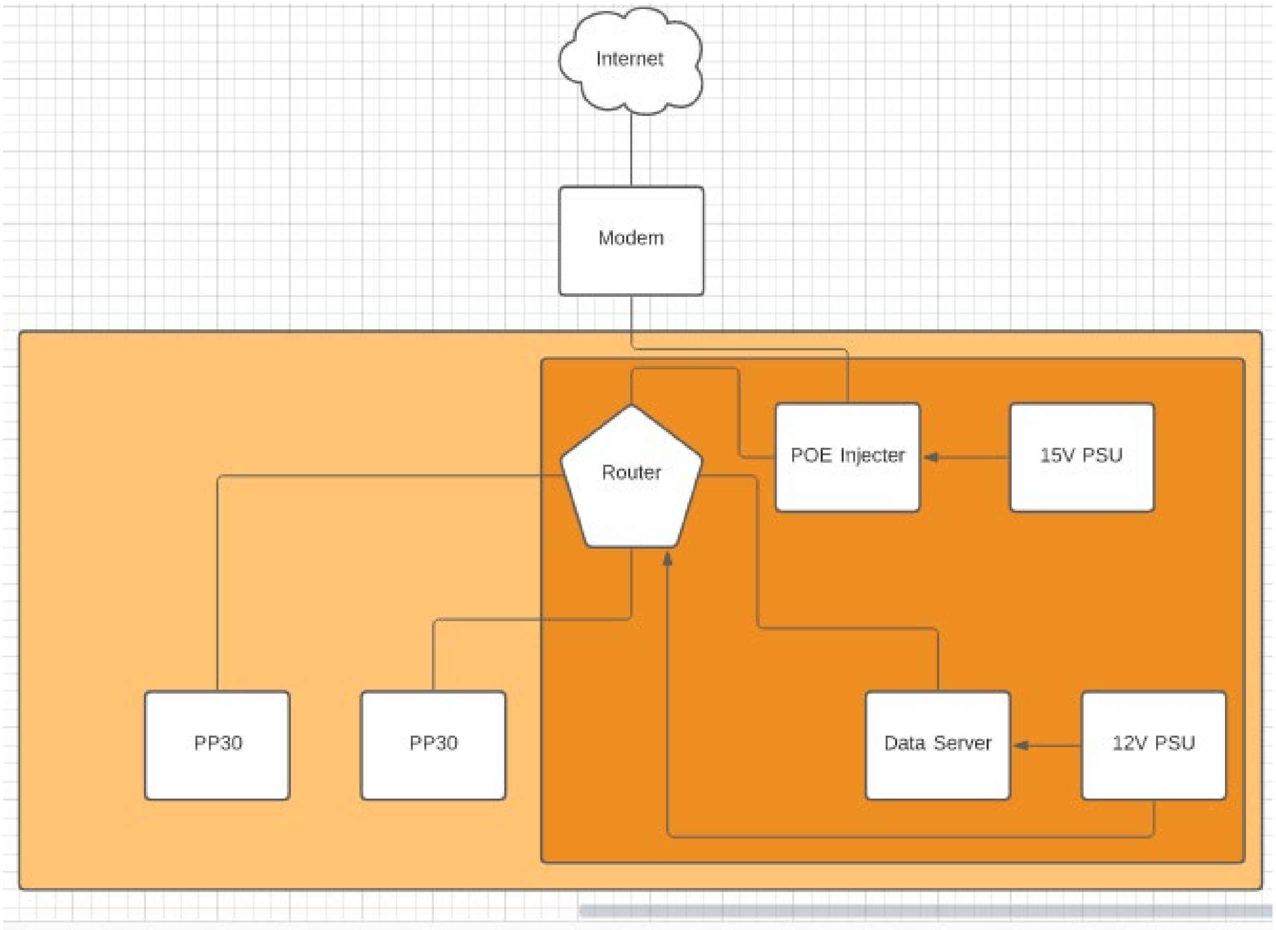
Remote Monitoring

System Design

The PP30 has a variety of sensors that transmit data associated with its operation, including generator frequency, generator voltages, power output, governor throttle position, and engine coolant temperature. The two PP30s need to be connected to a system to collect this data (Figure 7).

- **Data Server:** Stores this data then broadcasts it on a remote Server.
- **Router Connection:** Connects all the subunits together, allowing intercommunication between devices.
- **Modem to World:** Connects to the outside world, allowing technicians to download or view the data.
    - **12V PSU:** A 12 V power supply of electricity to server & router.
    - **15V PSU:** 15 V power supply of electricity to POE Injector
    - **POE Injector:** Allows wires used for LAN connection to supply electrical power with LAN cables and not require a separate power supply for the device.

Figure 7: Flowchart of Design (Implementation)



Container: light orange; Remote Monitoring Enclosure: dark orange (not to scale)

Source: All Power Labs, 2021

Engineering Validation Testing

Engineering validation occurred over five subsystems and components of the technologies developed in this agreement: the biochar offtake, CHAB module, and emissions controls of the Chartainer; the 50kW Microgrid CHP PP container system; and the remote monitoring common to both platforms. An iterative process was used to evaluate criteria for engineering validation testing (EVT) in case of failure in the evaluation phase of any section. This is detailed in Appendix A.

Biochar Offtake Validation

Biochar offtake was evaluated via test criteria and procedures for the following biochar categories:

- Offtake output
- Offtake temperature
- Throughput rate

- Geometry of offtake system components
- Utility and safety of the char.

A system boundary can be found in Appendix A.

The biomass flow rate was calculated by dividing the weight of biomass measured during batch loading by the time required to consume that feedstock. During the measurement period, operators typically took four biomass samples per day.

The energy input rate of biomass feedstock was calculated as:

$$\dot{E}_{FS} = \dot{m}_{FS} HHV_{FS}$$

where:

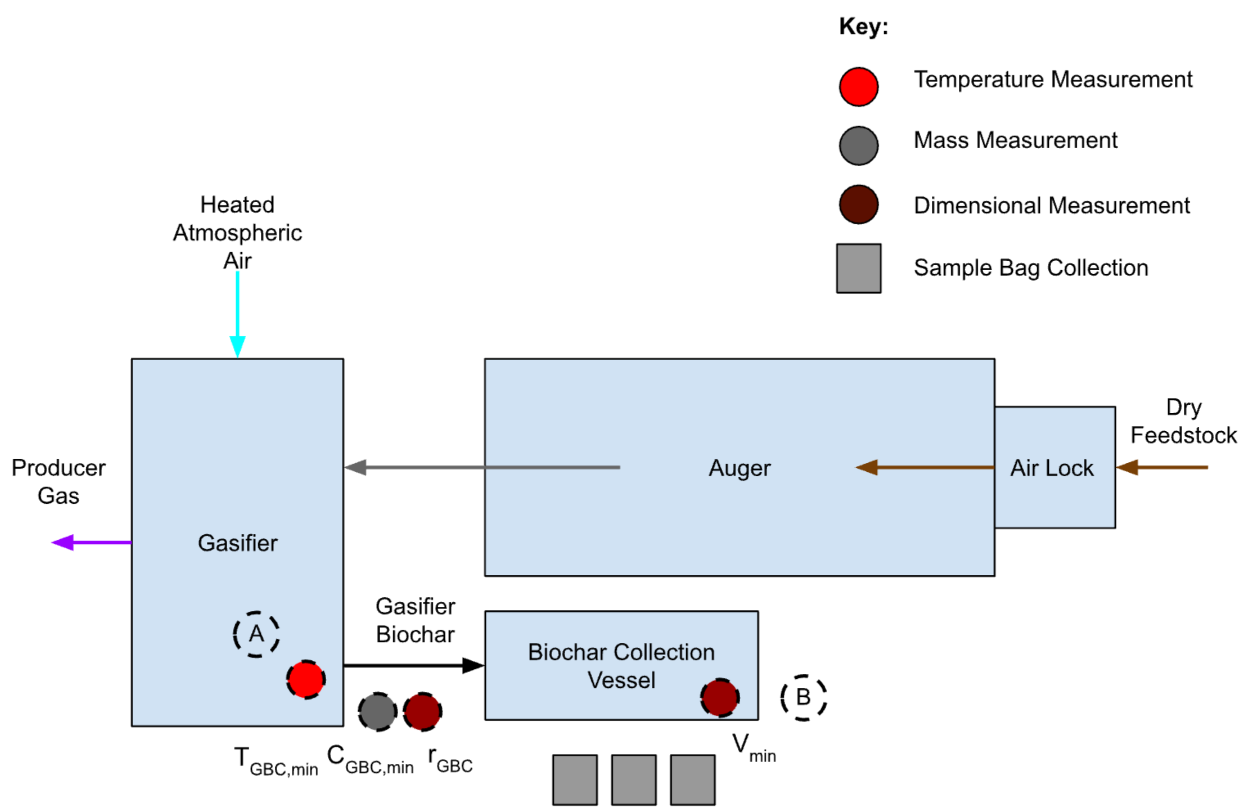
energy input rate of the feedstock [kWh/hr] equals mass flow rate of the feedstock [kg/hr] multiplied by the higher heating value of the feedstock [kWh/kg]

The biochar output rate was measured in batches when the operator removed it from the system as part of the engineering validation subtask.

Criteria

The diagram in Figure 8 shows the material flow relationships and testing locations for biochar offtake testing.

Figure 8: Biochar Offtake Subsystem Diagram



Source: All Power Labs, 2021

Biochar Offtake Locations

Biochar should be removed from the Biochar Collection Vessel (Location B) after each test period and have its weight and volume measured, recorded, and prepared for testing by filling three sample bags with at least 1 liter each of biochar. The samples must be collected according to the procedures in the EVT for subtask 3.1 (one for contaminated testing and two for basic characterization).

Threshold Values

Reflect key design criteria, biochar throughput rates, and temperature limits. Testing should be evaluated based on criteria and threshold values provided by the International Biochar Initiative (IBI). (Appendix B.)

- Biochar Output
    - The size of the biochar collection vessel must be greater than or equal to V_{min} and the vessel must be gas tight.
    - The radius of the output auger must be equal to or greater than r_{GBC} and the radius of the auger must be greater than twice the maximum particle size P_{GBC}, where "GBC" signifies gasifier biochar.
    - Biochar throughput rates
        - The rate of gasifier biochar production must be equal to or greater than $C_{GBC,min}$ to achieve the desired throughput rates.
- Biochar Characteristics
    - The gasifier biochar extraction temperature must be greater than or equal to $T_{GBC,min}$.
    - Biochar utility and Contaminant testing: Following the chain of custody procedures provided by laboratory partners, the biochar must meet or exceed the values stated in Appendix B respectively.

