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FINAL PROJECT REPORT

Innovative Microscale Biomass Gasifier Combined Cooling, Heating, and Power System

Gavin Newsom, Governor

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division manages the Natural Gas Research and Development Program, which supports energy-related research, development, and demonstration not adequately provided by competitive and regulated markets. These natural gas research investments spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

The Energy Research and Development Division conducts this public interest natural gas-related energy research by partnering with research, development, and demonstration entities, including individuals, businesses, utilities and public and private research institutions. This program promotes greater natural gas reliability, lower costs and increases safety for Californians and is focused in these areas:

- Buildings End-Use Energy Efficiency.
- Industrial, Agriculture and Water Efficiency.
- Renewable Energy and Advanced Generation.
- Natural Gas Infrastructure Safety and Integrity.
- Energy-Related Environmental Research.
- Natural Gas-Related Transportation.

Innovative Microscale Biomass Gasifier Combined Cooling, Heating, and Power System is the final report for Contract Number PIR-16-010 conducted by All Power Labs, Inc. The information from this project contributes to the Energy Research and Development Division's Natural Gas Research and Development 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 CEC at ERDD@energy.ca.gov.

ABSTRACT

Many light industrial and commercial markets considered as potential users for combined cooling, heating, and power (CCHP) are underserved and unserved because of its technological and economic challenges, and largely because of the existing natural gas infrastructure and current competitive advantages. The primary barrier to adopting micro-scale CCHP with adsorption chillers relate to limited effectiveness and high costs.

This project devised a novel solution for CCHP that has at least 80 percent total system efficiency, reduces natural gas consumption, provides thermal and electricity ratepayer benefits, and lowers greenhouse gas emissions. The project team achieved these goals by developing a cost-effective, bankable, 20-kilowatt electric packaged CCHP system, powered by a biomass gasification waste-to-energy platform and demonstrated its use in a real-world situation.

The project team conducted pilot testing and demonstrations, with one facility located at a fire-risk community in southern California, used mainly woody biomass, and the second one at All Power Labs workshop in Berkeley, used woody biomass and walnut shells, to power the biomass gasifier CCHP units. The team tested and validated the CCHP systems, demonstrating a replicable, scalable model for use in the commercial and light industrial sectors.

Keywords: biomass, gasification, pyrolysis, renewable electricity, carbon negative, forestry, tree mortality, climate change, biochar

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Introduction

Many light industrial and commercial markets rely heavily on natural gas as their energy source and, in 2018, these sectors used 27 percent of California's natural gas supplies. These markets are considered as potential users for combined cooling, heating, and power (CCHP) systems, yet are underserved and unserved because CCHP has technological and economic challenges. The main barriers to adoption of microscale CCHP with adsorption chillers are due to their limited availability, effectiveness, and California's dependency on natural gas.

Further, climate change is causing a forest health crisis in California, with a tree mortality emergency that has seen over one hundred million trees dead and at risk of being ignited in catastrophic wildfires that would emit substantial carbon emissions. There is a pressing need for an economical and climate-sensitive approach to reducing the risk of catastrophic wildfire, while also addressing the state's need for natural gas alternatives and clean renewable energy.

All Power Labs has been at the forefront of small-scale gasification technologies for more than 10 years, designing, engineering, building, and deploying compact biomass gasifier generators. The production of electricity from gasification creates multiple sources of heat, providing additional energy related opportunities when harnessed — including the generation of cooling by integrating an adsorption or absorption cooler.

The research conducted under this project developed the CCHP PP30 Power Pallet, which holds great potential for directly addressing the dependency on natural gas for combined heat and power (CHP) applications and contributing to California's clean energy goals. The developed technology improved the previous version of the All Power Labs' Power Pallet by integrating a more robust CHP and adsorption cooling system, which was selected based on the scale and energy range of the system and project.

The CCHP Power Pallet technology holds promise in supporting progress towards a number of important state energy policies and laws, including:

- Senate Bill 100 (De León, Chapter 312, Statutes of 2018) – California Renewables Portfolio Standard Program
- Execute Order B-55-18 to achieve carbon neutrality by 2045
- Senate Bill 350 (De León, Chapter 547, Statutes of 2015) – Clean Energy and Pollution Reduction Act of 2015
- Renewables Portfolio Standard Senate Bill X1-2, (Simitian, Chapter 1, Statutes of 2011); SB 107 (Simitian, Chapter 464, Statutes of 2006); SB 1078 (Sher, Chapter 849, Statutes of 2002)
- Assembly Bill 32 (Nuñez, Chapter 488, Statutes of 2006) – The Global Warming Solutions Act of 2006
- SB 1122 (Rubio, Chapter 612, Statutes of 2012) – Bioenergy Feed-in Tariff
- Senate Bill 96 (Rubio, Chapter 612, Statutes of 2012) – Committee on Budget and Fiscal Review, Statutes of 2013
- Proclamation of a State of Emergency 10-30-15

- Short-Lived Climate Pollutant Reduction Strategy (Draft 2015)

Project Purpose and Approach

All Power Labs developed the CCHP PP30 Power Pallet, a cost-effective microscale (less than 50 kilowatts [kW]) CCHP system powered by a biomass gasification waste-to-energy system. Biomass gasification is a process that converts biomass into a combustible gas through a thermal conversion process of the carbonaceous materials. This combustible gas can then be used to fuel an internal combustion engine to produce electricity and heat. This innovative CCHP Power Pallet system enables integration of its electrical, heating, and cooling outputs with light industrial, communities, and commercial building applications, reducing natural gas and electricity use.

The goals of this project were to reduce natural gas and electricity consumption and associated costs, mitigate greenhouse gas (GHG) emissions, and advance the technology to help reach statewide energy policy goals and demonstrate a replicable, scalable model for use in the commercial and light industrial sectors.

The researchers installed and tested this pilot system at a community micro-grid facility in a fire-risk community of Malibu in southern California, using wood waste left behind after the 2018 Woolsey fire and walnut shells to power the biomass gasifier CCHP unit.

All Power Labs addressed technical challenges through physical testing and refinement, including the following:

- The originally selected engine became unavailable for the project. The project team surveyed potential alternatives and conducted qualification testing on multiple engines before selecting an alternative. The final engine selected allowed increased power output (25 kW, up from 18 kW) and improved efficiency from a higher compression ratio.
- The CHP thermal circuit and related system efficiency experienced some technical challenges. The project team identified and tested several designs of the thermal system to maximize the captured heat at multiple points in the system. The team down selected to a design that incorporated strategically placed thermostats and connected the thermal circuit to a backup radiator that was able to control the heat in case the system overheated. The final design allows operation even when no heat is used by the customer.
- A new gas filtration system was designed to deal with the changes in gas characteristics in different gas temperature ranges. The resulting hot gas filtration system utilized custom heat exchangers to mine heat from the system to stabilize gas temperature to a range that reduces condensibles (tars) and can more easily be filtered.

The non-technical challenges focused on regulatory, interconnection, and permitting requirements, which were complex, costly, with a long approval process considering the scale of the project installation.

Third-party verification of the project benefits was conducted by The Schatz Energy Research Center that also assisted with knowledge and technology transfer activities. The research center created a measurement and verification plan to study and quantify the performance of the CCHP Power Pallet and included analysis of:

1. System performance, efficiency, and energy flow.
2. Gas emission rates (greenhouse gases and criteria pollutants).
3. Total electricity savings (from electricity output and avoided cooling from CCHP).
4. Total natural gas savings (from heat output from CCHP).
5. Operational and maintenance costs.

Researchers collected data for more than six months of operation and analyzed them to determine the benefits to the site host. The team identified numerous benefits including electricity savings (kWh), natural gas savings (therms), and emissions reductions (GHGs and criteria pollutants).

Project Results

The third-party verification team tested the CCHP Power Pallet in a controlled environment as well as in the field, with two units successfully designed, manufactured, installed, and operated for a total of over 750 hours. The project met the performance target of 80 percent total system efficiency (an increase from 25 percent efficiency once thermal energy was captured), and successfully used an innovative, small-scale renewable CCHP technology. Further, fuel efficiency improved from 1.2 kg/kWh to 1.0 kg/kWh, 22 kW continuous electrical output was produced, 48 kW of heat was captured, 25 kW heat was used for the adsorption chiller, producing 9 kW of cooling resulting in a coefficient of performance (COP) of 0.38. Independent analyses of the CCHP unit confirmed these goals were met, and that this technology can fill an actual market need with further refinement. The project team's site host and operating partner are engaged to continue working together to improve the technology and demonstrate its value in different applications.

Conclusions and Recommendations

This project expanded the team's knowledge of some of the most difficult challenges facing widespread deployment—technical issues, market readiness, and regulatory hurdles—and gave the involved parties a better understanding of how to overcome them and broaden the biomass market. Further, regulatory site challenges led All Power Labs to collaborate with new partners who were able to site and run the CCHP system in a disaster relief scenario in response to the Woolsey Fire in 2018 to provide, power, heat, cooling and water to a site hosting displaced families. The insights generated from this project helped the project team to understand how the CCHP Power Pallet can be scaled up and replicated in the future to meet new distributed and small-scale energy needs.

The project team gained and disseminated new knowledge about cogeneration technology and confirmed that the finished products were more efficient and generated more power than originally expected, while keeping a consistent price that is highly competitive. Additionally, the existing gasifier units were paired with novel complementary technologies—adsorption chillers and water extraction machines—that broaden the possible customer base for biomass processing. Future research will focus on extending the technical innovations of this work as well as expand the customer base.

The project team's recommendations to overcome the challenges listed include continued research to comprehend technical solutions and expanded outreach to inform market actors and regulatory agencies of the value of biomass in the renewable energy space. Biomass processing has an important role to play in the future world of electricity production, heating, and cooling; however, there is a need to continually communicate effectively the benefits to early adopters as well as other institutions (e.g. policy makers, regulatory agencies, industry standards groups). Many of the technical challenges posed by the research were compounded by difficulties communicating this important work to regulatory agencies.

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

The project team was able to leverage existing community outreach endeavors such as open houses and industry events to publicize the advances of the biomass CCHP. Additionally, the researchers and site host have been active in promoting this work to their respective communities. All Power Labs and site host Skysource won an award for a novel combination of the two entities' technologies increasing attention on All Power Labs' work. The disaster relief setting also allowed the project team to be introduced to agencies that can procure the technology to meet other policy goals in addition to the mission of the California Energy Commission.

Benefits to California

Biomass gasification power generation provides ratepayers with a new energy option, one that is on-demand, renewable, and not weather dependent. This project, built entirely of technology designed and manufactured in California, demonstrated a cost-effective way to address the light industrial and commercial market's dependencies for natural gas powered CCHP equipment, as well as a myriad of issues associated with climate change, including drought, wildfires, and the need for more renewable energy. This was achieved by the utilization of forestry waste to produce renewable power, heat, cooling and water while simultaneously sequestering carbon in the form of biochar. This project illustrated the viability of mobile gasification systems to fit into this market, while avoiding the use natural gas and sourcing the fuel from fire remediation efforts. The team demonstrated how this technology provides the potential for significant reduction of harmful emissions compared to using grid electricity and natural gas fueled equipment.