Procedure

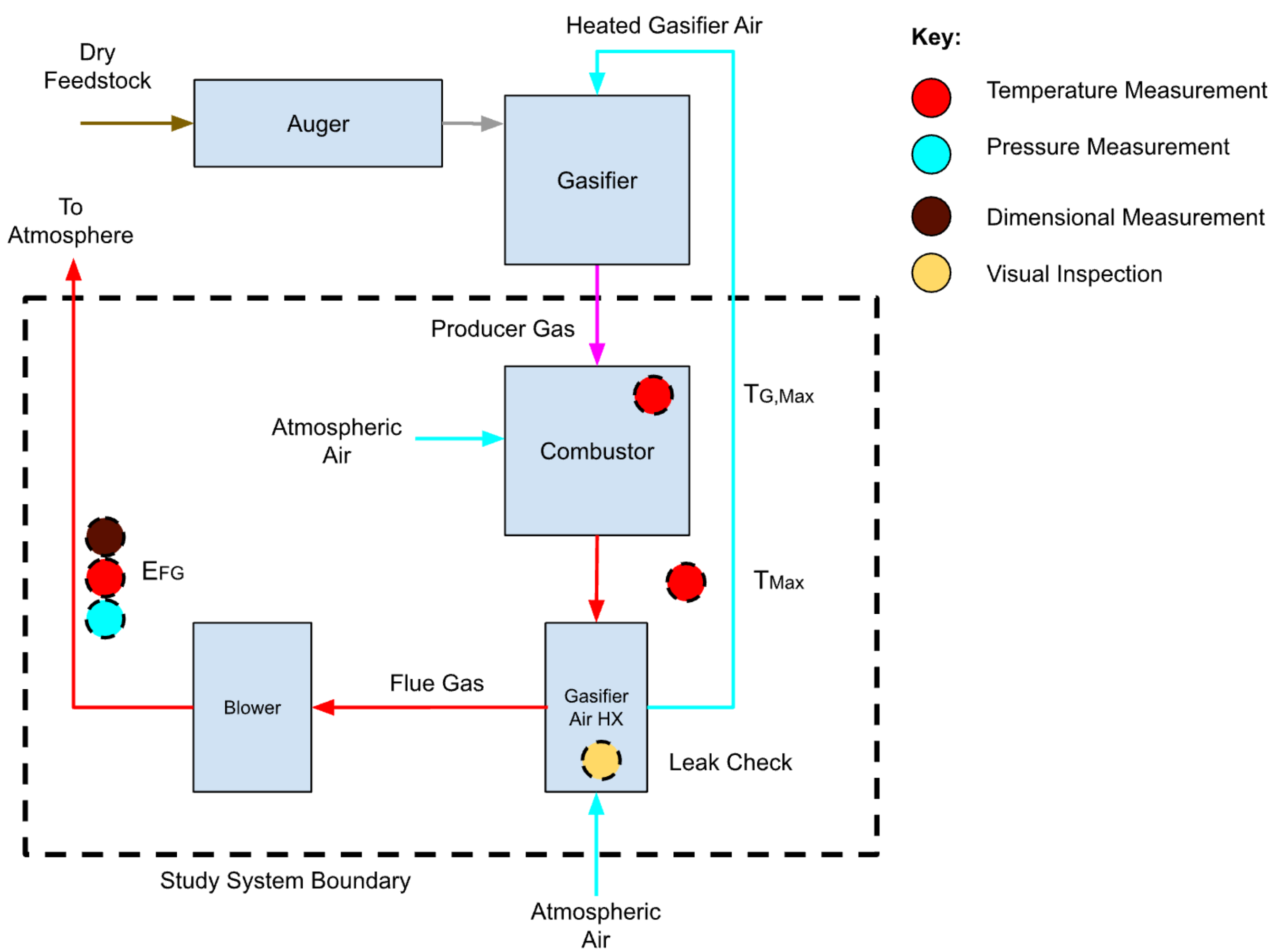
Test series for measuring these values were collected in two full datasets by performing the series twice. Data were collected for each criterion and repeated by adjusting process conditions to increase biomass throughput until maximum biochar output is achieved. One liter of biochar sample was collected and labeled from each run iteration and sent to third party labs for analysis following the chain of custody procedures provided by laboratory partners. The results were then compared to utility properties and contaminants. Details of biochar characteristics can be found in Appendix B.

CHAB/CHP Validation

Gasifier CHAB Module

Diagram in Figure 9 shows measurement locations for CHAB engineering validation within the overall Chartainer system.

Figure 9: CHAB Module System Diagram



Source: All Power Labs, 2021

Testing criteria and procedures for the CHAB module in following categories:

- Safety
- Module efficiency
- Study system efficiency.

The machine must reach steady-state running conditions before recording any results. Table 2 gives the threshold values used to evaluate the gasifier CHAB module.

Table 2: Threshold Values for Gasifier CHAB Module

Description	Symbol	Threshold value
Flue gas leak check	none	Pass
Gasifier CHAB internal temperature maximum	$T_{G,Max}$	1650°F (900°C)
Exposed Hot metal Surface Maximum Temperature	T_{Max}	140°F (60°C)

TMax is a temperature that will exclude burns or damage at touch.

Source: All Power Labs, 2021

- Safety
  - Flue gas leak check: with load set to the lower-end stable operation, inspect all plumbing connections at a safe distance for leaks (visually and acoustically).
  - Exposed metal surfaces check: with load to maximum, inspect all surfaces for hot spots using a thermocouple probe or an infrared thermometer to assure they are equal to or less than T_{Max}.
  - Gasifier CHAB module temperature: with load set to the maximum achievable biomass consumption, if the averaged gasifier CHAB temperature over a 10-minute run is below $T_{G,Max}$, the test passes.

CHAB Module Heat Available

Threshold values are provided to set performance criteria for the CHAB module heat available. Table 3 gives the threshold values used to define the criteria and the evaluation of the system.

Table 3: Threshold Values for CHAB Module Heat Available

Description	Symbol	Threshold value
CHAB module energy in the flue gas	EFG	500 kW

- CHAB module heat available
  a. Set process conditions to lower end stable operation.
  b. Record the temperature and flow rate on the outlet of the CHAB module.
  c. Calculate the energy in the flue gas and compare it to the threshold value.
  d. Adjust process conditions to increase biomass throughput.
  e. Repeat steps b through d until maximum achievable biomass consumption is reached.

Functional Testing and Evaluation: Emissions Monitoring Combustor

The emissions were evaluated through engineering validation testing focused on critical areas for testing criteria, testing procedures, and evaluation techniques used to assess the emissions of the Chartainer by providing goals and regulation values for criteria pollutant emissions.

- Criteria for emissions assessment
    - Governing body for emissions requirements: The authority having jurisdiction is the Bay Area Air Quality Management District (BAAQMD). Standards for criteria pollutants of CO and NOx were measured.
- Emissions goals
    - Criteria pollutant emission goals: monitoring equipment must be capable of measuring and logging criteria pollutants shown in Table 4. These targets are based on BAAQMD Regulation 9, Rule 7 for boilers and process heaters 2-5 MM BTU/hr.

Table 4: Criteria Pollutant and APL Goals

Criteria Pollutants	Nomenclature	APL Goal	Regulation
Carbon Monoxide	CO	400 ppmv, 3% O2	BAAQMD 9-7
Oxides of Nitrogen	NO_x	30 ppmv, 3% O2	BAAQMD 9-7

Source: All Power Labs, 2021

To pass, all measured criteria pollutants must be less than or equal to the emission requirements.

Functional Testing: Tuning Chartainer Combustor with Emissions Control Subsystem

The emissions control subsystem was evaluated through engineering validation testing to evaluate and tune the air/fuel ratio until optimal emission performance is determined.

Tuning air/fuel ratio with emissions control subsystem was done by repetitive testing varying the ratio in 0.5 increments from 1.5 to 4.0 for each load step, monitoring and maximizing the biomass throughput and minimizing emissions.

Feedstock Supply

Evaluation of failures in the existing installed base of PP30s reveals that improper feedstock is the most common cause of equipment failure, so feedstock supply and validation are critical to the project's ongoing success. Development of the swirl hearth architecture to be used in the CT gasifier is intended to allow a greater variety of feedstock to be used, such as minimum particle size and moisture content. An important goal of the feedstock supply plan was to determine new feedstock criteria for the CT reactor. Criteria, procedures, and standard operating procedures must be defined, documented, and communicated to feedstock suppliers and processes for ongoing review of these procedures will need to be developed.

- **Goals & Methods of Feedstock Qualification**
  - Achieve the feedstock characteristics that are acceptable for PP30 and Chartainer.
- **Steps required for feedstock handling**
  - Define any gaps in what is needed to meet the goals and methods.
  - Work with site operators to complete design of fuel delivery, handling, and processing.
  - Assist in procurement of any equipment needed to fill the gaps described above.
  - Work with site operators to perform the integration of systems per plan.

Site Preparation

Chartainer

Site validation was to be done at the Anderson Biomass Complex (ABC), a wood processing facility in Northern California chosen for their ample feedstock supplies and ability to prepare this according to design specifications. The Chartainer's portable design allows the system to be situated and moved to best meet the needs of ABC's operations.

The project team worked with ABC to review the equipment and methods they have in place for feedstock storage, transportation/conveying, and sifting (per ABC signed Partner Letter of Commitment), including the feedstock characteristics and methods described, but was not able to be used during this project primarily due to a catastrophic fire on the site that destroyed multiple buildings. Instead, the Chartainer was only operational at APL headquarters.

50 kW PP30 Container

Site validation was carried out at HREC in Mendocino County. Grid interconnection for full systems testing requires meeting strict rules and standards and was not able to be fulfilled during this agreement, so only off-grid power was generated. An additional unit was created at APL headquarters and demonstrated for CEC staff.

Plan Preparation

Figure 10 shows the basic outlay of administrative buildings at HREC. The main office is the white building at the northeast corner and at the southwest are two bran-like structures that housed feedstock and the deployed unit. These were directly across from a garage where operators workers could perform maintenance. This specific location also allowed for off-grid and on-grid use cases, but only off-grid power was generated during this project.

Figure 10: Basic Site Layout at HREC

Source: Google Maps, 2020

Appendix A contains a single line drawing of the 50 kW PP30 Container, and its system connections and dependencies expected to be required as part of the site approval processes.

Instrumentation, data logs, and field inspection were used to understand and validate system performance and dynamics. The team performed in-field testing to gain a deeper understanding of actual operations and associated challenges. Final performance and emissions testing included more than 40 hours of full system operations.

CHAPTER 3: Project Results

Summary of Results

The project team faced several challenges, but the results were successful and encouraging for further commercial and engineering developments. Table 5 gives an overview of the operating periods for the two products developed. These include the following units:

- **Chartainer:** This larger-scale platform had several improvements, resulting in greater efficiency. Of note is the dramatic increase in biomass input achieved in later runs, going from 35 kg of feedstock an hour to 69.4, then 74.8, and finally 127.2. Additionally, the Chartainer included a different combustion system that was radically reworked for later runs. All work was performed at the project team's Berkeley headquarters, including a demonstration run for CEC representatives in late 2022, with EVT showing successful outcomes.
- **First 50 kW Microgrid CHP PP Container (MG1001):** this unit went into the field with project partners in Mendocino County and tested real-world applications. The balance of systems for this unit also included a bespoke feed system. This unit had several hundred run hours that enabled the project team to develop the second unit that remained at APL and was used for engineering validation.
- **Second 50 kW Microgrid CHP PP Container (MG1002):** this unit was built and tested at All Power Labs headquarters in Berkeley, California and was demonstrated for CEC staff. EVT was done on this unit and showed successful results.

Table 5: Phases of Unit Runs

Product	Phase	Dates	Run Hours	Biomass Input [kg]
Chartainer v. 1.00	Development	6/7/19 – 10/22/20	152	5,319
Chartainer v. 1.01	Engineering validation	5/11/22 – 6/29/22	41	2,847
Chartainer v. 1.01	Extended operations	7/20/22 – 3/31/23	57	4,264
Chartainer v. 1.01	Measurement and verification	4/14/23 – 5/23/23	33	4,198
50 kW (MG1001)	Extended operations	2021	509	~5,400
50 kW (MG1002)	Engineering validation	2021–2022	18	657

Source: All Power Labs. 2021

Independent, third-party measurement and verification of system performance was conducted by RadKEM in 2022 and 2023. Multiple meetings were held remotely to review results, including electrical outputs, thermal outputs from the Chartainer combustor, reviews of efficiency, and biochar outputs. They noted an uptime during testing of a rough average of 6 hours per 40 hour work-week. They noted downtime periods to address feedstock auger jamming, broken V-band seals, poor valve sealing, grate and scroll wear, and cracks in the reactor. They note all causes of downtime were redesigned, fixed, or replaced on the Chartainer. This project partner found that APL was successful in developing both technologies and that they improved over the extended operations and further builds.

Chartainer

As the project team encountered challenges developing the Powertainer platform, including the difficulty of including all components in a one-container form factor and finding proper use cases for the size of power output, one of the biggest breakthroughs was the development of the derived Chartainer platform. With larger-scale biomass material inputs and outputs of heat and biochar, the Chartainer met the two project performance metrics of consuming 127 kg of feedstock per hour and converting greater than 10 percent of the mass of input waste material into biochar.

The Chartainer demonstrated its ability to use forestry biomass waste to create high temperature biochar (for example biochar created at temperatures more than 1,200°F [650°C]) and process heat energy of over 400 kW thermal. Failures of physical components (such as combustor flange warping) affected performance and testing and required several rebuilds that will inform future development of the technology. Chartainer development has experienced challenges, particularly regarding the combustion system, which was entirely redesigned to better control for safety and the biochar production, which the project team was able to attenuate to get much greater biochar yields per mass.

For reference, a simplified process flow diagram of the Chartainer is shown in Appendix B.

In engineering validation testing, the project team found that throughputs were limited by a few key factors: in terms of blower sizing, combustion needed to be run at relatively high air–fuel ratio values and with flue gas recirculation to manage internal temperatures and ensure that the processes occurring to the feedstock, biochar, and gasses produced in the unit happen in reliable and optimal ways. The team wanted to cap these higher temperatures at 1,650°F (900°C) but were unable and will need to introduce greater heat exchange capacity in the future. This limited the amount of producer gas generated relative to air and therefore drew on the gasifier and feedstock consumption rates were lower and less reliable at the outset. The project team did not initially anticipate these blower-related issues and they interrupted regular operation, and this was overcome in redesigns that were more consistent and had higher biomass throughput and biochar yield by volume.

Secondly, the Chartainer did not implement a full heated pyrolysis auger due to budgetary and time limits: this constrained the material residence time and the pyrolysis combustion process to within the gasifier which impacted feedstock consumption rates. Lastly, the biochar was removed in a batch-based barrel system at approximately one-hour intervals and required a five-minute shutdown of gas draw on the system. Operating with continuous removal—a feature added after engineering validation testing was completed—would have increased throughputs by approximately 109 percent. Throughput rates steadily increased during the period.

Following the approach in the biochar offtake EVT, the operator noted the time and mass of biochar as shown in Table 6:

Table 6: Chartainer Production Results During EVT Period

Run Date	Operating Hours [hr]	Biomass Input [kg]	Char Output [kg]	Biomass Consumption Rate [kg/hr]	Char Production Rate [kg/hr]	Char Yield [%]	Feedstock
05/11/22	5	n/d	n/d	n/d	n/d	n/d	AS
05/13/22	2.42	n/d	n/d	n/d	n/d	n/d	AS
05/19/22	4	155.1	19.5	38.8	4.9	12.57%	AS
05/26/22	4.05	249.2	42.4	61.5	10.5	17.01%	AS
05/27/22	2	33.1	13.1	16.6	6.6	39.58%	AS
06/01/22	3.08	244.0	40.6	79.2	13.2	16.64%	GWRY
06/03/22	4.75	393.8	56	82.9	11.8	14.22%	GWRY
06/08/22	4.66	433.4	73.8	93.0	15.8	17.03%	GWRY
06/14/22	2.83	402.4	57.7	142.2	20.4	14.34%	GWRY
06/23/22	1.5	191.2	29.2	127.5	19.5	15.27%	GWRY
06/24/22	3.33	341.9	59.1	102.7	17.7	17.29%	GWRY
06/29/22	3.13	403.0	71.9	128.8	23.0	17.84%	GWRY
Cumulative	40.75	2847.1	463.3	87.31	14.33	18.18%	

Feedstock: AS = American Soil Woodchips, GWRY = Green Waste Recycle Yard tree service woodchips. Source: All Power Labs, 2021

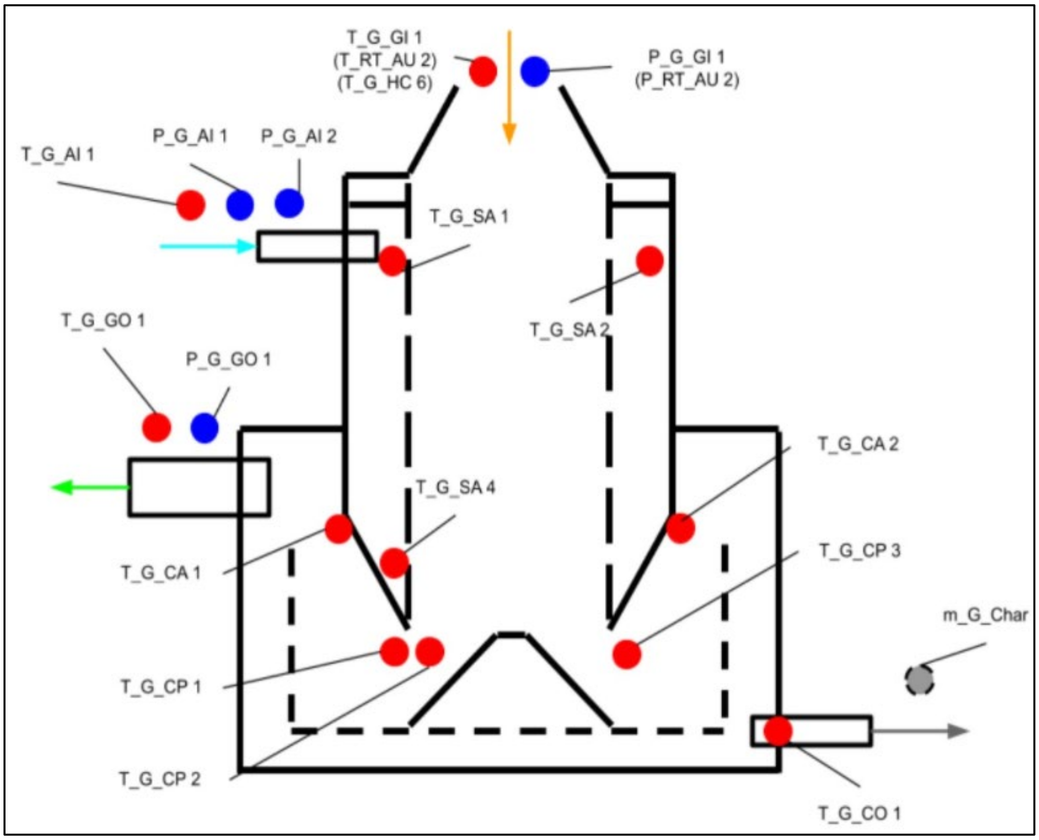
The temperature the biochar is exposed to influences the biochar's properties, including:

- Bulk conductivity (how graphitic the char is),
- Hydrogen to carbon (H/C) ratio, and
- Polycyclic Aromatic Hydrocarbon (PAH) concentration.

Biochar temperature was measured with a thermocouple at location T_G_CP1 as shown in Figure 11. Over runs during the engineering validation period, this location dropped below 1,110°F (600°C), however in 9 of 11 runs the average temperatures were above. Temperature variability increased over the runs and was suspected to be from increased grate shaking and biochar throughput. Elaboration on biochar testing can be found in Appendix B.

In addition to biochar, the main output of the Chartainer is heat. The gasifier CHAB module was evaluated for safety and efficiency. For safety concerns, leak checks, exposed hot metal surfaces, and temperatures were tested, as shown in Table 7. (Note that in this table and subsequent images, "CB2" and "CB3" are measurement points related to before and after the combustor throat.)

Figure 11: Gasifier Instrumentation Locations



Source: All Power Labs, 2021

Table 7: Threshold Measurements for Gasifier CHAB Module

Description	Symbol	Threshold value	Measurement Results	Pass/Fail
Flue gas leak check	none	Pass	Warpage of flanges	Fail
Gasifier CHAB internal temperature maximum	TG,Max	1,650°F (900°C)	CB2 and CB3 both exceed 900°C after the first 5000 hrs.	Fail
Exposed Hot metal Surface Maximum Temperature	TMax	140°F (60°C)	Most measured surfaces exceed the 60°C temperature limit	Fail

Source: All Power Labs, 2021

Due to the innovative nature of the Chartainer, the project team had a variety of challenges and system failures that required redesigning and rebuilding. The following examples are illustrative of the process of revision required to improve safety: Combustor flange failures occurred due to warping of the combustor's air heat exchanger (HX) flange (Figure 12) and the mating flanges on the puff lid, resulting in failure of the seal integrity and subsequent introduction of ambient air into the system.

Figure 12: Combustor Air HX Flange Warping

Source: All Power Labs, 2021

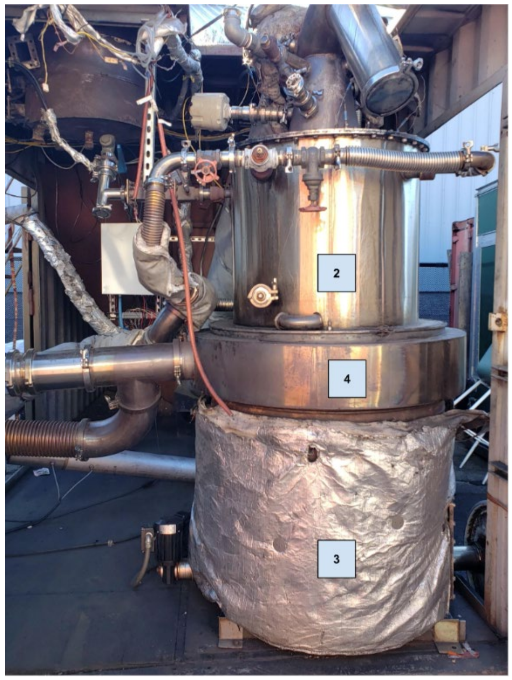
The failure of the air HX impacted the operation of the gasifier. Instead of the gasifier annulus heating up from preheated air from the air HX, the gasifier air supply plumbing from the air HX would heat up. This indicated that the heat exchanger had been breached. The failure was confirmed by pressurizing the inlet port with compressed air and putting a pressure gauge on the outlet port (Figure 13). No pressure was measured. Inspection was conducted with a small camera inserted through ports on both sides of the Air HX. Multiple locations with failed welds were observed. The Air HX was then disassembled, visually inspected and a process of analysis and repair was conducted.

Figure 13: Pressure Testing and Heat Exchanger Damage

Source: All Power Labs, 2021

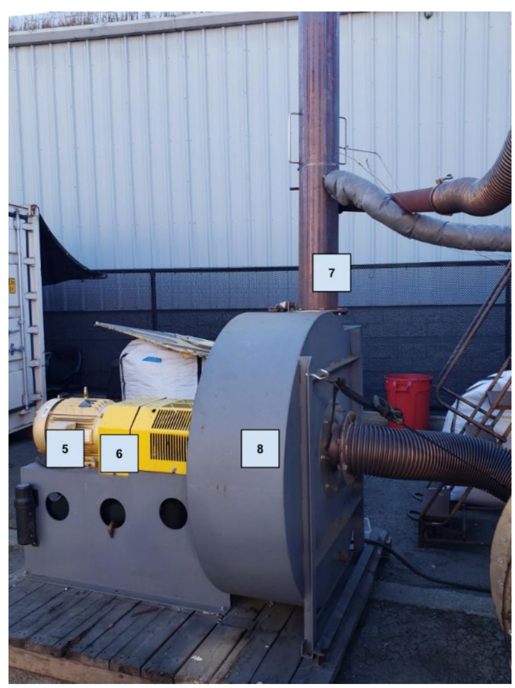
The project team discovered that the surface temperatures of some of the equipment locations were measured at more than 140°F (60°C). Future versions of the Chartainer will have greater insulation to ensure safety and compliance with UL standards. See the units and various points of measurement are indicated with boxes superimposed on the photos in Figures 14 to 17.

Figure 14: Temperature Measurement and Gasifier Measurement Locations



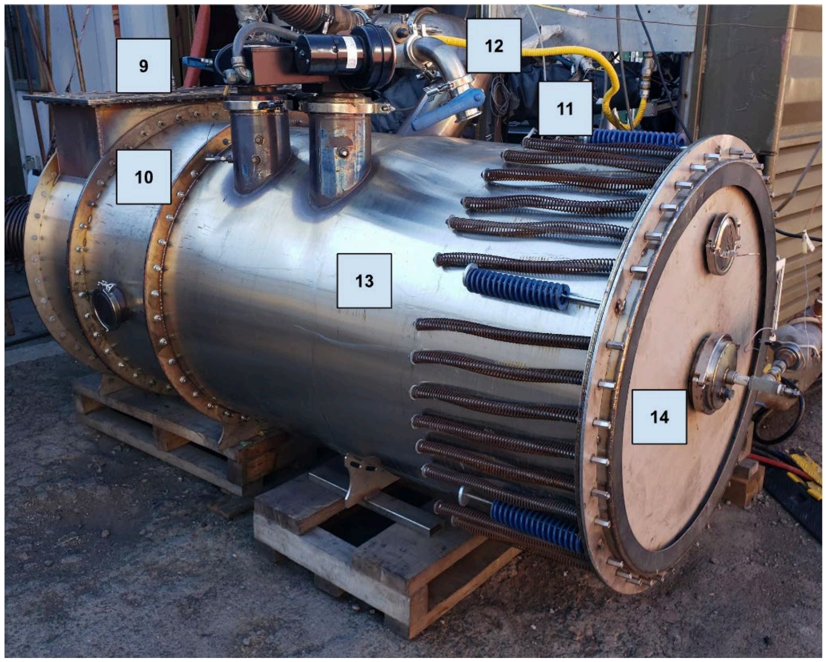
Source: All Power Labs, 2021

Figures 15 and 16: Gasifier and Blower Measurement Locations



Source: All Power Labs, 2021

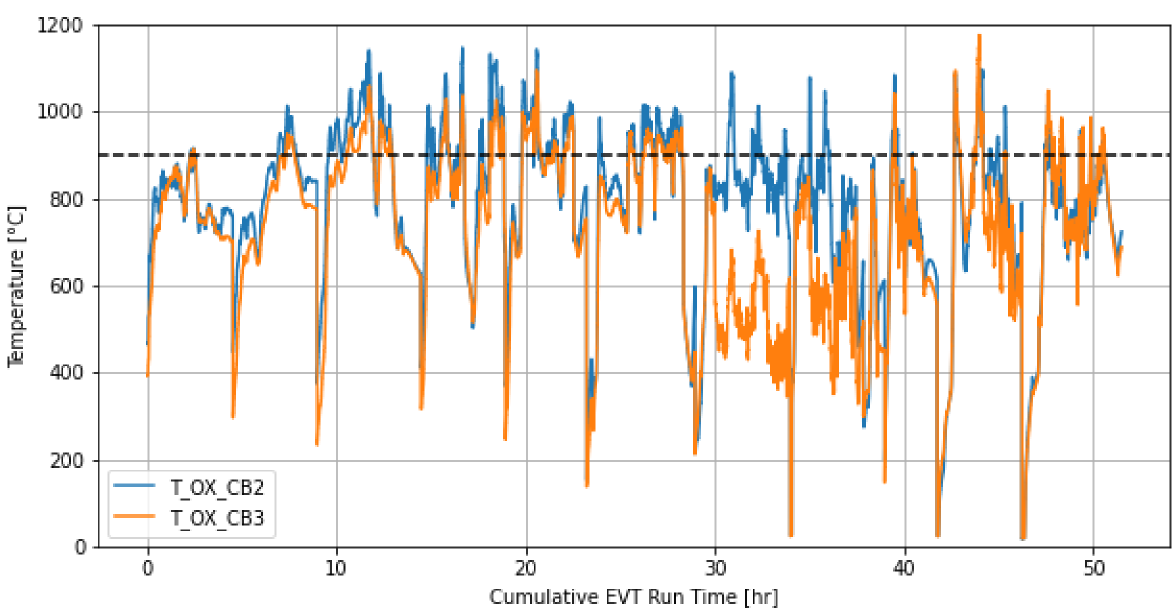
Figure 17: Combustor Measurement Locations