The CCHP Power Pallet offers benefits to California ratepayers through 1) offset consumption of electricity and natural gas, 2) economic value of offset energy use, and 3) avoided greenhouse gas emissions. Large-scale use in forestry management would reduce risk of wildfires and contribute to the responsible processing of wood waste.

Table ES-1 summarizes the reduced energy demand totaling more than $42,000 from each mechanism for a single CCHP Power Pallet prototype.

Table ES-1: Energy Reduction from Combined Cooling, Heating, and Power Power Pallet Prototype

Mechanism	Energy Offset	Economic Value	Avoided Emissions
1. Electricity Offset	158 MWh/yr	$28,130/yr	38 tonnes CO_{2e}/yr
2. Cooling Offset	22.2 MWh/yr	$3,950/yr	5 tonnes CO_{2e}/yr
3. Heating Offset	7,100 therm/yr	$7,670/yr	38 tonnes CO_{2e}/yr
4. Natural Gas Electricity Offset	6,100 therm/yr	$2,630/yr	0*

*** Avoided emissions from natural gas power plants is captured under mechanism 1.**

Source: Schatz Energy Resource Center

In addition, the carbon sequestration potential (that is, capacity to store carbon long-term) of the biochar is particularly groundbreaking because very few technologies exist that can sequester atmospheric carbon, which is what the CCHP Power Pallet can do when paired with the natural forest ecosystem — an innovative and groundbreaking bio-energy with carbon capture and storage technology. The biochar produced from this energy technology enables the sequestration of carbon that would otherwise have been released into the atmosphere. Furthermore, by combining the production of electricity, heat, and cooling with the production of the biochar byproduct, the environmental benefit is greatly increased.

When used at scale, the CCHP Power Pallet is anticipated to result in job creation across the multiple sectors involved in similar biomass energy projects, including manufacturing, feedstock supply chain (harvesting, processing, and transportation), equipment operation, construction, and project development.

This project sets the groundwork for future studies and projects expanding on the microgrid and fire risk mitigation use case established at the Sky Source Ranch in Malibu. For example, after the Woolsey fire in 2018, the region has an unstable utility grid.[1] This issue is exacerbated by the high winds that blow off the Pacific Ocean which can take down power lines and disrupt access to grid power. All Power Labs and Sky Source LLC created a small microgrid to address these challenges experienced at the Sky Source Ranch after the Woolsey fire and plans to expand and scale this microgrid to create a resilience hub to address a larger region affected by these same issues.

[1] "California power outages hit more than 500,000 amid high winds and fires across the state" (October 24, 2019) by Hannah Fy and Jaclyn Cosgrove, in *The Los Angeles Times.*

CHAPTER 1: Introduction

The light industrial and commercial markets currently rely heavily on natural gas. Industry and state actors have shown an increasing interest and reliance on distributed combined cooling, heating, and power solutions.

Project Goals and Objectives

The goals of this project are to reduce natural gas consumption, provide natural gas and electricity investor-owned utility (IOU) ratepayer benefits, reduce greenhouse gas (GHG) emissions, break technological barriers that block reaching statewide energy policy goals, and to provide tangible benefits to disadvantaged communities. The project team set out to achieve all of these goals by accomplishing its overall objective: to develop a cost-effective, bankable, 20kW$_e$ packaged combined cooling, heat, and power (CCHP) system with adsorption cooling, powered by a biomass gasification waste-to-energy platform, known as the CCHP Power Pallet (Figure 1).

Figure 1: Combined Cooling, Heat, and Power Power Pallet Front and Back

Source: All Power Labs, Inc.

This CCHP system was integrated with and powered by the Power Pallet, an All Power Lab's biomass gasification waste-to-energy platform, its patented compact architecture allows it to sit within the footprint of a shipping pallet. The project conducted pilot testing and demonstration in a fire-risk community in southern California, using forecast waste, and walnut shells to power the biomass gasifier CCHP unit. The objective of those activities were to test and validate the CCHP Power Pallet in a real world use case, with the objective to demonstrate a replicable, scalable model for use in the commercial and light industrial sectors, which it is highly appropriate for, but underserved by combined heat and power (CHP) and CCHP technology.

The Schatz Energy Research Center (SERC) provided third party verification of the project benefits and assist with knowledge and technology transfer by writing an article in a peer-reviewed journal.

The measurement and verification performed by SERC comprised an energy balance of the gasifier CCHP system, electricity and natural gas reductions for the site host, economic savings on electricity and natural gas, and emissions reductions including GHG and criteria pollutants. Instruments were installed on the gasifier CCHP and at the site host's facility before commissioning the system. The team collected data over six months of operation then analyzed to determine the benefits to the site host. To determine project benefits, the following calculations were performed:

- Electricity savings (kWh)
- Natural gas savings (therms)
- Emissions reductions (GHGs and criteria pollutants)
- Energy balance on gasifier CCHP system
- Generator operational data

The research under this project fits directly within the larger narrative of California's energy policy, as well as other policies and laws. Outlined below are additional policies the CCHP Power Pallet technology fits into:

- Senate Bill 100 (De León, Chapter 312, Statutes of 2018) California Renewables Portfolio Standard Program Statutes of 2018: SB 100 specifies 60 percent renewable energy by 2030 and 100 percent clean energy by 2045
- SB 350 (De León, Chapter 547, Statutes of 2015) Clean Energy and Pollution Reduction Act of 2015: SB 350 requires the following: 1) the amount of electricity generated and sold to retail customers per year from eligible renewable energy resources be increased to 50 percent by December 31, 2030; 2) the California Energy Commission to establish annual targets for statewide energy efficiency savings in electricity and natural gas final end uses of retail customers by January 1, 2030; and 3) provide for transformation of the Independent System Operator into a regional organization.
- Renewables Portfolio Standard (SB X1-2, [Simitian, Chapter1, Statutes of 2011]; SB 107 [Simitian, Chapter 464, Statutes of 2006]; SB 1078 [Sher, Chapter 849, Statutes of 2002]: These measures, in sum, require retail sellers and local publicly owned electric utilities to increase the amount of energy procured from eligible renewable energy resources to meet at least 33 percent of their total retail sales by 2020, in what is known as the Renewables Portfolio Standard.
- Assembly Bill 32 (Nuñez, Chapter 488, Statutes of 2006) The Global Warming Solutions Act of 2006: AB 32 created a comprehensive program to reduce GHG emissions in California. GHG reduction strategies include a reduction mandate of 1990 levels by 2020 and a cap-and-trade program. AB 32 also required the California Air Resources Board to

develop a scoping plan that describes the approach California will take to reduce GHGs. They must update the plan every five years.

- SB 1122 (Rubio, Chapter 612, Statutes of 2012) – Bioenergy Feed-in Tariff: SB 1122 requires the CPUC to direct the investor-owned electric utilities to collectively procure at least 250 MW of eligible renewable energy from small-scale bioenergy projects with capacities of 3 MW or less.
- SB 96 (Rubio, Chapter 612, Statutes of 2012) Committee on Budget and Fiscal Review, Statutes of 2013: SB 96 stipulates that in administering the EPIC program, the Energy Commission fund research, and development and demonstration programs and projects that:
  - May lead to technological advancement and breakthroughs to overcome barriers that prevent the achievement of the state's statutory energy goals and
  - May result in advancements on the most significant technological challenges
- Proclamation of a State of Emergency 10-30-15: Governor's 10-30-2015 Proclamation of a State of Emergency to protect communities against unprecedented tree die-off. The EPIC program is accelerating the schedule for release of the EPIC bioenergy solicitation in response to this proclamation.
- Short-Lived Climate Pollutant Reduction Strategy (Draft 2015): Short-lived climate pollutants are powerful climate forcers that remain in the atmosphere for a much shorter period than longer-lived climate pollutants, such as carbon dioxide (CO_2). Their relative potency, when measured in terms of how they heat the atmosphere, can be tens, hundreds, or even thousands of times greater than that of CO_2. The impacts of short-lived climate pollutants are especially strong over the short term. Reducing these emissions can make an immediate beneficial impact on climate change.

Technology Background

All Power Lab has been at the forefront of small-scale gasification technologies for more than 10 years, designing, engineering, building, and deploying compact biomass gasifiers, largely for off-grid power use in the developing world. Figure 2 depicts the development of the Power Pallet.

The project CCHP PP system was built on the All Power Lab 20kW Power Pallet — a complete biomass power generation solution that converts organic woody byproducts, like wood chips and nut shells, into electricity and heat. The product is a compact and integrated system — from biomass in, to power out.

The All Power Lab's Power Pallet is distinguished from prior biomass gasification power generation systems by its compact size, lack of tarry filter water byproducts, and affordable price (3-time reduction over comparable systems). It is a "power-in-a-box" solution that delivers the hands-off non-tended operation expected from contemporary power generation equipment.

These advantages are the result of significant advances in electronic control and waste heat recycling. An onboard computer provides the expertise usually required from a trained operator. A multi-stage gasification architecture, combined with an innovative gasifier-engine thermal integration, significantly improves tar conversion, fuel flexibility and moisture tolerance. The result is a technically advanced solution that is practical for everyday use, by regular everyday operators, in a wide variety of markets.