Source: All Power Labs, 2021

Maintaining lower temperatures with the combustor reduces stresses on the metals to improve longevity and reduces the formation of nitrogen oxides. Two locations were instrumented within the combustor. Consolidated logs of those two locations during the mor than 50 hours of EVT operation are shown in Figure 18. Later runs used flue gas recirculation and increased combustion air–fuel ratio which reduced temperatures with occasional deviations above 1,650°F (900°C).

Figure 18: Combustor Temperatures



Source: All Power Labs, 2022

In terms of efficiency, to determine available thermal energy in the flue gas, flue gas velocity was measured with a pitot tube and temperature measured with a thermocouple and measured 410 kW at 82.9 kg/hr., which is below the expected threshold value of 500 kW thermal. However, the feedstock throughput during the measurement was well below target and the project team needs to investigate why before this product is brought to market. Higher available heat for applications such as firewood drying, or industrial heating applications will provide value that can yield a financial model for funding and scaling.

Emissions control tests conducted for this agreement sought to understand the emissions performance of the Chartainer combustor and understand how to optimize its performance to meet the defined targets. Many measurements during the testing met carbon monoxide (CO) targets, but few achieved both CO and oxides of nitrogen (NOx) targets. Assessing the make-up of emissions is crucial for regulatory compliance and market adoption of the technology. These results are shown in Tables 8 and 9. The project team was surprised by these emissions failures and further investigation will be necessary to ensure compliance.

Table 8: Criteria pollutant and APL Measurements

Criteria Pollutants	Nomenclature	APL Goal	Measurement Results	Pass/Fail
Carbon Monoxide	CO	400 ppmv, 3% O2	2022-05-19: 2.13% Passing	Fail
Oxides of Nitrogen	NO_x	30 ppmv, 3% O2	2022-06-08: 1.16% Passing	Fail

Source: All Power Labs, 2022

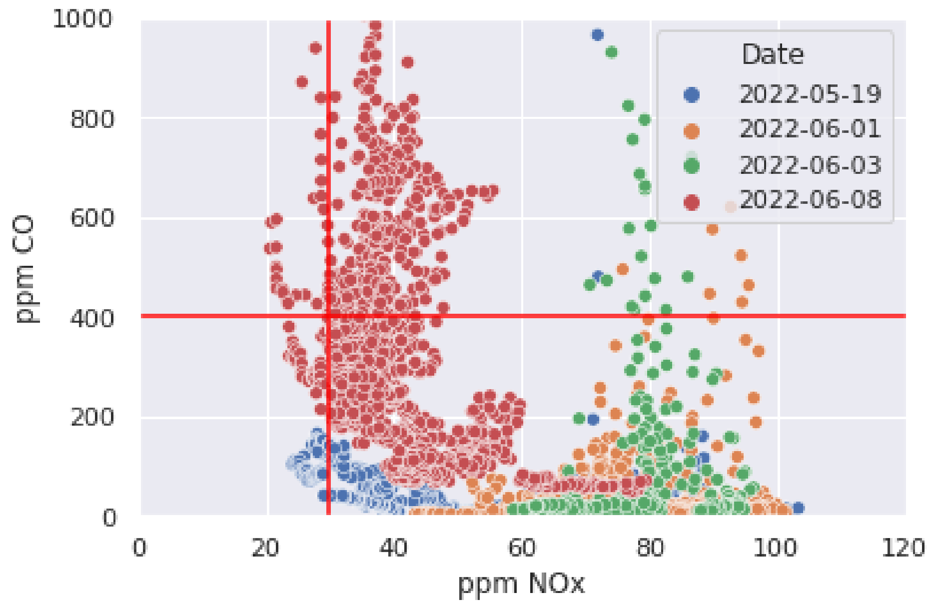
Table 9: Emissions Testing Passing Results and Operating Conditions

Date	Percent CO Passing Measurements (<400 ppm CO)	Percent Total Passing Measurements (<400 ppm CO, <30 ppm NOx)	Average Feedstock Throughput [kg/hr]	Conditions
2022-05-19	20.57%	2.13%	38.8	No Secondary Air Flue Gas Recirculation.
2022-06-01	34.75%	0%	79.2	No Secondary Air. Flue Gas Recirculation.
2022-06-03	8.84%	0%	82.9	Secondary Air. Flue Gas Recirculation.
2022-06-08	34.76%	1.16%	93.0	Secondary Air. Flue Gas Recirculation.

Source: All Power Labs, 2022

Higher throughput operation appeared to increase the challenge of managing emissions, with the CO/NOx curve shifting upwards towards CO (Figure 18).

Figure 18: CO vs. NOx Emissions

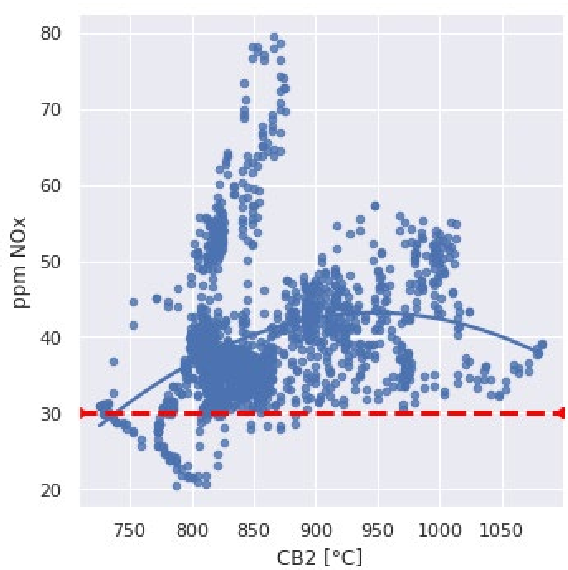


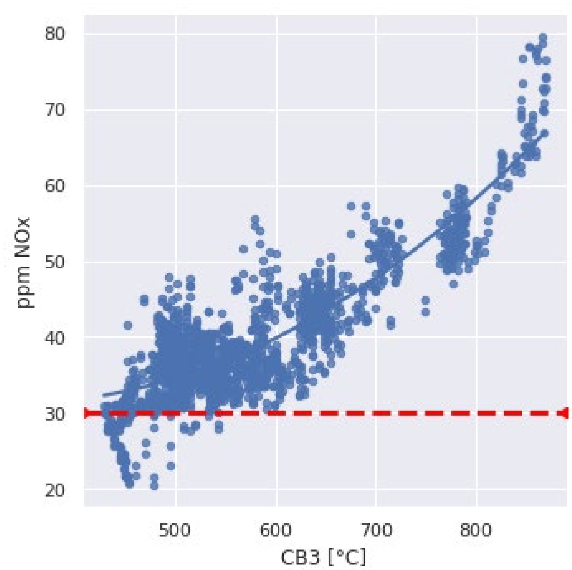
Results from 4 testing days show the relationship between CO and NOx

Source: All Power Labs, 2022

Managing temperatures in the combustor should assist in achieving targets. Future work by the project team to improve emissions will involve mixing in the combustor to reduce hot spots: these points of high temperature can exacerbate NOx formation (Figures 19 to 22). The cyclonic configuration does not lead to effective mixing.

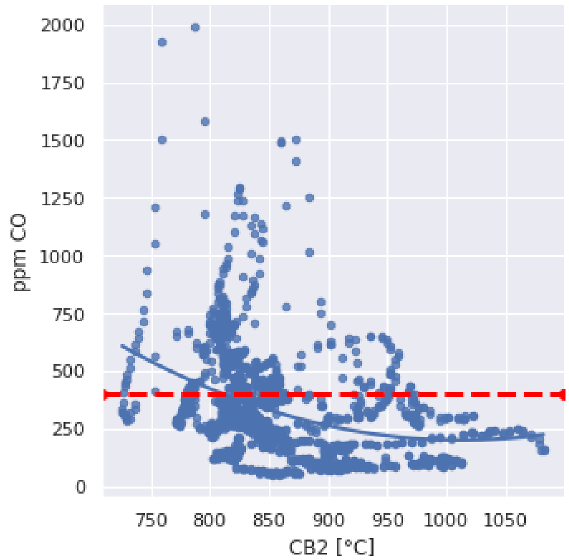
Figures 19 and 20: Nitrogen Oxides vs. CB2 & CB3 Temperatures, 2022-06-08

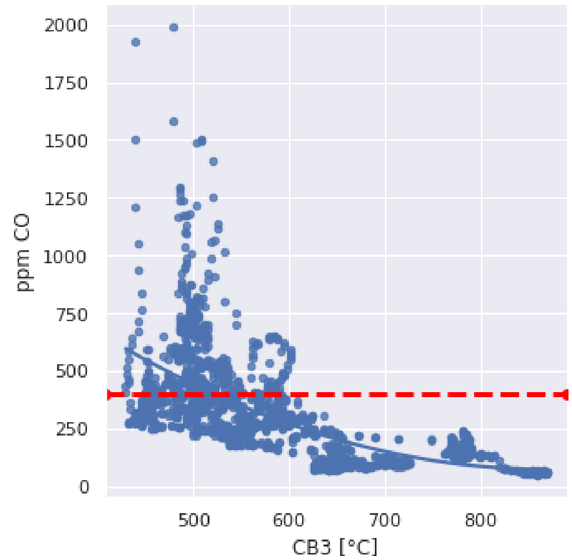




Source: All Power Labs, 2022

Figures 21 and 22: Carbon Monoxide vs. CB2 & CB3 Temperatures, 2022-06-08

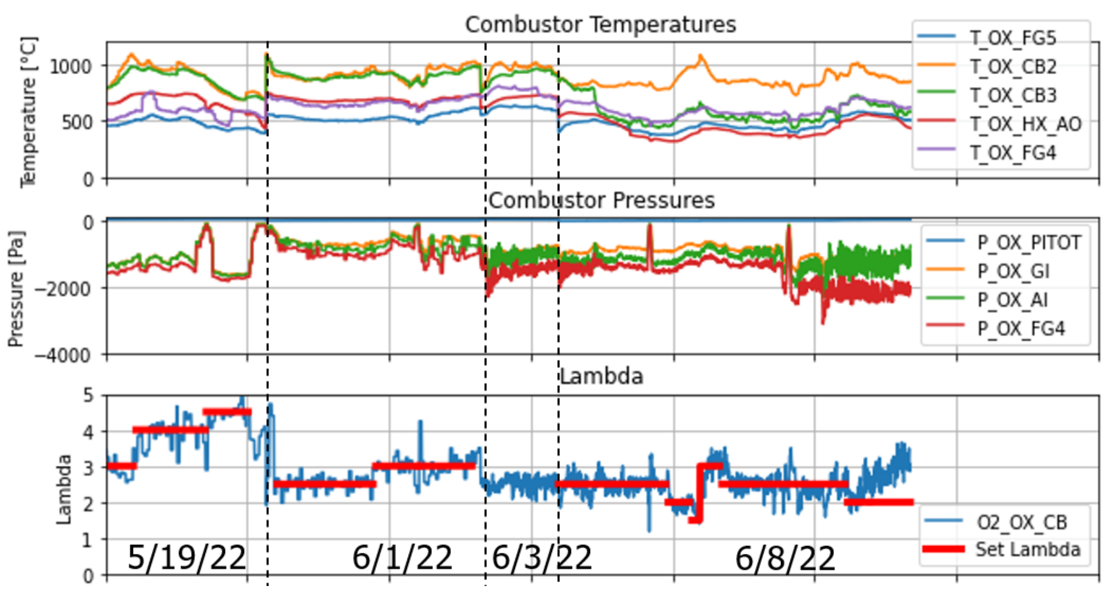


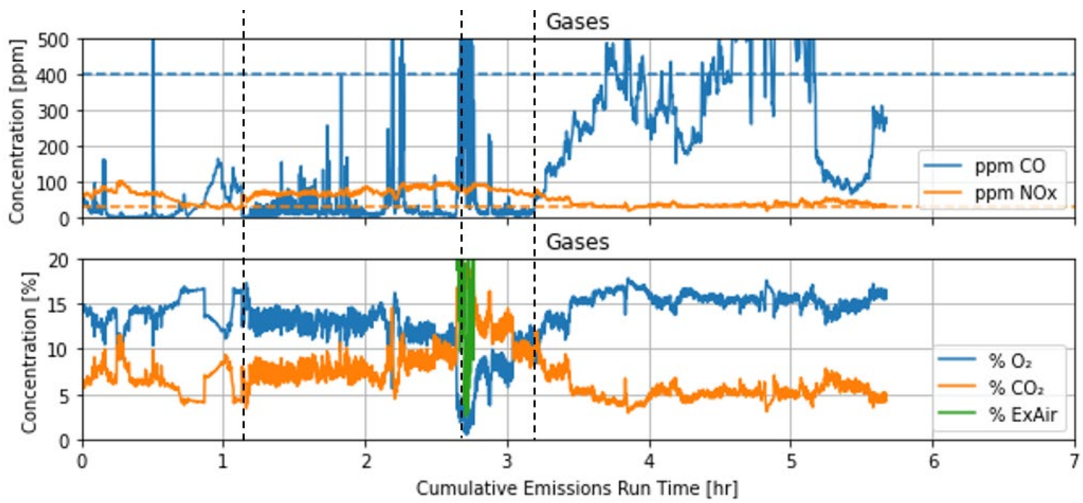


Source: All Power Labs, 2022

During emissions testing, air–fuel ratio was adjusted from 1.5 to 4 across multiple runs (Figure 23), these tests were conducted over a range of average run feedstock throughputs from 38.8 to 93 kg/hr. Testing on June 8, 2022, used flue gas recirculation, which dropped NOx emissions relative to earlier runs, but increased CO emissions. Final operational settings significantly lowered CO to around 100 ppm (25 percent of 400 ppm emissions target), however NOx was still above target. If operating temperatures with these conditions were reduced (increasing CO but decreasing NOx), the targets may be achieved. Further modifications to the design and operating conditions will improve performance.

Figure 23: Combustor Temperatures, Pressures, Air–Fuel Ratio, and Emissions Plot





Source: All Power Labs, 2022

50 kW Microgrid CHP PP Container

The project team tested a PP30 50 kW Microgrid Container (MG1001) in-field in Mendocino County, California and had a second unit (MG1002) that was run at All Power Labs headquarters in Berkeley, CA. During the period of performance testing at each site, the technology met many of the performance targets set in the testing plan: during engineering validation testing, 50 kW Microgrid CHP PP Container was able to sustain the design 50 kW output when run at an alternating current (AC) frequency of 72 hertz (Hz); at 60 Hz, one of the PP30s only produced 16 kW over the testing periods, resulting in a total output of 41 kW. In real-world applications, customers who would like to connect to the utility grid can use inverter-based systems which can convert a higher frequency output to 60 Hz. As mentioned previously, interconnect was not finalized in this agreement, but the project team discovered that this inverter-based method is a faster path to grid interconnection than direct synchronous generator interconnection that would require 60 Hz operation.

A simplified study system boundary of the 50kW unit is included in Appendix B for reference, as is a table elaborating on outcomes of functional testing. A diagram for Microgrid Electrical Configuration for EVT Testing is found in Appendix A.

Containerizing the existing Power Pallet system and ensuring that two units could synchronize for power generation involved a process of design and build to ensure basic operator access and proper functioning. Several aspects of the 50kW unit were tested to ensure reliable operation and to meet basic objectives, such as the actual generation of 50 kW electrical:

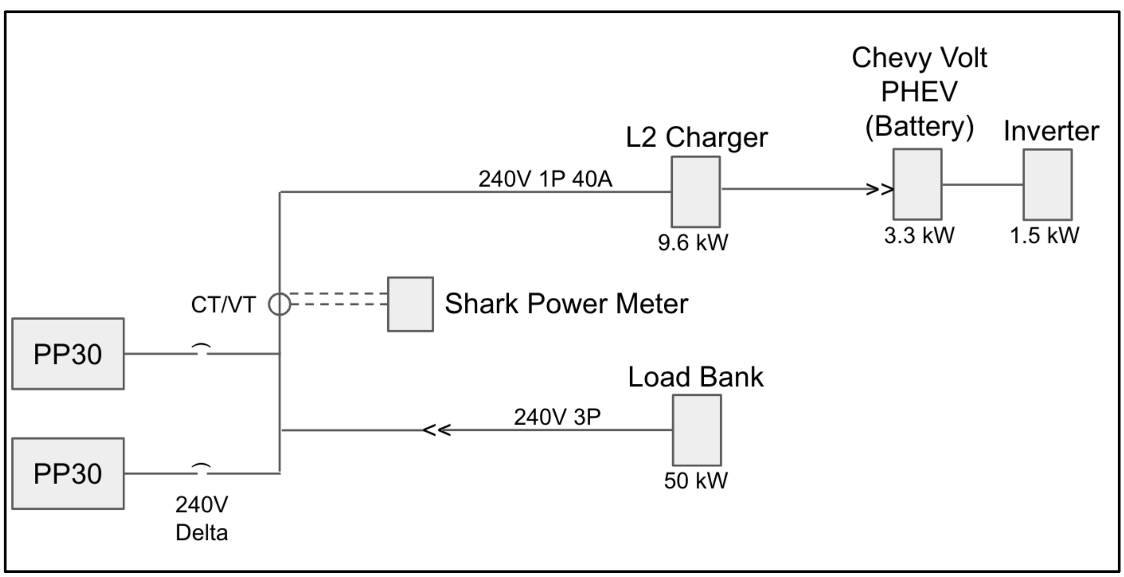
- **Synchronization:** the 50 kW units contain two separate Power Pallet gasifiers. These sub-units were successfully synchronized, and load was provided by a resistive load bank. This confirms that the technology can reliably operate and produce power.
- **Container Ventilation:** radiator fans had a combined value of 8,000 cubic feet per minute or 13,500 m^3 per hour, significantly over the 132 m^3 minimum value. The ability to ventilate is key for safety.

- **Feed Supply:** data from the MG1001 unit installed in Hopland, California was calculated by taking the average feedstock delivery rate of the system during extended operation at roughly 40 kg/hr and dividing by the duty cycle of the fuel auger (5% or 3 minutes every hour). The calculated maximum feedstock delivery is 800 kg/hr. This greatly exceeds the required delivery rate of greater than 65 kg/hr.
- **Bridging/Jamming:** the testing was conducted on MG1002 using wood chips from Green Waste Recycling Yard in Richmond, California with no significant operator intervention related to jamming or bridging of the feed system. This validates that the feed system developed in this agreement can be operated with less intervention.

Measured and calculated values were used to evaluate the PP30 performance. For calculated values, two sets of calculations, which are worst- and best-case scenarios, were carried out. The energy content of the fuel was assumed to vary approximately between the minimum and maximum numbers for Douglas fir feedstock (4.76–5.01 kWh/kg Fuel, derated by 10 percent due to the fuel dry basis moisture content of 7.8 percent). Measurements were collected at various points in the system with power meters to measure electrical power delivery and a BTU meter to monitor the thermal power delivery from the CHP system. Figure 24 shows an overview of the system boundary.

One of the key differentiating factors between the Chartainer and the 50 kW units is the production of electrical power. Engineering validation testing from July 14, 2022, results for electricity are shown in Figures 26 and 27. A Level 2 charger was integrated into the microgrid and used to charge plug-in hybrid electric vehicle (PHEV) batteries, supplying power downstream (Figure 25).

Figure 24: 50 kW Microgrid Electrical Configuration for EVT Testing



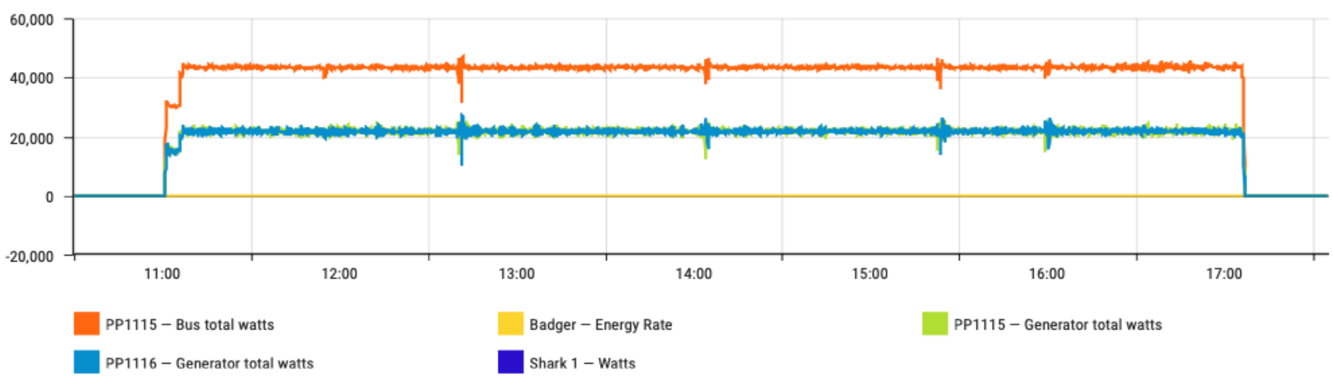
Nominal component power ratings shown.

Source: All Power Labs, 2020

Figure 25: Layout of MG1002 During EVT Testing at APL Berkeley

Source: All Power Labs, 2022

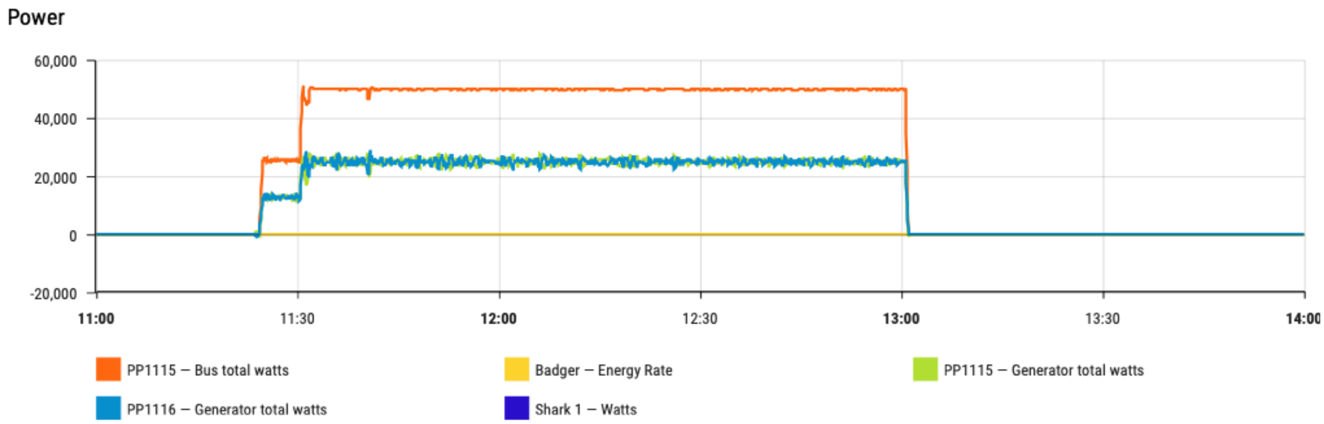
Figure 26: Power Generation from 2 PP30 Units During EVT (60 Hz) by Time of Day



Test on 7/15/22 ran over 6 hours, with combined power generation at 43 kW. Periodic power variation during feedstock refilling events.