Figure 2: History of the Power Pallet

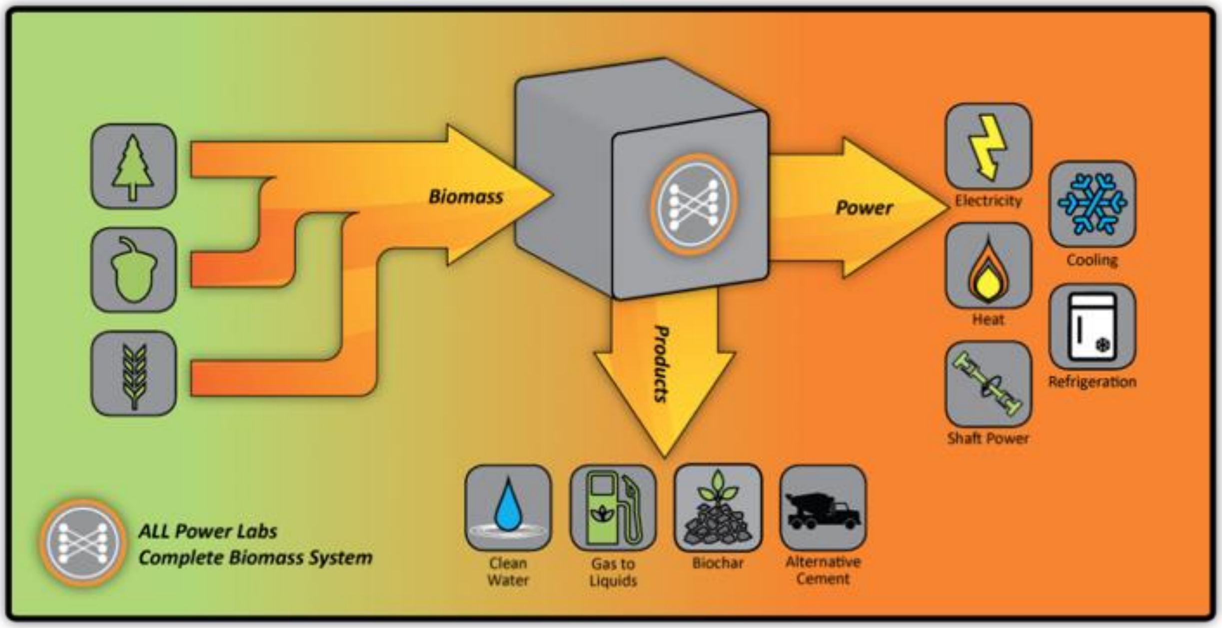
2011	2012	2013	2014	2015	2016	2017	2018
GEK	PP10	PP20					PP30
v1.04	v1.06	v1.08	v1.09		v1.1		v2.0
Prototype GEK	**Prototype Generation 1**	**Prototype Generation 2: Various Iterations and Improvements**					**Prototype Generation 3: CEC-funded to improve system efficiency, increase power ouptut, control emissions, and change architecture model**
Mild steel Experimenters Gasifier Kit (GEK); Integrated genset to create Power Pallet (PP).	GEK & PP with v4 reactor and 304 stainless steel.	GEK discontinued; Last 4-series gasifier architecture; Optional grid tie module available.	Introduction of PP's v5 gasifier architecture, resolving bell packing and allowing longer continuous operations; New making methods for scaled manufacturing; Improved gas quality.		PP w v5.X gasifier improves performance, reliability, Design improves gas quality (tar <100 mg/m3)		

Source: All Power Labs, Inc

The long-term goal of All Power Lab is to deploy at scale a new type of energy product- an individual scale waste-to-power-and-products appliance. Imagine a "personal computer of personal scale energy", or a "universal organics converter"; a machine which intakes a broad range of organic byproducts already onsite and converts them to multiple forms of "power and products", right where needed. This type of multi-gen platform is uniquely enabled by the process flows of a biomass gasification-based power generation system.

A biomass-based gasifier- engine system has the potential to replicate most of the power and product conversion pathways typically enabled by fossil fuel combustion and/or chemical upgrading. As such, All Power Lab's end goal is to create a novel product which can output biomass-based replacements, for all the power and product types listed below. Figure 3 shows the flow diagram of Power Pallet.

Figure 3: Power Pallet Inputs and Outputs Diagram



Source: All Power Labs, Inc.

The purpose of this project was to expand the current heat output of the Power Pallet by developing new recovery circuits to capture heat from the engine block, engine exhaust and the producer gas. This improvement creates the uniquely flexible CHP system that can operate from 100 percent heat with no electricity generation, to standard maximum electricity generation with residual waste heat capture.

Market and Technology Challenges

The Power Pallet is a technology with immense potential to address and contribute towards California's clean energy goals. The premise behind the Power Pallet and its design is that it fits within a form that the world already knows how to easily transport and can be moved to the sources of fuel rather than relying on large centralized plants where fuel needs to be transported large distances, potentially offsetting the value of the fuel itself. The largest obstacles experienced to demonstrate the technology in a real-world application relates directly to non-technical challenges. Local and permitting agencies are generally unaware of this type of technology resulting in a longer timeframe and higher permitting costs required for permit approval. To have a viable portable energy solution that can offset and replace the need for natural gas while also addressing challenges related to climate change and California's wildfires, incentives and non-technical requirements need to be established that better support new energy technology options.

CHAPTER 2: Design and Validation Testing Results

Combined Cooling, Heat, and Power Pallet Design Summary and General Discussion

Under the scope of the engineering development, the project team designed and tested a CCHP Power Pallet prototype focusing on the development of integrated CHP, the addition of a genset enclosure, emissions control, improved system efficiency, and integrating an adsorption cooler. The CCHP Power Pallet consists of the following modules and subsystems:

- Gas Making Module
    - Hopper Feed System
    - Gasifier
    - Emissions Control
    - Flare
    - Filter
- Power Generation Module
    - Enclosure
    - Engine Genset
    - Engine Cooling System
    - Automation and Controls

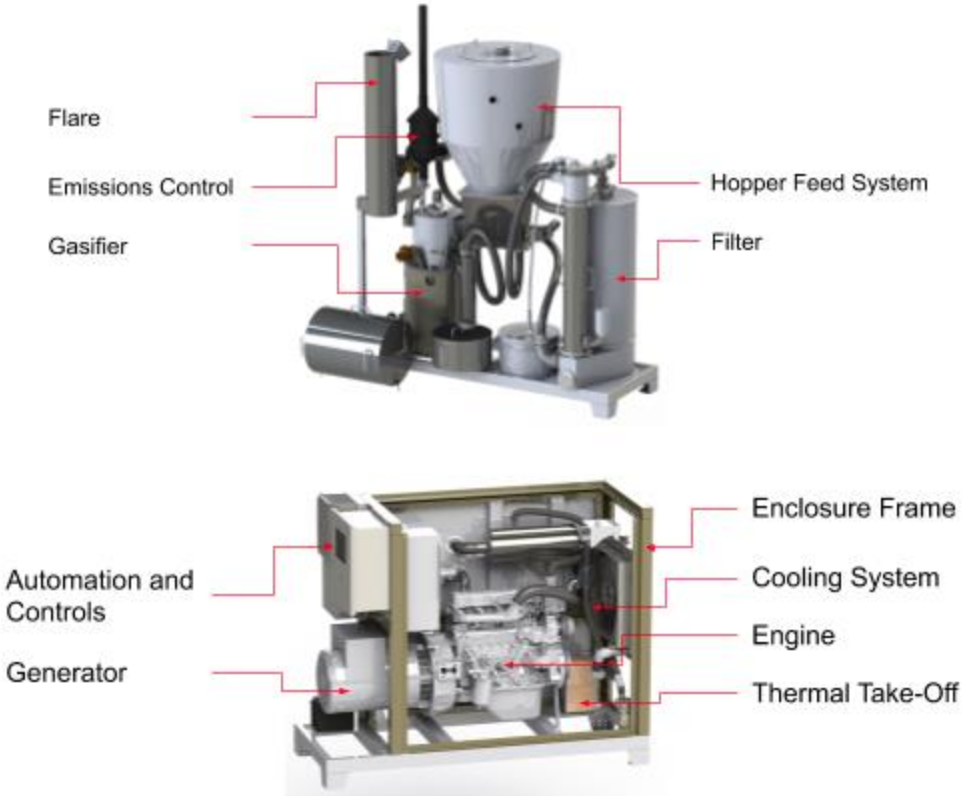
Figure 4 illustrates the Power Pallet, composed of two distinct modules.

Figure 4: Combined Cooling, Heat, and Power Pallet Rendering with Module Call-Outs

Source: All Power Labs, Inc.

Figure 5 depicts the gas-making module top and power-generation module below.

Figure 5: Module Rendering with Subsystem Call-Outs



Source: All Power Labs, Inc.

Standard Operating Conditions and Major Assumptions

Table 1 gives the standard operating conditions and basic test information for each category of testing. All maintenance tasks are up-to-date in accordance with the All Power Labs user manual[2] (such as oil change, gas line cleaning, filter change, etc.).

Three sets of scenarios, worst, intermediate, and best-case scenarios, were carried out to evaluate the improved prototype (Power Pallet 30) performance. This section describes the results provided for each CHP module for the intermediate scenario.

Three sets of scenarios were carried out because large sources of measurement error became prevalent as the EVT data was analyzed. The major sources of error that were adjusted to provide a worst, intermediate, and best-case scenario were the energy content of the fuel, gasifier efficiency, and fuel consumption.

[2] "All Power Labs Carbon Negative Power & Products." *Support*, All Power Labs, www.allpowerlabs.com/support.

Table 1: Improved Power Pallet Prototype (PP30) Standard Operating Parameters for Combined Cooling, Heating, and Power Pallet Testing

Maintenance Interval	CHP Module, Adsorption Cooling, and Genset Improvements	Enclosure and CHP Mounting	Emissions
Engine Type	Ashok Leyland	Ashok Leyland	Ashok Leyland
Engine Coolant Type	Water	Water	Water
Engine Timing	21 degrees	21 degrees	21 degrees
Engine compression ratio	12:1	12:1	12:1
Lambda Set Point (engine air fuel ratio)	1.017	1.017	1.017
Electrical Genset Configuration	Series Star (also Y)	Series Star (also Y)	Series Star (also Y)
Electrical Frequency	60 Hz	60 Hz	60 Hz
Electrical Power Phase	3 Phase	3 Phase	3 Phase
Gasifier Type	s5.04	s5.04	s5.04
Biomass Fuel Type	Wood chips (Douglas Fir No Bark)	Walnut shells	Wood chips (soft/hardwood mix)
Exhaust catalyst	DCL [3] three-way catalyst model # 2-DC45 2.5(SLIP)	DCL[2] three-way catalyst model # 2-DC45 2.5(SLIP)	DCL[2] three-way catalyst model # 2-DC45 2.5(SLIP)
Test date	6/26/18	6/28/18	5/3/18

Source: "All Power Labs Carbon Negative Power & Products." https://www.allpowerlabs.com/support.

The energy content of the fuel was provided by the external database (ECN Phyllis2)[4] and assumed to vary approximately between the minimum and maximum numbers for tree species Douglas fir (4.5–6.0 kilowatt-hour per kilogram [kWh/kg] fuel) with an approximate median of 5.5 kWh/kg fuel.

[3] DCL International Inc., website: http://www.dcl-inc.com/.

[4] "ECN Phyllis2." *ECN Environmental & Energy Engineering*, ECN Biomass & Energy Efficiency, 21 Mar. 2016, www.ecn.nl/phyllis2/Home.

The gasifier efficiency was based off best and worst cases from testing done by All Power Labs.

The fuel consumption was measured with an assumed error of 2 kg plus or minus.

The sources of error is discussed in greater detail in the discussion sections. Table 2 provides the key variables that were adjusted for 25 kilowatts (kW) and 16 kW.

Table 2: Key Variables with Significant Error in Best, Intermediate, and Worst-Case Scenario

Scenario	Fuel Energy Content	Gasifier Efficiency	Fuel Consumption in 1 hour
Best	4.5 kWh/kg Fuel	60%	25.3 kg @ 25 kW 16.6 kg @ 16 kW
Intermediate	5.5 kWh/kg Fuel	70%	27.3 kg @ 25 kW 18.6 kg @ 16 kW
Worst	6.0 kWh/kg Fuel	80%	29.3 kg @ 25 kW 20.6 kg @ 16 kW

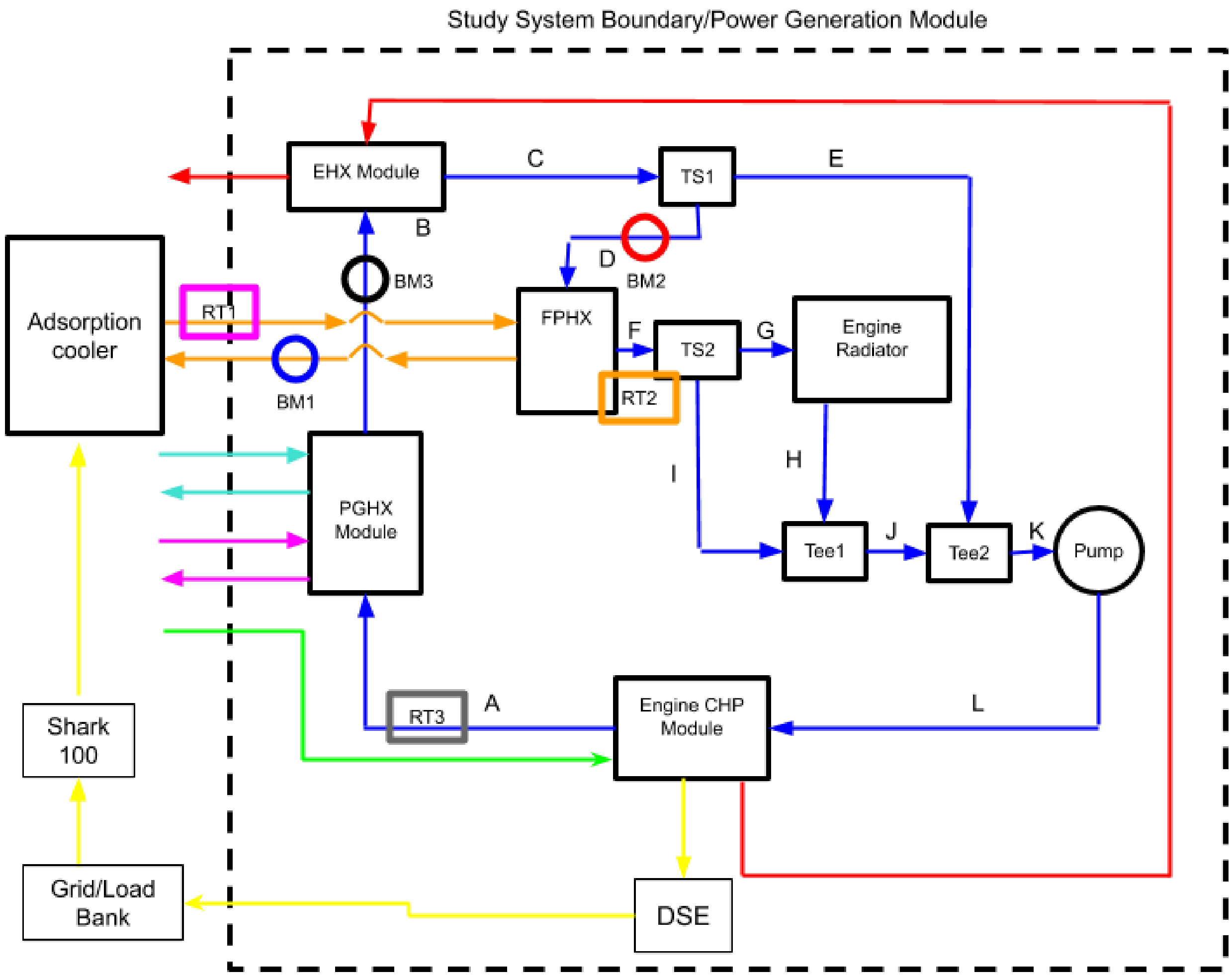
Source: All Power Labs, Inc.

Figure 6 illustrates the study system boundary and the location of key components that are to be tested. The fluid type and interaction are illustrated to provide a clear picture of which components are contributing to CCHP applications.

The system boundary studied throughout the engineering and validation testing (EVT) is primarily focuses on the power generation side of the improved prototype (PP30). The conversion from biomass to producer gas was not measured directly since the gas-making side was not included in the study system boundary. The modules included are the following:

1. CHP Modules: Engine CHP module, Exhaust CHP module, Producer gas CHP module.
    a. Engine CHP module – The engine itself exchanges heat with the engine coolant loop to be used for CHP applications.
    b. Exhaust CHP module – The EXH module is a heat exchanger that transfers heat from the exhaust gasses of the Ashok Leyland engine into the coolant loop for CCHP applications.
    c. Producer gas CHP module – The PGHX CHP module is a heat exchanger that transfers heat from the producer gas to the engine coolant loop for CHP applications.
2. Adsorption Cooling Module:
    a. The adsorption cooling module uses an adsorption process to create a chilled water loop from the hot engine coolant loop.
3. Enclosure and CCHP Mounting System:
    a. The enclosure is a metal frame and panels designed to keep all engine components enclosed as well as reduce noise levels.
    b. The CCHP mounting system is the hardware used to physically mount the CHP modules.

Figure 6: Process Flow Diagram of Power Pallet Used for EVT Testing



Abbreviations: EHX Module: Exhaust heat exchanger CHP module, PGHX module: Producer gas heat exchanger CHP module, FPHX: Flat Plate Heat Exchanger, RT1: Remote temperature sensor 1, RT2: Remote temperature sensor 2, RT3: Remote temperature sensor 3, BM1: Badger meter 1, BM2: Badger meter 2, BM3: Badger meter 3, TS1: Thermostat 1, TS2: Thermostat 2, DSE: Deepsea electronics engine control box.

Color-coding system: Dark Blue: Engine coolant loop, Red: Ashock Leyland engine exhaust, Yellow: Electrical output, Light Blue: Engine air intake, Violet: Producer gas, Green: Air fuel mixture for engine operation, Orange: Adsorption cooling loop for heat extraction.

Source: All Power Labs, Inc.

4. Genset Improvements:
    a. Genset improvements describe major design changes of the engine and electrical generator.
5. Emissions: brief description
    a. The emissions control system is a catalyst in line with the Ashok Leyland engine exhaust. The catalyst reduces the emissions to meet regulation and emissions targets.

The following are definitions used throughout the engineering validation testing:

- Heat Fraction: The heat fraction, represented by the letter E, of a given heat exchanger is defined here as the amount of thermal energy contribution from a heat exchanger to the coolant loop divided by the total amount of energy contained in the producer gas. This value represents the amount of thermal energy each CHP module is contributing.
- Engine CHP module: The engine CHP module is the Ashok Leyland engine. The Ashok Leyland engine is the internal combustion engine on the power pallet used for electrical power generation. The engine provides waste heat which is exchanged between the internal combustion process of the fuel and the coolant loop used for CHP applications.
- Exhaust CHP module: The engine exhaust CHP module is the exhaust heat exchanger. The module is a heat exchanger that exchanges heat between the engine exhaust gasses and the coolant loop used for CHP applications.
- Gasifier CHP module: The gasifier CHP module represents the producer gas heat exchanger. The module is a heat exchanger that exchanges heat between the producer gas and the coolant loop for CHP applications.

Engineering Validation Testing for Combined Heat and Power Modules

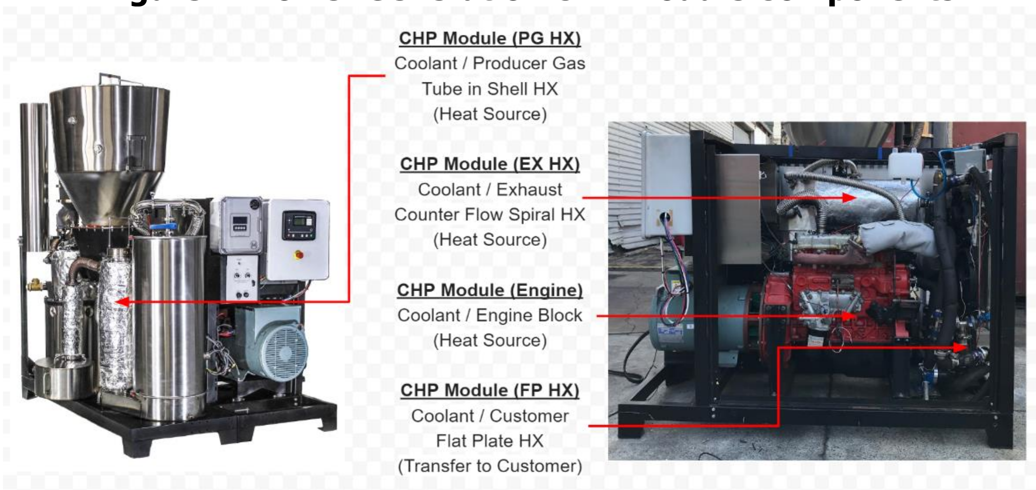
The Power Pallet CHP module is an extension of the engine cooling system, which was customized to gain thermal energy from a combination of the engine block, producer gas, and engine exhaust which otherwise would be wasted to atmosphere. The captured thermal energy is intended to reach 90–94 Celsius (°C) [194-201.2 Fahrenheit (°F)] and can be used by a project to offset thermal loads by connecting to a water to water plate heat exchanger labeled above as "thermal take-off". Any excess heat not used goes through the radiator-cooling loop before going back into the engine.

The design of the CHP circuit includes stainless steel corrugated plumbing, heat exchangers, thermostats, a pump, radiator and fan, and insulation.

Design Drawings

Figure 7 depicts CHP module heat exchanger (HX) locations on the improved prototype PP30. The CHP module EVT section provides testing criteria, results, and a discussion for each CHP module. Three CHP modules were tested and reported: Producer gas CHP module (PGHX), Exhaust gas CHP module (EXHX), and Engine CHP module. A flat plate heat exchanger (FPHX) was used to export thermal energy to CHP applications. The FPHX was purchased from Outdoor Furnace Supply with known heat exchange efficiencies, therefore no testing was not required for the FPHX.

Figure 7: Power Generation CHP Module Components



Abbreviations: PG HX, Producer gas heat exchanger, EX HX, Exhaust gas heat exchanger, FP HX, Flat plate heat exchanger

Source: All Power Labs, Inc.