Source: All Power Labs, 2022

Figure 27: Power Generation From 2 PP30 Units (72 Hz) by Time of Day



Test on 7/14/22 operating at 72 Hz yielded a combined power output above 50 kW.

Source: All Power Labs, 2022

The 50 kW units also produce heat and biochar, like the Chartainer and tests qualifying those co-products are summarized in Table 10.

Table 10: Functional Testing Results: Operation of System at Various Loads

Test	Symbol	Threshold Value	Description
Battery Charge and Electricity Delivery	None	Pass	Reported: The batteries were connected and charged with 25.6 kWh of power, and delivered 5.0 kWh on 7/15/22
Maximum Feedstock Consumption	CFC	≥50 kg fuel/hr	Qualified Pass (due to measurement variance) 47 to 53 kg/hr
Biochar Production	CBC	Measure - kg/kWh	Measured: 0.044 kg/kWh
CHP Thermal Energy Production	ECHP	≥1.5 kW th/kW elec	Pass, 1.59 kWt/kWe
Overall System Efficiency	nmin	≥0.5	Qualified Pass (due to measurement variance) Best Case 49.2% Worst case 46.7%

Source: All Power Labs, 2021

Results provided in this section reflect both best and worst scenarios.

- **Battery Charge and Electricity Delivery:** The batteries were connected to the Power Pallets and could receive charge during the entire 6-hour test period, which is more than the 10 minutes required. The PHEV battery was connected to an external inverter, providing 120 V AC to power the required loads (lights and fans). The inverter provided 5.03 kWh of power during the test period, with an average load of 0.838 kW.

- **Feedstock Consumption:** The feedstock consumption was measured by weighing the feedstock added to each unit during the run and topping them off after the test period was completed. The final fuel consumption was 49 kg/hr. There was variance due to the accuracy of the scale used, with subsequent measurements on the same barrel varying by +/-2 kg. This gives a variance on each measurement of up to 6 percent. The first found mass was assumed to be correct, and the average measured consumption (49 kg/hr) was within that tolerance (47 to 53 kg/hr). Feedstock consumption on an electrical energy production basis was 1.04 kg dry biomass/kWh electricity.
- **Biochar Production:** The produced biochar was captured in the Ash Collection Vessel. The vessel was emptied before the test was run, and a tare weight obtained. After the 6-hour test, the collected biochar was measured in the vessel, and the tare weight recorded: 11.5 kg of biochar was produced during the test, giving 0.044 kg of biochar per kWh of electricity produced. There was a 9 percent difference in the mass of the biochar produced between the two units. The amount of biochar produced at any time is variable given the dynamics of the unit operation. Some of the elements that produce this variance are grate shaker operation, char bed dynamics, and operation of the ash auger. Biochar yield (biochar mass output per biomass input) was 3.9 percent.
- **Biochar Characterization:** A sample of the biochar from the EVT run was sent to Soil Control Laboratories for analysis. All values fell within the stated threshold values as set by the International Biochar Initiative (IBI). The organic carbon content places it in the Class 1 category. The H/C ratio was exceptionally low (an indicator that the biochar is highly recalcitrant and would emit extraordinarily little CO2 back to the atmosphere if applied to soil). There were no significant contaminants found.
- **CHP Thermal Energy Production:** 419.6 kWh of thermal energy was delivered during the test period. It was utilized by passing the CHP fluid through a radiator with a fan blowing across it. The generated hot air was used to dry wood chips for Power Pallet operation. The CHP system did not use all the available thermal energy generated by the Power Pallets, as the radiator fans still turned on occasionally during the test period. Regardless, the kWt/kWe ratio of 1.594 exceeded the targets. Note that the PP30s did not have exhaust gas heat exchangers installed, reducing the captured heat and total efficiency compared with units tested under a prior CEC grant (CEC PIR-16-010).
- **Overall System Efficiency:** The calculated overall system efficiency range of 50 to 52 percent passed the required ≥50 percent. Note that this value excludes the remaining potential energy in the biochar, with an assumed energy density of 29.3 MJ/kg (as used in CEC PIR-16-010). Treating biochar removed as an inefficiency, rather than intentional, results in a total system efficiency of 46 to 49 percent.

Data collected during MG1002 operation for the engineering validation period are shown below and reflect most of the items listed in the test plan. Data in Figures 28 and 29 are from the previously mentioned July 15 engineering validation testing period.

Figure 28: Coolant Temperatures of PP30 and CHP Temperature of Badger Meter

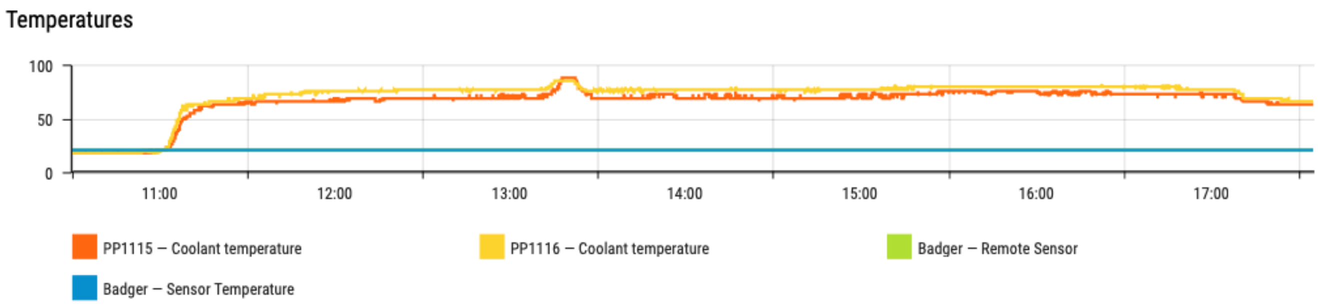
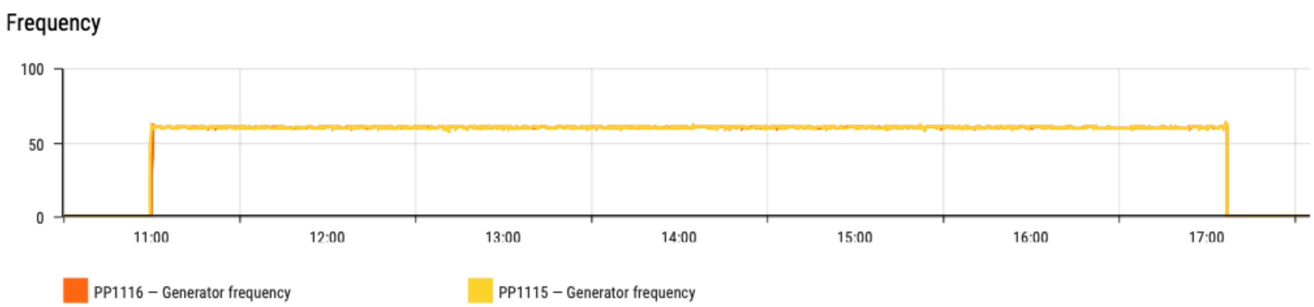


Figure 29: Generator Frequency of the PP30



Source: All Power Labs, 2022

Remote Monitoring

While the two products developed in this agreement differ substantially in their size, outputs, and intended use cases, one common component of both is remote monitoring, which was developed across the two product lines. The remote monitoring enclosure mounted on the rear of the modular enclosure in the MG1001 50 kW unit is depicted in Figure 30.

The project team was able to get the remote monitoring system to successfully operate. While the Mango system successfully operated and collected data from both Deep Sea 8610 MKII generator controllers on the Power Pallets in the 50 kW container, there were protracted issues with cellular modem connectivity. The project team had to change service providers several times to ensure regular service with the rural and remote in-field partner. Additionally, exposure to the elements resulted in corrosion on connectors. The latter problem was solved with some design changes, but the former is a matter that needs to be explored further and the project team currently has a new grant agreement with the CEC that includes some remote monitoring upgrades to this platform.

Figure 30: Remote Monitoring Enclosure Mounting in MG1001

Source: All Power Labs, 2020

The Mango system was accessed from laptops and computers onsite using the Wi-Fi from the onboard router. Overall, the engineering validation for this subsystem was successful for off-site system installation and operation and off-site system interface, but was a failure at complete off-site performance monitoring, as the team was only able to gather three out of four data points required for monitoring. This is still an engineering achievement and has led directly to current revisions on this platform.

Additionally, the team was able to successfully achieve long-term operations over 53 days in 2021 and had no issues with on-site data acquisition system installation and operation.

Future off-site monitoring with a stable remote monitoring system will be integrated for the Chartainer, but was not pursued during this agreement, as it was not deployed in-field. The project team was also able to successfully gather data from extended operation of the Chartainer's remote monitoring subsystem. Measurements from the remote monitoring subsystem were used to determine the failures as the unit during downtime events and were successful as a diagnostic tool.

CHAPTER 4: Conclusions/Recommendations

The technology developed has multiple benefits and is consistent with several of California's clean energy and climate goals. Some of the regulatory drivers, including California Senate Bill 1383 (Lara, Chapter 395, Short-lived climate pollutants: methane emissions: dairy and live-stock: organic waste: landfills), which decreases greenhouse gas emissions by reducing the organic materials sent to landfills and Senate Bill 85 (Committee on Budget and Fiscal Review, Chapter 14, Budget Act of 2020), which provides funding for various wildfire and forest resilience proposals. In addition to the responsible management of biomass, Assembly Bill 32 (Nunez and Pavley, Chapter 488, Air pollution: greenhouse gases: California Global Warming Solutions Act of 2006), Global Warming Solutions Act of 2006 has provided a framework for reducing the statewide carbon footprint and sequestration via biochar is a growing solution. This is all in addition to the fundamental mandate of the California Energy Commission, which has a statutory basis to convert to renewable energy via Senate Bill 350 (De León and Leno, Chapter 547, Clean Energy and Pollution Reduction Act of 2015), as well as the Electric Program Investment Charge (EPIC) Program, which funded this work. Lastly, the work in this agreement was successful in meeting the scope of work goals and objectives.

The commercialization and further engineering development of these solutions has implications for several actors.

- **Commercial markets:** The production of biochar at scale has enormous potential for carbon credit markets. Using these technologies at scale in rural or agricultural contexts paired with urban and metropolitan larger corporate partners represents immense potential for private sector coordination in carbon sequestration.
- **Utilities:** Distributed generation from renewable sources is critical for grid stability and resiliency. California has seen electrical system failures and utility partners are incentivized to find alternative generation schemes for system redundancy.
- **Industry:** The conversion of waste material to assets holds huge promise for commercial partners. Entities like green waste recyclers and tree service companies are desperate to eliminate tipping fees and reduce the logistics of hauling material offsite. Additionally, the larger scale machinery developed in this agreement meets pain points for actors in forestry and orchard management.
- **Consumers:** California ratepayers have some of the highest electricity costs in the United States. Distributed, renewable generation can reduce these costs and avoid public safety power shutoff events in emergencies, such as wildfires. This also has large public health and safety implications.
- **State actors:** Public forestry agencies are particularly desperate in California to reduce the number of dead and dying trees as a crucial component of wildfire mitigation.

As elaborated earlier, the project team learned valuable technical lessons about combustor design, effective biomass flow, and useful remote monitoring systems, but also scaling logistics and market drivers consistent with the pivot from Powertainer platform.

The project team will continue development of the Chartainer platform and is investigating smaller-scale and economical solutions to expand customers. The project team also better understands the necessities for future development of Powertainer with investment and has been able to deploy 50 kW units to some customers since this agreement. Furthermore, CEC funding from this agreement enabled further funding with the agreement EPC 20-012, part of the BRIDGE program that has realized some future development opportunities already, particularly building on the swirl hearth subcomponent. This proprietary technology can allow future market opportunities that can convert this into a technology platform with a potential for different outputs such as renewable natural gas. These greater development opportunities provide engineering challenges that will keep the project team exploring for several years to refine its core gasification technology to meet new and different customer needs.

Market opportunities for the technology or knowledge developed include:

- **Government agencies:** forestry agencies needing biomass disposal solutions, disaster relief entities that require off-grid power, local and tribal governments with mandates for off-grid resilience, and food waste, composting, and reforestation programs that are enhanced in their efficacy by biochar.
- **Private sector:** an immediate customer is processors of biomass such as nut shells and wood waste, but also utilities interested in distributed generation schemes (including electric vehicle charging), agricultural customers such as vineyards. The last customer represents an interesting market opportunity that the project team had not considered prior to this: due to the intermittent nature of their waste disposal and energy output needs, the project team has explored having licensing agreements or mobile fleets, based on rentals models. Finally, off-grid and experimental customers like eco-villages or academic institutions or community choice aggregator entities are motivated to find innovative solutions that may lead to further engineering opportunities for the project team.