Engineering and Validation Testing Criteria

Criteria used in the engineering and validation testing (EVT) were defined in the EVT plan and are the following:

- Safety
  - Coolant leak check: No visible leaks allowed from the engine CHP module, exhaust CHP module, and Producer gas CHP module.
  - Exhaust leak check: No exhaust leaks allowed from the exhaust CHP module.
  - Producer gas leak check: No leaks are allowed from the Producer gas CHP module.
  - Pressure relief: Mechanism must be installed and working properly.
  - Exposed hot metal surfaces: No surface allowed over a threshold maximum temperature, represented by (TMAX), that is exposed and not marked.
  - Coolant temperature minimum (TCoolant,Min)/maximum (TCoolant,Max): If at any point the coolant temperature rises above a threshold temperature TCoolant,Max or the coolant temperature is maintained below a threshold temperature TCoolant,Min.
- Engine CHP Module Efficiency
  - The heat fraction of the coolant loop CHP module: The engine CHP module heat fraction, represented by E_{Cool}, must be maintained at or above a threshold value of E_{Cool} to achieve a threshold study system efficiency of at least n_{min}.
- Exhaust CHP Module Efficiency
  - The heat fraction of the exhaust CHP module: The Exhaust CHP module heat fraction, represented by E_{EXH}, must be maintained at or above E_{EXH} in order to achieve a study system efficiency of at least n_{min}.

- Producer gas CHP Module Efficiency
    - The heat fraction of the producer gas CHP module: The producer gas CHP module heat fraction, represented by E_{PG}, must be maintained at or above E_{PG} to achieve a study system efficiency of at least n_{min}.
- Study system efficiency
    - Use the heat fractions of the CHP modules to ensure the study system efficiency, represented by n_{min}, is equal to or greater than n_{min}.

EVT Results and Changes Made to Improve Results

Results provided in this section reflect the intermediate scenario. Results from all scenarios are provided in Appendix A. Detailed heat fraction and efficiency calculations are provided in Appendix A. Table 3 presents the CHP modules testing results and corresponding threshold values from the criteria section.

Discussion

Safety

- Leak check: All engine coolant lines in the engine, producer gas, and exhaust gas CHP modules were assembled with appropriate watertight connections. No visible leaks were present in or around the systems and passed the evaluation. The most challenging task was assembling the coolant lines in such a way that they would not leak and still fit within the footprint of the Power Pallet.
- Pressure Relief: All pressure relief mechanisms were installed on the Power Pallet. The pressure relief mechanisms were installed on the top of the radiator and the highest point on the coolant loop. The mechanisms were installed in two locations such that relief would be provided to all parts of the system during all circumstances. The test passed the evaluation. The most challenging tasks were sourcing the correct pressure relief mechanisms and choosing locations such that pressure relief would be provided to the entire system under all circumstances.

Engine CHP Module

- Exposed hot metal surfaces engine CHP module: All hot metal surfaces for the engine cooling loop were marked appropriately and passed the evaluation. The surface temperatures on the engine, specifically the exhaust manifold, reach values as high as 800 C. To reduce risk to the operator a caution sign is attached to the enclosure door stating that hot surfaces are inside and to wait until the machine has had time to cool before servicing.
- Engine coolant temperature minimum and maximum: The engine coolant temperature was maintained below the maximum acceptable coolant temperature. However, the engine coolant temperature reached values below the minimum threshold and did not pass the evaluation. The motivation behind this test is to ensure the engine operates efficiently and is not damaged from extreme temperatures. Despite engine temperatures as low as 131 F (55 C) the engine showed no sign of degradation or a reduction in power. This indicates that the minimum allowable temperature should be

decreased. The primary challenges were to ensure proper thermostat operation for maintaining engine temperatures and radiator sizing for dumping excess heat.

Table 3: Criteria and Results of the Engine, Exhaust, and Producer Gas Heat Exchanger Combined Heat and Power Modules

Test	Symbol	Threshold Value/Criteria	Measurement	Result
Coolant leak check	None	None	Visual	Pass
Exhaust leak check	None	None	Visual	Pass
Producer gas leak check	None	None	Visual	Pass
Pressure Relief	None	None	Visual	Pass
Exposed hot metal surfaces Engine CHP Module	T_{Max}	$\leq$ 140 F (60 C) or Appropriately Marked	1475 F (800 C)	Pass (Appropriately Marked)
Exposed hot metal surfaces Exhaust CHP Module	T_{Max}	$\leq$ 140 F (60 C) or Appropriately Marked	575 F (300 C)	Pass (Appropriately Marked)
Exposed hot metal surfaces producer gas CHP Module	T_{Max}	$\leq$ 140 F (60 C) or Appropriately Marked	41 F (58 C)	Pass
Engine, producer gas, exhaust CHP module coolant temperature minimum and maximum	$T_{Coolant,Max}$ $T_{Coolant,Min}$	$\leq$ 220 F (105 C) @ 103 kPa $\geq$ 158 F (70 C) @ 103 kPa	217 F (103 C) EX HX Outlet 133 F (56 C) Engine inlet	EXHX Outlet: Pass Engine inlet: Fail
Engine CHP module heat fraction	E_{Cool}	$\geq$ 0.28	0.25 @ 25 kW 0.36 @ 16 kW	Pass
Exhaust CHP Module heat fraction	$E_{EX\ HX}$	$\geq$ 0.17	0.14 @ 25 kW 0.21 @ 16 kW	Pass
Producer gas CHP Module heat fraction	E_{PG}	$\geq$ 0.08	-0.056 @ 25 kW -0.045 @ 16 kW	Fail
Study system efficiency check	n_{min}	$\geq$ 0.80	0.72 @ 25 kW 0.82 @16 kW	Pass

Source: All Power Labs, Inc.

- Coolant loop heat fraction: The engine coolant loop heat fraction was greater than the threshold value and passed the evaluation. The most challenging part of the Engine coolant CHP module was sourcing thermostats that would maintain the inlet and outlet temperatures to obtain required Engine CHP module heat fraction. Future prototypes will include more insulation to increase the module heat fraction.
- Study system efficiency check: The study system efficiency was above the required system efficiency and passed the evaluation at 16 kW. The study system efficiency is a ratio of the combination of the electrical power and thermal power out of the system.

  The team studied three scenarios due to three main sources of error: variability in the pallet scale used to measure fuel consumption, unknown higher heating value of the fuel used, and unknown gasifier efficiency. Figure A.5 in Appendix A shows the study efficiency plot for each scenario. Efficiencies varied from 50 to 130 percent. However, the efficiency of 130 percent is incorrect and is due to error in measurements of key variable. It was assumed for the test performed on June 26, 2018; the gasifier efficiency was the same as previous internal All Power Labs testing. The higher heating value of the biomass was obtained from literature. The assumptions of the gasifier efficiency and the higher heating value proved to variable and need to be measured for future testing.

  The pallet scale variability could be due to coolant circulation on and off the gasifier side of the skid. Since the gasifier side of the improved prototype (PP30) was only measured by the pallet scale and not full scale, fluctuations due to coolant circulation may result in mass addition and subtraction that was not measured.

  For future work, gathering data to calculate gasifier efficiency is needed. Using a bomb calorimeter is necessary to quantify properly the higher heating value of the fuel. Placing the pallet scale under the entire skid will provide more consistent results.

Engine Exhaust Combined Heat and Power Module

- Exhaust leak check: After pressure leak testing the exhaust system, no leaks were visible, and the test passed the evaluation. One challenging obstacle was the fabrication of the flanges to mate with the coolant and gas lines.
- Exposed hot metal surfaces exhaust CHP module: Hot metal surfaces on the exhaust stack and pass through for the exhaust cooling loop were above the maximum allowable temperature. The surfaces above the maximum allowable temperature were marked and passed the evaluation. The surface temperatures on the pass through from the enclosure to the pyrocoil reached values as high as 300 °C (572 °F) .
- Exhaust CHP module coolant temperature minimum and maximum: The engine coolant temperature was maintained between the minimum and maximum acceptable coolant temperatures and passed the evaluation. The motivation behind this test is to ensure the engine operates efficiently and is not damaged from extreme temperatures. The primary challenges were to ensure proper thermostat operation for maintaining engine temperatures and radiator sizing for dumping excess heat.
- Exhaust CHP module heat fraction: The exhaust coolant loop heat fraction was above the required value and passed the evaluation. The most challenging part of the exhaust CHP module was integrating the exhaust flanges with the power pallet coolant and gas

flanges. Future prototypes will include more insulation to increase the module heat fraction.

Producer Gas Combined Heat and Power Module

- Producer gas leak check: After pressure leak testing the producer gas module system, no leaks were visible, and the test passed the evaluation. The fabrication of the entire producer gas module was challenging. The cleaning of the producer gas module is another ongoing challenge and currently time consuming.
- Exposed hot metal surfaces producer gas CHP module: All metal surfaces for the PG module were below the maximum acceptable temperature and passed the evaluation. The low temperatures were a result of the outer shell of the PG module being insulated with cool atmospheric air passing through the outer jacket.
- Producer gas CHP module coolant temperature minimum and maximum: The PG module inlet and outlet coolant temperatures were maintained between the minimum and maximum acceptable coolant temperatures and passed the evaluation. The motivation behind this test is to ensure the engine operates efficiently and is not damaged from extreme temperatures. The primary challenges were to ensure proper thermostat operation for maintaining engine coolant temperatures and radiator sizing for dumping excess heat.
- Producer gas CHP module heat fraction: The producer gas module heat fraction was less than the required value and negative. The negative heat fraction indicates that heat is transported out of the engine coolant and into one or both producer gas or air fluids. The study system efficiency threshold was still achieved at 16 kW despite the negative heat fraction from the producer gas CHP module. This indicates that the combination of the engine CHP and exhaust CHP modules adequately compensate for the producer gas CHP module.

  The two most challenging parts of the producer gas CHP module was the fabrication and cleaning. The fabrication is time consuming due to moving parts and the separation and heat transfer of three working fluids. The cleaning of the producer gas module is an ongoing obstacle that is under testing. Scrubbing the module with solvents and heating the module are two methods under consideration.

  Future prototypes will include more insulation to increase the module heat fraction. The required heat fraction will be decreased if the overall efficiency goals are met.