Recommendations or suggested next steps that could enable increased production and adoption include:

- Further research and development funding from CEC to address new feedstocks mentioned above and to convert the technology to a more flexible platform.
- Deployment funding from CEC to get units into the hands of customers who are interested in being first adopters, such as the forestry and disaster relief agencies that have acute needs and can also rapidly scale solutions by being a larger-scale customer.
- Reduced administrative and permitting overhead for projects are necessary to make future projects like this possible. Even with grant funding, issues like protracted permitting provide difficulty getting in-field deployments, particularly as permitting agencies do not typically have regimes that include this kind of technology solution.

- Carbon sequestration with biochar in composting with food waste or in reforesting and soil remediation can be powerful replicable solutions.
- The project team also suggests novel approaches to funding, such as stacking state grants with federal ones or catalytic funding mechanisms, like the Climate Tech financing program that can enable early-stage deployments. By having public/private partnerships, the CEC can de-risk private investment and bridge the gap with larger investment rounds for early-stage companies. Additionally, encouraging advanced carbon commitments, such as with corporations that pre-purchase or commit to purchase carbon removal credits, can connect grant recipients with guaranteed markets and funders.

GLOSSARY AND LIST OF ACRONYMS

Term	Definition
ABC	Anderson Biomass Complex
APL	All Power Labs, the agreement recipient
BAAQMD	Bay Area Air Quality Management District
biochar	A fixed carbon product, like charcoal, that is one of the co-products from APL's gasification and pyrolysis systems
CEC	California Energy Commission, a state agency that supplied this agreement
CHAB	Combined heat and biochar
CHP	Combined heat and power
CT(+)	The Chartainer, a CHAB machine developed by APL in this agreement
EPIC	Electric Program Investment Charge
EVT	Engineering Validation Testing
gasification	A chemical process that converts solid mass into gasses at high temperature
HREC	Hopland Research Extension Center
IBI	International Biochar Initiative
MG1001	First 50 kW Microgrid CHP PP Container
MG1002	Second 50 kW Microgrid CHP PP Container
PHEV	plug-in hybrid electric vehicle
PP	Power Pallet
PP30	APL's latest generation of the Power Pallet biomass gasifier
PT(+)	The Powertainer, a CHP machine initially developed by APL in this agreement
pyrolysis	A stage in gasification and combustion where heat causes materials to decompose
TAC	Technical Advisory Committee

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Appendix A: Diagrams

March 2024| CEC-500-2024-023

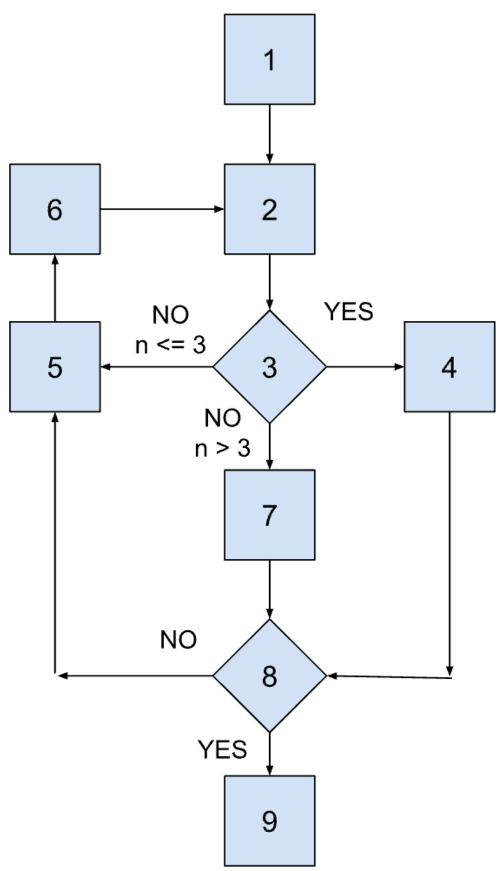
APPENDIX A:
Diagrams

A list explaining each step in Figure A-1 is shown.

1. Test to be performed: Attempt = n, n = 0
2. Perform the test n = n + 1
3. Does the test pass or fail?
4. Yes: Record the data
5. No n <= 3: Record the data and failure mode
6. Develop and implement a solution
7. No n > 3: Record the data and explain the failure
8. Is it safe to continue testing?

Yes: continue testing

Figure A-1: Iterative Failure Problem Solving Method for EVT

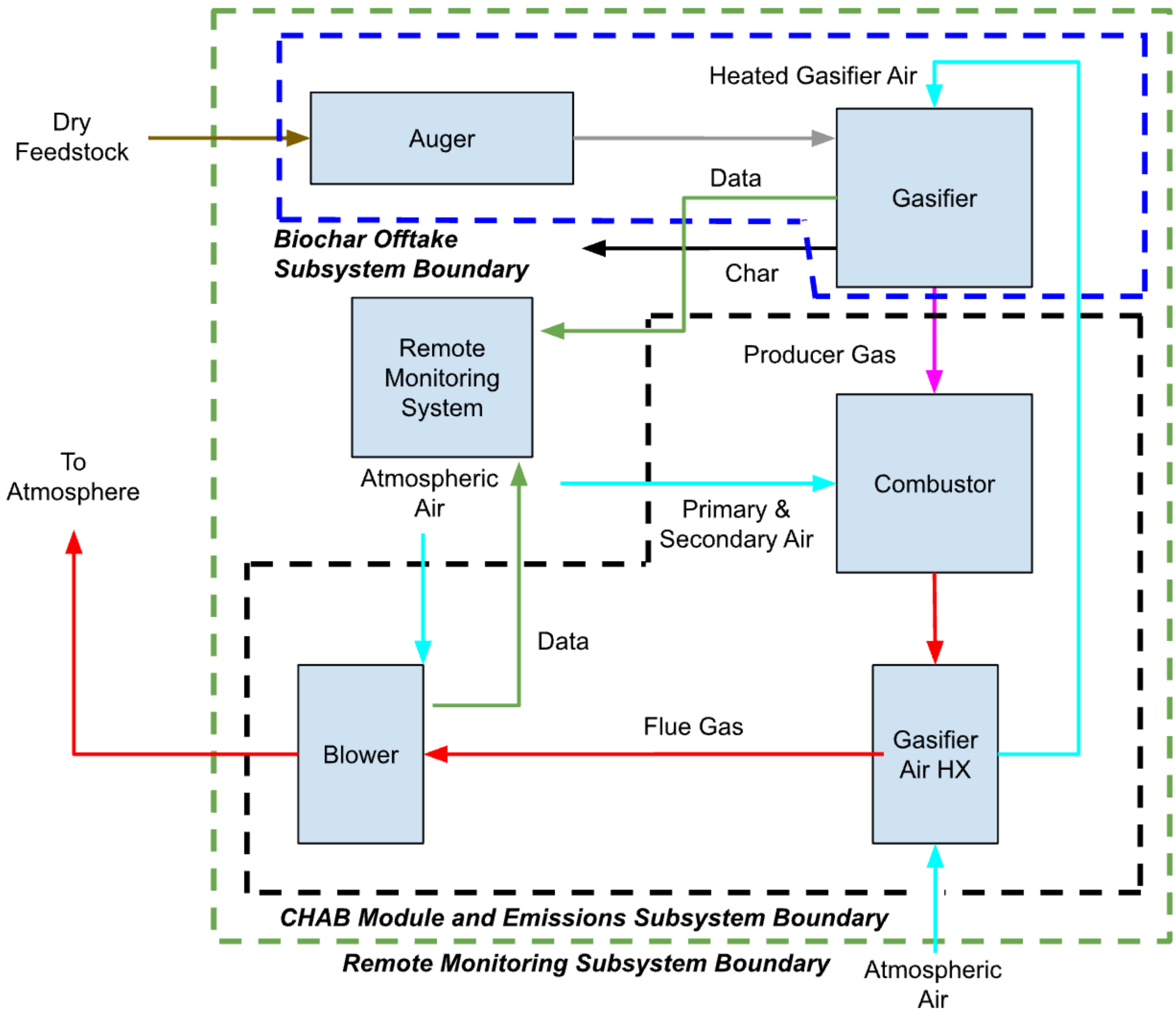


Source: All Power Labs, 2020

1. Figure A-2 illustrates the full system with the subsystem boundaries indicated by dashed outlines which each have their own set of criteria and validation protocols.

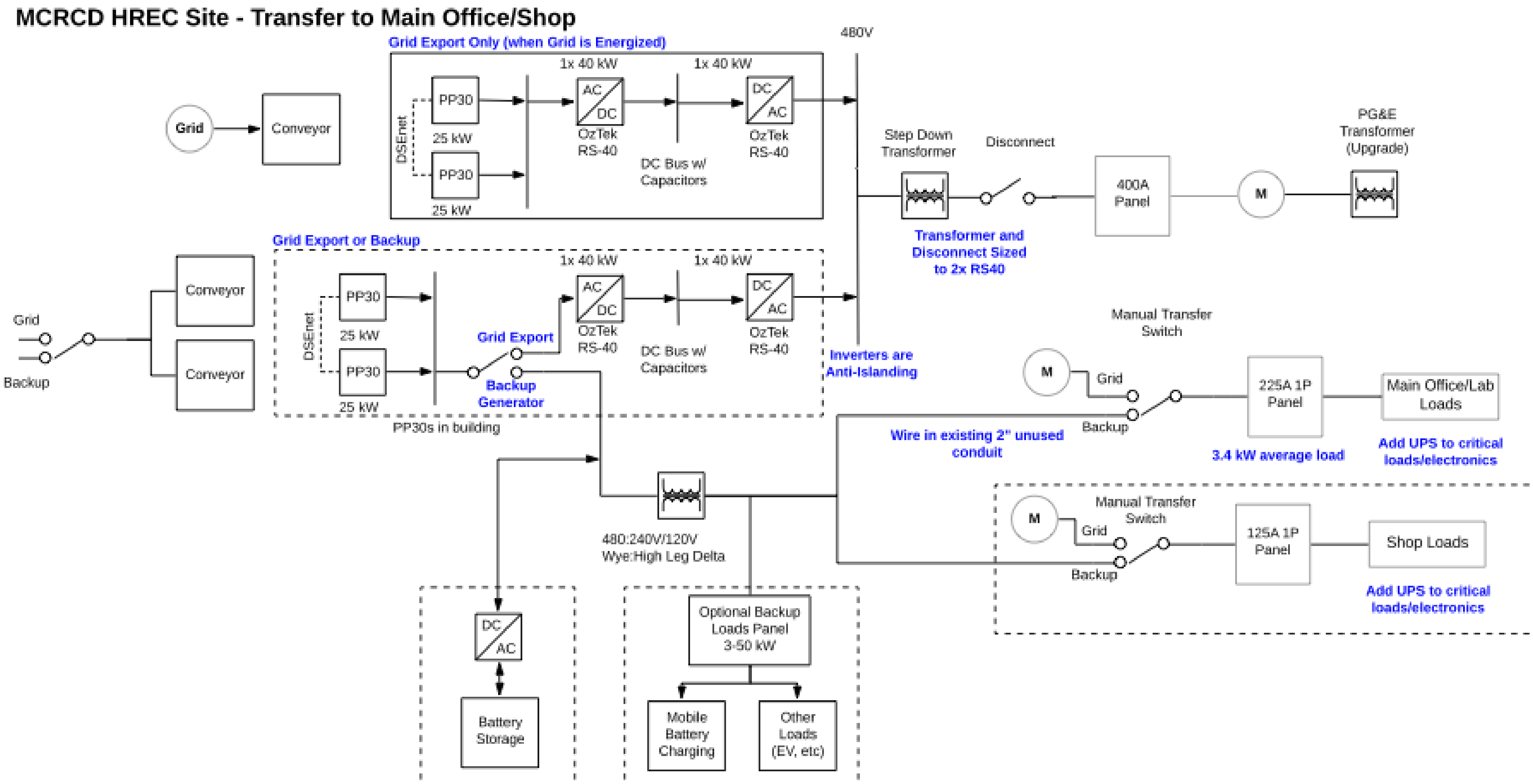
    - Blue outline: Biochar offtake
    - Black outline: CHAB and emissions
    - Green outline: Remote monitoring