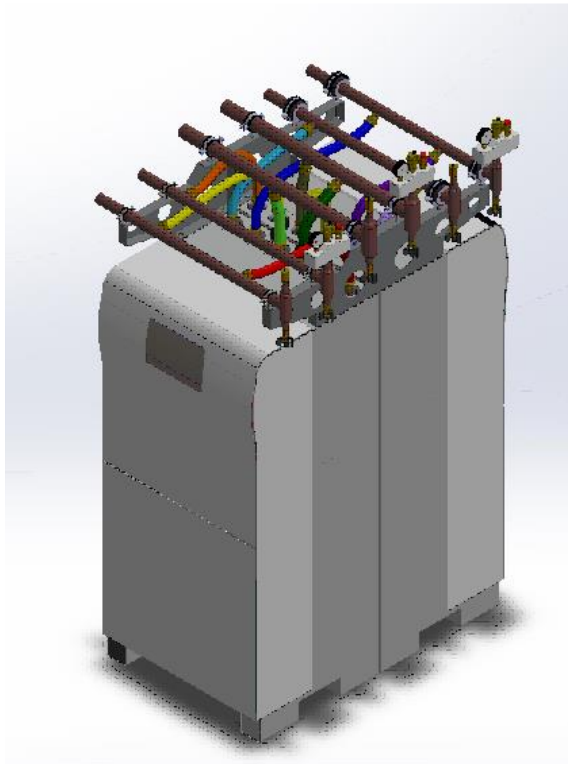
Adsorption Cooling Module

The adsorption cooling module is a standalone adsorption cooler manufactured by a German-based company Fahrenheit. The adsorption cooling module uses heat produced by the Power Pallet's CHP system to produce cooling. Adsorption coolers and absorption coolers are different based on the phase changing working medium used to convert heat into cooling. Absorption cooling systems use liquid sorbents while adsorption cooling systems use solid sorbents. The selected adsorption cooler uses silica gel as the phase changing working medium.

Design Drawings

Figure 8 illustrates the adsorption cooling (AdCo) module from Fahrenheit. The adsorption cooler is shown fully assembled for cooling applications.

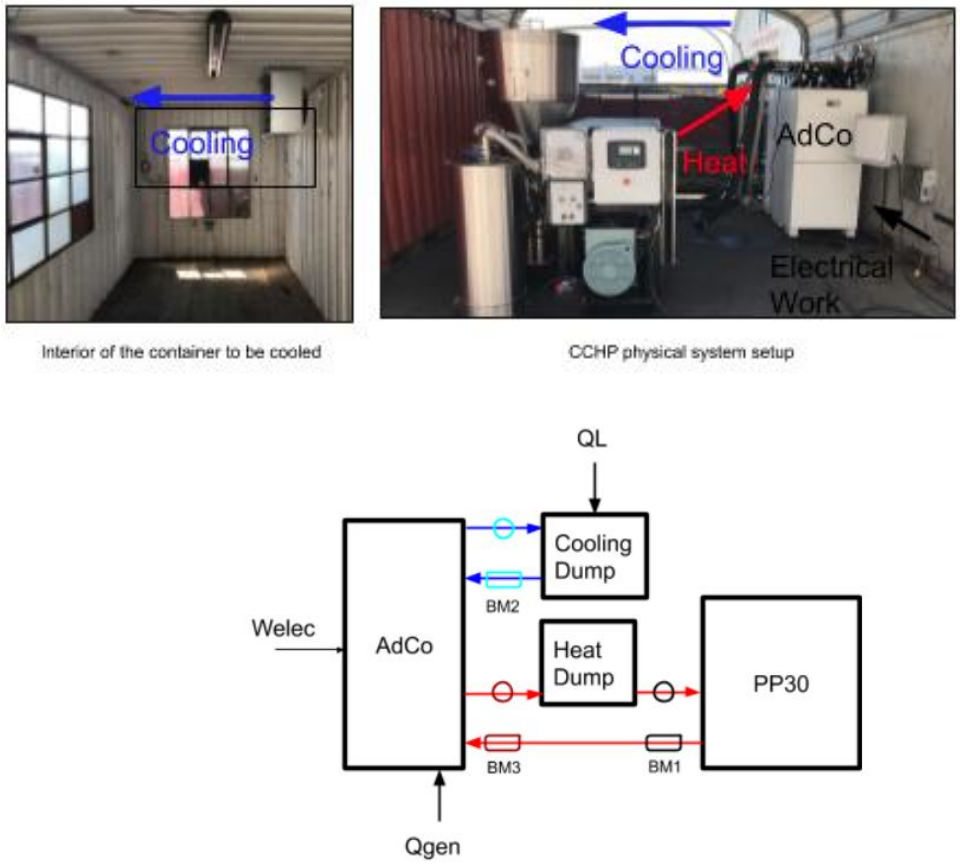
Figure 8: Rendering of the eCoo 2.0/20 Adsorption Cooling (AdCo) Module from Fahrenheit



Source: All Power Labs, Inc.

Figure 9 illustrates the CCHP photos with the flow diagram. Figure 9 includes a shipping container used for refrigeration, the CCHP setup with the Power Pallet and adsorption cooler attached, and a process flow diagram. The process flow diagram illustrates the interaction between the Power Pallet, the adsorption cooler, and the atmosphere. For instance, the Power Pallet is providing hot water to the adsorption cooler and the adsorption cooler is dumping unusable heat Q_{gen} and absorbing heat from the shipping container Q_L to create a refrigerated area.

Figure 9: Combined Cooling, Heating, and Power System Set-Up with Adsorption Cooling Unit



Left: Refrigerated Area, Right: Power Pallet with Attached Adsorption Cooler, Bottom: Process Flow Diagram of CCHP System Abbreviation: PP30: Power Pallet 30, AdCo: Adsorption cooling Module, W_{elec}: work electric, Q_{gen}: Wast heat dump to atmosphere, Q_L: Heat absorbed from are to be cooled, BM1: Badger meter 1, BM2: Badger meter 2, BM3: Badger meter 3.

Source: All Power Labs, Inc.

Engineering and Validation Testing Criteria

Criteria used in the EVT were defined in the EVT plan and are the following:

Safety

- Leak check: No visible leaks allowed from the adsorption cooling module.
- Pressure relief: Pressure relief mechanism must be installed and working properly.
- Exposed hot metal surfaces: Any surface over a temperature T_{Max} that is exposed and not marked.
- Coolant temperature minimum/maximum: If at any point the coolant temperature rises above $T_{Coolant,Max}$ or the coolant temperature is maintained below $T_{Coolant,Min}$.

Efficiency

- The heat fraction of the adsorption cooling (AdCo) module: The heat fraction represented by E_{AdCo}, must be maintained at or greater than E_{AdCo} to achieve a study system efficiency of at least n_{min}.

System Efficiency

- Use the heat fraction of the adsorption cooling module to ensure the study system efficiency is equal to or greater than n_{min}.

Engineering and Validation Testing Results and Changes Made to Improve Results

Table 4 provides the results from the evaluation phase of the AdCo module section. The maximum exposed temperature T_{Max} was suggested by Ungar and Stroud[5] based on testing of human limitations to temperature and touch. The heat fraction of the AdCo module is defined in the beginning of the section.

Table 4: Evaluation Results Adsorption Cooling Module

Test	Symbol	Threshold Value	Measurement	Result
Leak check	None	None	Visual	Pass
Pressure Relief	None	None	Visual	Pass
Exposed hot metal surfaces	T_{Max}	$\leq$ 140 F (60 C) or Appropriately Marked	86 F (30 C)	Pass
AdCo temperature minimum and maximum	$T_{AdCo,Max}$ $T_{AdCo,Min}$	$\leq$ 220 F (105 C) @ 103 kPa $\geq$ 86 F (30 C) @ 103 kPa	180 F (82 C) AdCo Max 122 F (50 C) AdCo Min	Pass
AdCo Heat Fraction	E_{AdCo}	$\geq$ 0.53	0.48 @ 25 kW 0.59 @ 16 kW	Pass
Study system efficiency check	n_{min}	$\geq$ 0.80	0.72 @ 25 kW 0.82 @ 16 kW	Pass
Coefficient of performance (COP) of AdCo	COP AdCo	None	0.389	Not Required
AdCo Cooling Capacity	None	None	9.2 kW of Refrigeration	Not Required

Source: All Power Labs, Inc.

[5] Ungar, Eugene, and Kenneth Stroud. "A New Approach to Defining Human Temperature Standards." NASA/Johnson Space Center.

Discussion

- Leak check: All AdCo fluid lines were assembled with appropriate watertight connections. No visible leaks were present in or around the system and passed the evaluation. The most challenging task was moving large pieces of equipment into place such that the fluid lines would be kept to a minimum in length.
- Pressure Relief: All pressure relief mechanisms were installed on the AdCo. The pressure relief mechanisms were installed on the top of the AdCo. The mechanisms were installed in three locations such that relief would be provided to all parts of the system during all circumstances.
- Exposed hot metal surfaces: The hot water line was properly insulated and maintained below the maximum allowable temperature therefore the test passes the evaluation. As testing was performed, it was noted that the hot water lines should be kept as short as possible to avoid unnecessary heat loss and subsequent excessive insulation use.
- AdCo temperature minimum and maximum: The AdCo temperature was maintained between the minimum and maximum acceptable fluid temperatures and passed the evaluation. The motivation behind this test is to ensure the AdCo operates efficiently and is not damaged from extreme temperatures. The primary challenges were to ensure a proper heat dump was available in case of high temperature spikes.
- AdCo heat fraction: The AdCo heat fraction is the total amount of heat used by the AdCo from the customer loop on the PP. The AdCo heat fraction is above the threshold heat fraction and the overall efficiency is above the required efficiency, therefore the AdCo heat fraction passes the evaluation. The primary challenges with the AdCo were purging the system of all air and insulating the customer fluid lines so no heat is lost. The AdCo was tested at two different PP electrical load outputs: 16 kW and 25 kW. The results show the study efficiency and heat fraction were greater at 16 kW. This indicates the machine has an optimal operating setting in between 16 kW and 25 kW.
- Study system efficiency check: The study system efficiency was above the required system efficiency and passed the evaluation at 16 kW. The study system efficiency is a ratio of the combination of the electrical power and thermal power out of the system. The use of the AdCo contributed to the high study system efficiency number presented in this section because the AdCo utilized thermal energy from the Power Pallet CHP system. Sources of error and improvements were discussed in the engine coolant loop CHP module section.
- Coefficient of performance (COP) of AdCo: The COP is defined as the ratio of the desired output to the required input. The COP was determined to be 0.389. This means for every unit of work put into the adsorption cooler approximately 0.4 units of cooling is achieved. Even though the COP was not part of the criteria listed in the EVT, it is a good metric to report for comparison to other cooling technology.

- AdCo Cooling Capacity: The adsorption cooler capacity provides a sense of the amount of energy that the adsorption cooler can remove from a space to be cooled. Using the inlet and outlet temperatures of the adsorption cooler cooling loop, the amount of energy per unit time that may be extracted can be calculated. The amount of energy that can be absorbed by the low temperature circuit was determined to be 9.2 kW. The following values are common in practice to describe the capability of a refrigeration system of the calculated size.
    - 9.2 kW of refrigeration
    - 552 kJ/min of refrigeration
    - 2.6 ton of refrigeration

  A system running with the cooling capacity described above can typically provide cooling to a 180 m^2 residence space.