Figure A-2: Study Subsystem Boundaries With Dashed Lines



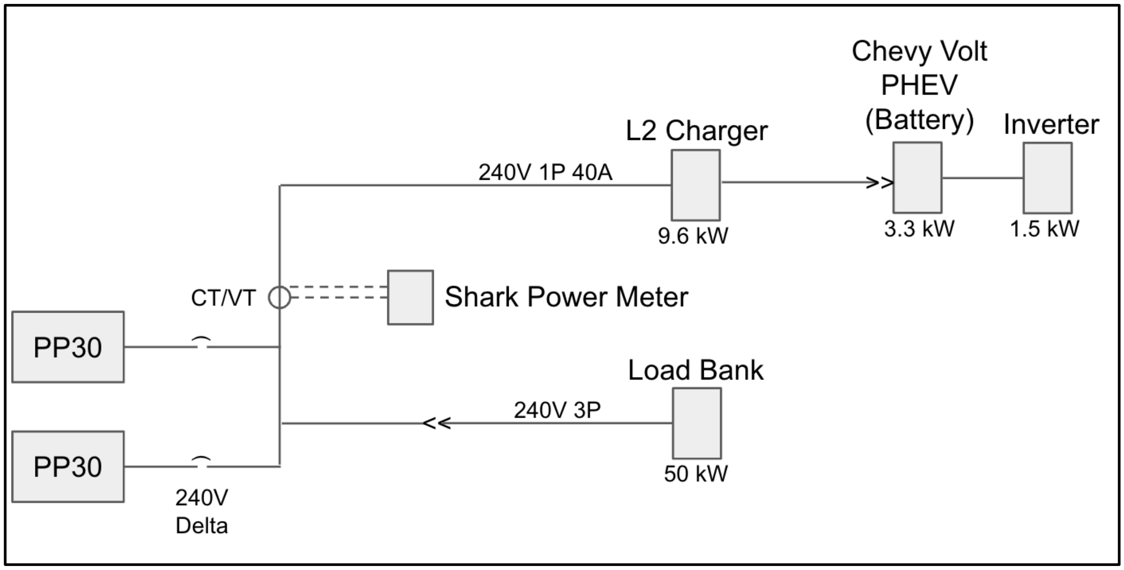
Source: All Power Labs, 2020

Figure A-3: Diagram of System Connections and Dependencies at HREC



Source: All Power Labs, 2020

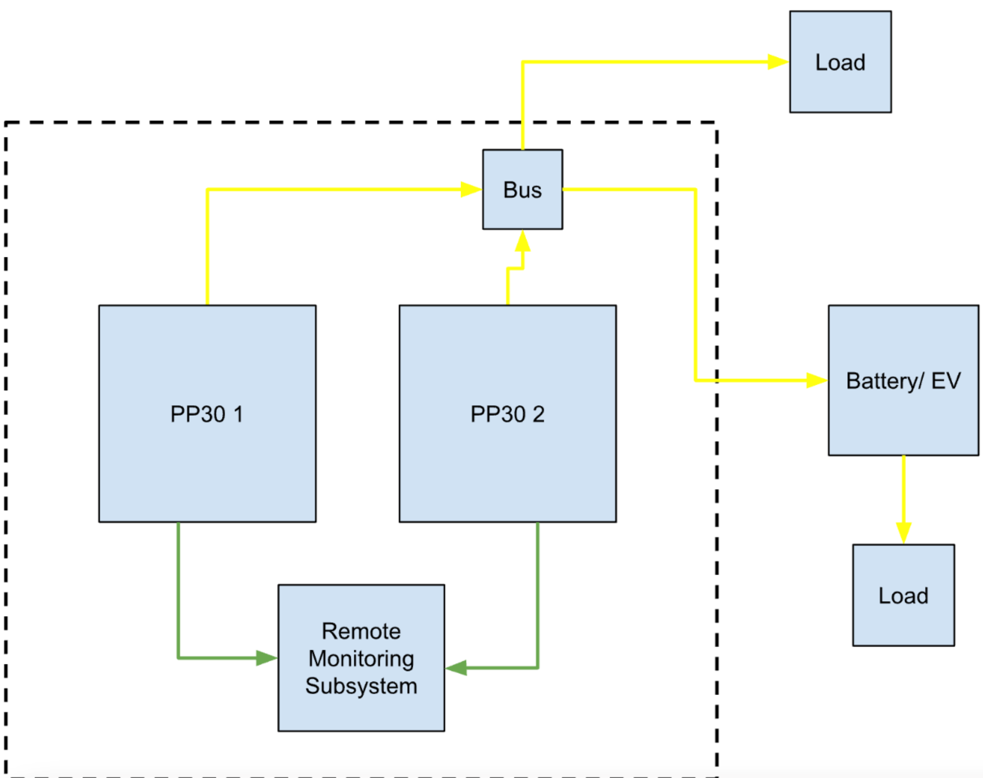
Figure A-4: 50 kW Microgrid Electrical Configuration for EVT Testing



Nominal component power ratings shown.

Source: All Power Labs, 2020

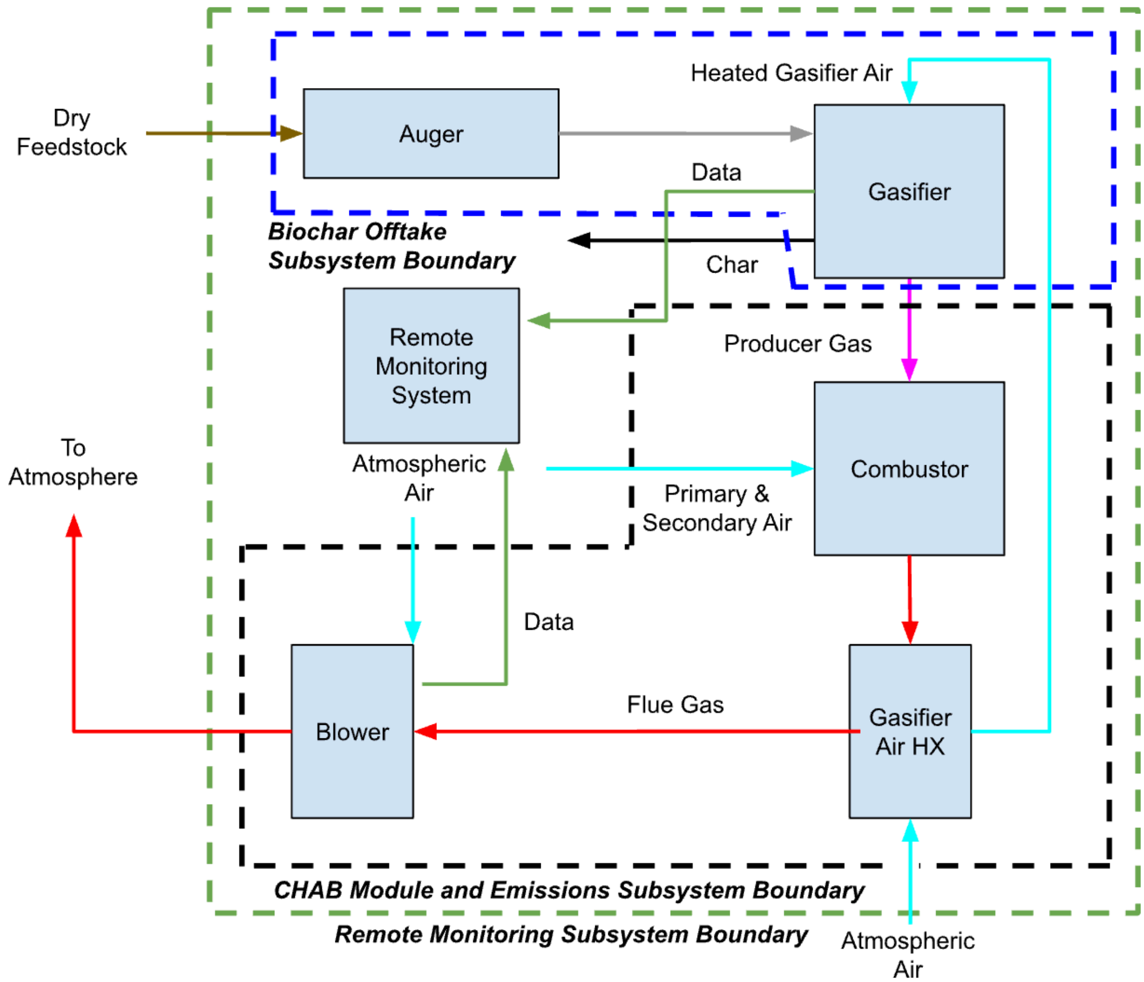
Figure A-5: Remote Monitoring 50 kW System Boundary



Source: All Power Labs, 2020

Remote Monitoring boundary for the Chartainer, represented by the green dashed line. The black line represents the CHAB module and the blue line the gasifier assembly. Note this boundary is identical to Figure A-2 and is included for reference and convenience.

Figure A-6: Remote Monitoring Chartainer Study System Boundary With Dashed Green Lines



Source: All Power Labs, 2020

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Appendix B: Testing Elaboration

March 2024 | CEC-500-2024-023

APPENDIX B: Testing Elaboration

Results of biochar testing follow in Table B-1 and B-2. The International Biochar Initiative identifies three classes of biochar, based on their composition percentage of organic carbon. Broadly, a higher percentage is more desirable, and "Class 1" biochar is the most pure and useful.

Figure B-1: Functional Testing: Integrated 50 kW Microgrid CHP PP Container Results

Test	Symbol	Threshold Value	Results	Description
Synchronization between PP30s	None	Pass	Pass	The units were synchronized and exported
Container Ventilation	Q	≥132 m^3/hr	13,500 m3/hr, Pass	The Power Pallet radiator fans provide 8,000 cubic feet/min or 13,500 m^3/hr of ventilation
Container Feed System Supply	CPPFS	>65 kg fuel/hr	Est. 800 kg/hr, Pass	The system provided roughly 40 kg/hr of fuel running on a 5% duty cycle (3 minutes every hour). Calculated max delivery is 800 kg/hr
No Jamming/ Bridging or Alarm	None	Pass	Pass	The units operated during the test period with no alarms

Table B-2: Abridged Basic Utility Properties of Biochar Values Provided by International Biochar Initiative and Reported Values

Description	Threshold Value	Reported Values
Organic Carbon (C_{Org})	10% Minimum (% of total mass, dry basis) Class 1: ≥60% Class 2: ≥30% and <60% Class 3: ≥10% and <30%	94.40 (Class 1)
H:C_{org}	0.7 Maximum (molar ratio)	0.04
Total Ash	Declaration (% of total mass, dry basis)	2.5
pH	Declaration (pH)	10.45

During this agreement, the project team was also able to send biochar samples to be tested to the International Biochar Initiative standards by Soil Control Laboratories, which has an extensive testing regiment that measured several properties of the biochar and measured for contaminants. The project team sent them five samples of biochar generated by the Chartainer, two from 2019 runs, and three from 2022 runs. Tables B-3 and B-4 provide an overview of the most important values.

Table B-3: Abridged Results of IBI Biochar Basic Utility Testing

Description	Threshold Value	Sample A Results (7/19/19)	Sample C Results (6/8/22)	Sample D Results (6/14/22)	Sample E Results (6/29/22)
Organic Carbon (C_{Org})	10% Minimum (% of total mass, dry basis) Class 1: ≥ *60%* Class 2: ≥ *30%* and <60% Class 3: ≥ *10%* and <30%	88.6 - CLASS 1 - PASS	93.4 - CLASS 1 - PASS	91.2 - CLASS 1 - PASS	94.0 - CLASS 1 - PASS
$H:C_{org}$	0.7 Maximum (molar ratio)	0.27 - PASS	0.25 - PASS	0.27 - PASS	0.20 - PASS
Total Ash	Declaration, % of total dry mass	4.2	1.5	3.7	1.4
pH	Declaration (pH)	9.8	9.19	9.24	10.32
Liming (if pH is above 7)	Declaration (%$CaCO_3$)	6.5	15.7	7.4	6.6
Surface Area Correlation	m^2/g dry	248	321	242	277

Table B-4: Results of IBI Testing for Biochar contaminants

Description	Threshold Value	Sample B Results (~2018)	Sample C Results (6/8)	Sample D Results (6/14)	Sample E Results (6/29)
Polycyclic Aromatic Hydrocarbons (PAHs), total (sum of 16 US EPA PAHs)	6 - 300 mg/kg dry wt.	69.8 - PASS	N/A	N/A	26.7 - PASS
Dioxins/Furans (PCDD/Fs)	17 ng/kg WHO-TEQ dry wt.	ND - PASS	N/A	N/A	ND - PASS
Polychlorinated Biphenyls (PCBs)	0.2 - 1 mg/kg	ND - PASS	N/A	N/A	ND - PASS

Note: ND = non-detect. N/A - not applicable - no data available.

All samples passed Basic Utility Testing requirements. Four samples were tested for PAH, Dioxins/Furans, and PCBs, and the presence of metals and all passed. Only one sample slightly exceeded the most stringent levels for nickel concentration per IBI standards.