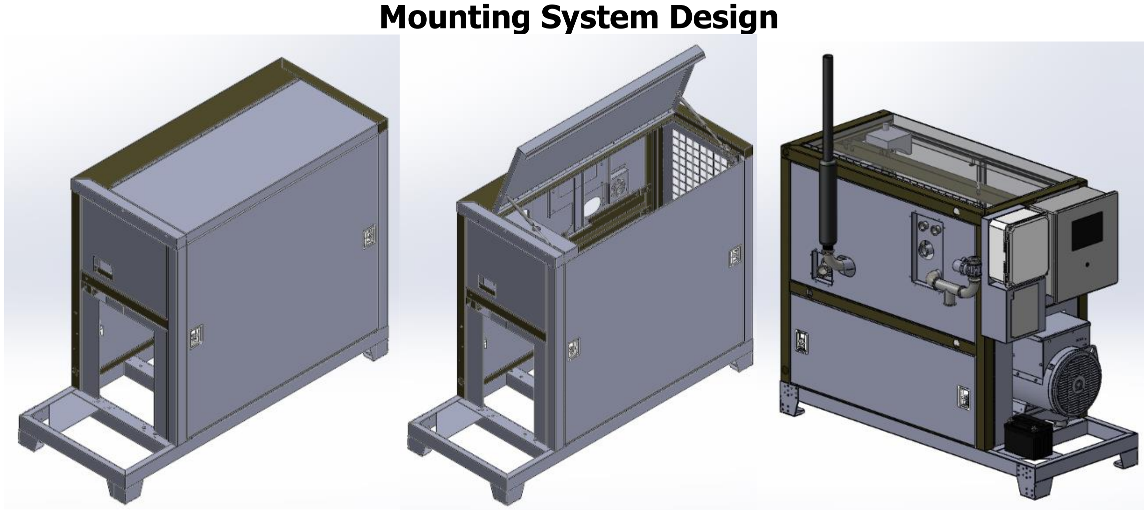
Enclosure and Combined Cooling, Heating, and Power Mounting System

The enclosure and CCHP mounting system represent the final productization required to meet sound and safety requirements. The enclosure is made up of a frame and enclosure panels. The frame, in addition to holding the enclosure panels, is used as the armature for secure other components such as the heat exchanges used in the CHP circuit. The automation system, genset controller, auxiliary box, and radiator are also mounted to the enclosure frame. The large genset enclosure panel can be completely removed in order to service any of the power generation components and the enclosure hood was designed similar to that of a car hood with gas spring supports to allow for additional access to components. Insulation was used with the enclosure panels to reduce the sound coming from the engine.

Design Drawings

Figure 10 illustrates the design of the enclosure around the Power generation side of the Power Pallet 30.

Figure 10: Rendering of the Enclosure and Combined Cooling, Heating, and Power Mounting System Design



Source: All Power Labs, Inc.

Engineering and Validation Testing Criteria

Criteria used in the engineering validation testing plan were defined in the following areas:

Enclosure

The enclosure was evaluated through engineering validation testing. This section provides insight into critical areas for testing criteria, testing procedures, and evaluation techniques used to assess the engine enclosure.

- Sound dampening
  - Decibel measurements of the power pallet surrounding area: decibel levels, represented by the symbol B, must not exceed $B_{c,3}$ from any angle c at three feet and $B_{c,21}$ from any angle c at 21 ft.
- Temperatures on the interior of the enclosure
  - Temperatures inside the enclosure at critical points: temperature measurements must not exceed $T_{Int,n}$ at critical points for any amount of time.
- Temperatures on the exterior of the enclosure
  - Exposed hot metal surfaces: Any surface over T_{Max} that is exposed and not marked.
- Ventilation
  - Ventilation of harmful or explosive gases such as carbon monoxide and hydrogen (CO and H_2): proper ventilation with flow rate Q must be present and the ventilation location must not pose a risk to the operator.

CCHP Mounting System

The purpose of this section is to provide an engineering validation test plan to evaluate the CCHP mounting system. This section will evaluate the CCHP mounting system by providing test criteria and procedures for various mounting stress tests.

- CCHP mounting stress test
  - System tipping due to refueling: System must not tip at any time due to refueling.
  - Vibration resistant hardware: All hardware must be vibration resistant.
  - Structural rigidity of CCHP mounting system: The CCHP mounting system must not deform or shear in anyway due to normal operation.

Engineering and Validation Testing Results and Changes Made to Improve Results

Enclosure Results

Table 5 provides the results from the evaluation phase of the enclosure.

Table 5: Evaluation Results Enclosure

Test	Symbol	Threshold value	Measurement	Result
Sound dampening 3 ft	$B_{c,3}$	$\leq$ 80 db	80.2 dbA 77.7 dbA 79.3 dbA 77.2 dbA	Pass
Sound dampening 21 ft	$B_{c,21}$	$\leq$ 72 db	70.7 dbA 71.0 dbA 72.0 dbA 71.4 dbA	Pass
Temperatures on the interior of the enclosure	$T_{Int,n}$	$\leq$ 176 F (80 C)	85.6 F (29.8 C) 97.2 F (36.2 C) 95.0 F (35.0 C)	Pass
Temperatures on the exterior of the enclosure	T_{Max}	$\leq$ 140 F (60 C) or Appropriately marked	96.4 F (35.8 C)	Pass
Ventilation	Q	$\geq$ 4 m^3/hr	>5000 m^3/hr	Pass

Source: All Power Labs, Inc.

Discussion: Enclosure

- Sound dampening: The noise levels from all directions in the 3 foot (ft) range were at or under 80 dbA. Noise levels from 21 ft away were measured under 72 dbA. The threshold noise levels of 80 dbA and 72 dbA at 3 ft and 21 ft respectively where chosen due to operator safety and noise regulation. The largest technical challenge was the modification to the enclosure to ensure all plumbing fixtures would fit while reducing holes in the enclosure to mitigate noise levels. To overcome the challenge, the project team design pass through points for the plumbing. Another obstacle was insulating the enclosure with noise absorbing material to further reduce the noise levels.
  For future testing, gaps around the electrical generator or genhead should be reduced. In Figure 10 the electrical generator is protruding through the enclosure. Gaps around the electrical generator allow noise to pass through the enclosure.
- Temperatures on the interior of the enclosure: The temperature measurements were at three critical locations. The selected locations help monitor the temperature of the internal electronics, the ambient temperature in the enclosure, and the interior surface of the enclosure. All three critical temperatures were determined to be below the maximum allowable temperature and passed the evaluation.
- Temperatures on the exterior of the enclosure: The temperature on the exterior of the enclosure remained below the maximum allowable temperature for an exposed metal surface and any temperature greater than the maximum allowable temperature was marked indicating danger.
- Ventilation: The airflow rate provided by the radiator fans is more than 5000 cubic meter per hour. The flow rate was based on air velocity measurements taken over a

ten-minute period and cross-sectional area measurements of the radiator. This is 1000 times the threshold value. The ventilation easily passed the evaluation process.

Mounting System Results

Table 6 provides the results to the criteria from the CCHP mounting system.

Table 6: Evaluation Results Combined Cooling, Heating, and Power Mounting System

Test	Symbol	Threshold Value	Measurement	Result
System tipping due to refueling	None	Must not occur	Visual	Pass
Vibration resistant hardware	None	Must be installed	Visual	Pass
Structural rigidity of the CCHP mounting system	None	Must not fail	Visual	Pass

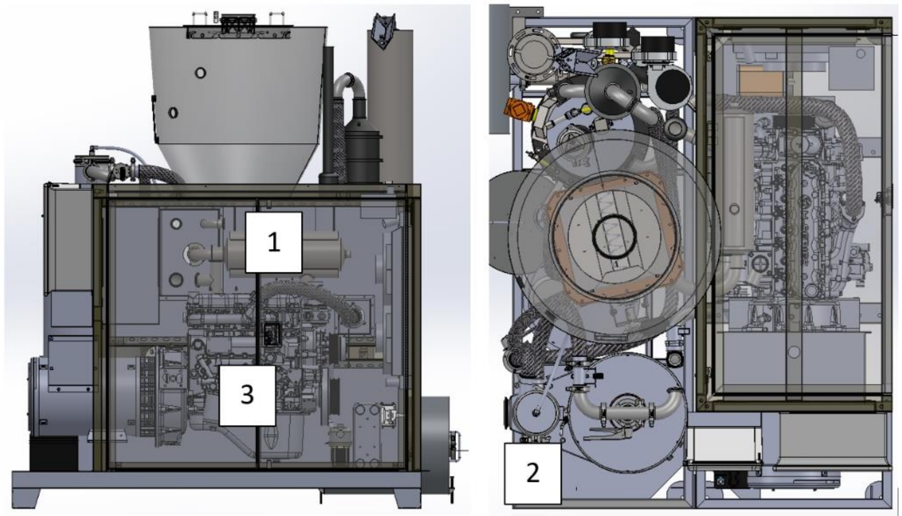
Source: All Power Labs, Inc.

Discussion: Combined Cooling, Heating, and Power Mounting System

- System tipping due to refueling: Testing was performed during the month of May 2018, where PP1096 was refueled on more than 10 occasions. PP1096 never tipped due to any reason while refueling. Through good design coordination, the center of gravity of the Power Pallet was placed such that the unit has no chance of tipping. Although not tested, refueling is not recommended during extreme weather conditions such as a tornado.
- Vibration resistant hardware: All hardware on PP1097 was vibration resistant (lock-washers, serrated nuts, lock-nuts, or the use of thread locking fluid) and passed the evaluation shown in Table 6. The screws attaching the enclosure panels to the skid were not assembled with vibration resistant hardware. However, thread locking fluid was used to make the hardware vibration resistant.

  Structural rigidity of the CCHP mounting system: The rigidity of the CCHP mounting system was tested by observations while the system was in operation. The exhaust heat exchanger module shown as 1, producer gas module shown as 2, and the engine shown as 3 in Figure 11 were all securely mounted to the skid under standard run conditions. No excessive vibrations or deformation were observed while under run conditions. The major obstacle was correctly integrating the engine mounting system with the skid. Several iterations had to be tested to obtain the optimal position of the engine to produce the desired footprint.

Figure 11: Mounting System 1 Exhaust, 2 PG, and 3 Engine



Source: All Power Labs, Inc.

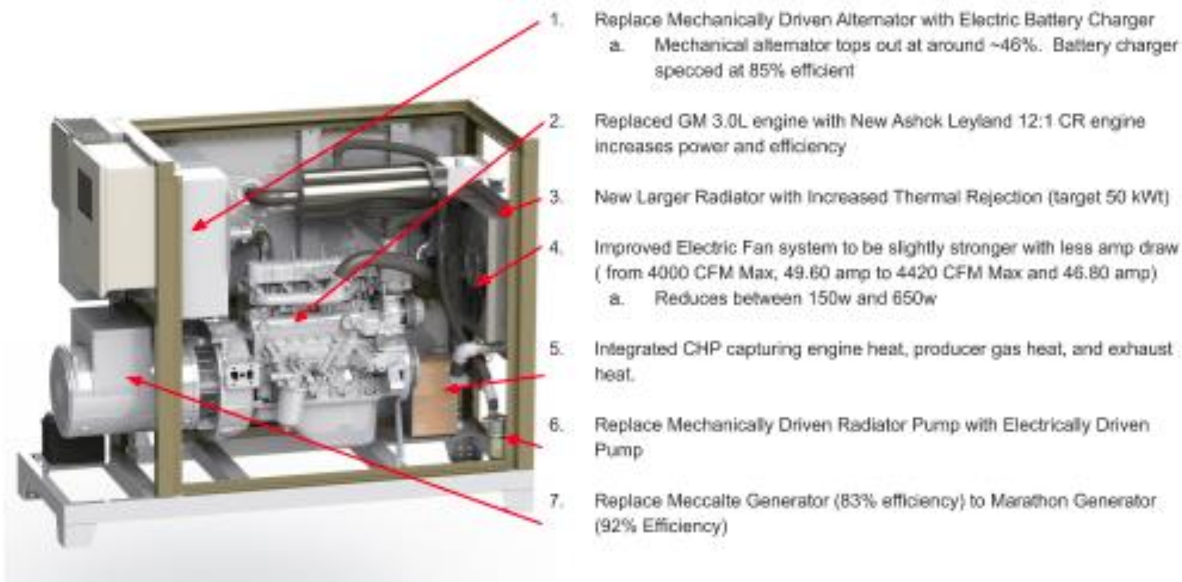
Genset Improvements

The CCHP Genset required many changes and improvements to meet the performance targets established for this project. One of the criteria used to select the generator was the capability to provide higher efficiencies. The Marathon generator has 92 percent efficiency compared to the 83 percent efficiency of the previously used generator. In addition, the selection of the new Ashok Leyland engine was based on strategic supplier relationship and long-term market strategy. The Ashok Leyland engine provides increased power output via increased displacement and increasing the compression ratio to 12:1 for improved efficiency. The redesigned genset system replaced the traditional low efficiency mechanical components with higher efficient electric components. For instance, the project team replaced the mechanical alternator with an electric battery charging system, the mechanical radiator fan with an electric fan with speed control, and the mechanical water pump with an electric water pump. All these replacements are more efficient and reduce parasitic load to the engine.

Design Drawings

Figure 12 illustrates the specific components that were improved for greater overall efficiency.

Figure 12: Genset Improvement Callouts



Source: All Power Labs, Inc.

This section provided an engineering validation test plan to evaluate genset improvements. This section provides test criteria and procedures for the following categories: engine performance, generator performance, and overall genset performance. The set of criteria used are the following:

- Engine performance
  - Engine compression: The Ashok Leyland compression ratio $r_{c,AL}$must be greater than the General Motor (GM) Vortec compression ratio of 10.5:1.
  - Engine efficiency: Engine efficiency must be calculated by using the manufacturer electric generator efficiency $\eta_{gen,Mar}$, the fuel energy content, and the measured electrical power. The engine efficiency must be greater than the stated GM Vortec engine efficiency 0.20.
- Generator performance
  - Generator efficiency: Compare the manufacturer efficiency of the Mecc Alte electrical generator 0.82 with the manufacturer efficiency of the Marathon electrical generator $\eta_{gen,Mar}$. The Marathon generator efficiency must be greater than 0.82.
- Overall genset performance
  - Genset efficiency: Calculate the overall genset efficiency η_{genset} by using the measured electrical power and the measured fuel energy content. The genset efficiency must be greater than 0.22.

Engineering Validation Testing Results and Changes Made to Improve Results

Table 7 shows the resulting values from testing performed more than two hours on April 12, 2018. Two power output levels, 16 kW and 25 kW, were tested for one hour each.

Table 7: Measured and Calculated Values for the Genset with Results

Test	Symbol	Threshold value	Measurement	Result
Engine Compression Ratio	$r_{c,AL}$	> 10.5:1	12:1	Pass
Engine Efficiency	$\eta_{AL,elec}$	> 0.20	0.280 @ 25 kW 0.263 @ 16 kW	Pass
Generator Efficiency	$\eta_{gen,Mar}$	> 0.82	0.92	Pass
Genset Efficiency	$\eta_{genset,elec}$	> 0.22	0.257 @ 25 kW 0.242 @ 16 kW	Pass

Source: All Power Labs, Inc.

Appendix A provides the detailed calculations related to the engine and genset efficiency.

Discussion

- Engine performance: The Ashok Leyland engine compression ratio is greater than the General Motor engine compression ratio. The project team chose a higher compression ratio to improve efficiency. During testing, the most problematic issue to overcome was spark ignition. The high compression ratio lead to spark ignition problems due to higher and longer activation energy required to ignite the air/fuel mixture. This problem was overcome by adjusting the engine timing and power delivered to the ignition coils. For future work, the compression ratio will be adjusted to determine an optimal compression ratio.
- Engine efficiency: The engine efficiency of the Ashok Leyland engine is higher than the General Motor engine efficiency. The project team chose the higher engine efficiency for economic reasons. A higher engine efficiency leads to more kWh for the customer. The largest hurdle to overcome was the selection of the engine. The selected engine must meet the efficiency criteria and adhere to other criteria: high compression ratio, flexible production, cost, and reliability. The selected Ashok Leyland engine matched the efficiency requirement and the other criteria. Further investigation into how other factors affect engine efficiency is needed, such as fuel type, load sweeps, and ambient conditions.
- Generator performance: The generator performance is dependent on the generator efficiency. The Marathon generator efficiency is greater than previous used generators, such as the Mecc Alte generator efficiency. The selected Marathon generator has greater efficiency. The primary motivation for the increased efficiency is due to the

ability to convert more energy into electrical energy and produce more kWh. Again, the largest hurdle to overcome was the selection of the generator. The selected generator must meet the minimum required efficiency to achieve overall efficiency goals.

- Genset performance: The genset does perform with an efficiency higher than the required genset efficiency. The genset efficiency is the combined efficiency of the Ashok Leyland engine and the Marathon generator. The combination of the two is enough to fulfil the genset performance requirement. The largest technical challenge was to integrate the Ashok Leyland engine with the Marathon generator. Due to the difference between the manufactures, the engine-generator integration needed a special hardware such as British bolts to connect the physical engine and generator together.

Emissions

The emissions control system represents the combination of improved engine configuration and the use of a catalytic converter, which uses oxidation and reduction reactions to convert toxic gases and substances into less harmful pollutants. The project team selected a three-way catalyst because its ability to use a rich air mixture. The engine configuration that maximized emissions reduction while using this three-way catalyst used a timing of 20 degrees and a lambda set point of 1.02.

Engineering Validation Testing Criteria

- Criteria for emissions assessment
    - Governing body for emissions requirements: The governing body will be the California Air Resources Board (CARB), the Environmental Protection Agency (EPA) standards for emissions from small scale stationary power generators, and the San Joaquin Valley Air Pollution Control Districts (SJVAPCD).
- Emissions goals
    - Criteria pollutant emission goals: monitoring equipment must be capable of measuring and logging criteria pollutants shown in Table 8.
    - Greenhouse gas emission goals: monitoring equipment must be capable of measuring and logging criteria pollutants shown in Table 9.

Engineering Validation Testing Results and Changes Made to Improve Results

Table 8 shows the criteria pollutants examined during the engineering validation testing, which Includes, criteria pollutant goals, regulation, and emission results. Criteria Pollutants are pollutants for which ambient air quality standards have been established. The major criteria pollutants are carbon monoxide (CO), Sulfur Oxides (SO_X), and Nitrogen Oxides (NO_X). The emissions regulations were discussed with a third-party consultant who determined engines below 50 Horsepower are exempt from criteria pollutant emissions.[6]

[6] Emissions Questions for the South Coast grant Emissions . *Emissions Questions for the South Coast grant Emissions Email*. Email between Brendan Quinlan, Bear Kaufmann, and Ray Kapahi. May 2018.

Table 8: Criteria Pollutant Goals, Regulation, and Results

Criteria Pollutants	All Power Lab Goal	Regulation	Results	Evaluation
Carbon Monoxide (CO)	≤ 75 ppmvd* CO @ 15% O2	Exempt (<50 HP)	34 ppmvd CO @ 15% O_2	Pass
Sulfur Oxides (SO_x)	≤ 0.03 g-SO_X/hp-hr	Exempt (<50 HP)	0 g-SO_X/hp-hr	Pass
Nitrogen Oxides (NO_x)	≤ 9 ppmvd (parts per million by volume, dry basis) NO_X @ 15% O_2	Exempt (<50 HP)	0 ppmvd NO_X @ 15% O_2	Pass

*** Parts per million by volume, dry basis**

Source: All Power Labs, Inc.

Table 9 shows the greenhouse gas pollutants examined during the EVT, which includes greenhouse gas pollutant goals, regulation, and emission results. Again, the emissions regulations were discussed with a third-party consultant who determined engines below 50 Horsepower are exempt from certain emissions-related regulations.

Table 9: Greenhouse Gas Goals, Regulation, and Results

Greenhouse gases	All Power Lab Goal	Regulation	Results	Evaluation
Carbon Dioxide (CO_2)	769.9 grams/kWh	Exempt (GHG)	1330 grams/kWh (direct biogenic emissions)	Fail

Source: All Power Labs, Inc.

Discussion

Testing was focused on the assessment of the Ashok Leyland exhaust emissions. A DCL International three-way catalyst was used to reduce pollutants contained in the exhaust gases. Different configurations of air to fuel ratio and spark timing advance were investigated to find the best engine setup at the maximum achievable electrical power output. Biomass moisture and filter status affected the engine performances and hence the maximum power output was 23.2 kW.

The instrument used for testing engine emissions was the MRU Vario Plus syngas analyzer suitable for the measurement of diatomic oxygen O2, carbon monoxide (CO), Nitrogen oxide (NO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and carbon dioxide (CO_2) concentrations.

After the first set of tests, the engine instability led to emission performance issues. For this reason, the proportional, integral, and derivative (PID) controllers of the governor and the air to fuel regulator were tuned. The result was a more stable engine speed and a more constant lambda value.

The found optimal air to fuel ratios were 1.017 and 1.020. For both, the team investigated a set of different spark timing advance (20, 21, 22, 24 and 26 degrees before top dead center). In particular, the emissions in the configuration Air fuel ratio 1.017 and timing 21 degrees before top dead center (°BTDC) were recorded for 10 minutes. The values of the pollutants in this configuration are under the limits set by All Power Labs regarding CO, NO_X and SO_X.

The recorded the spikes in the CO concentration (up to 300 ppmvd @ 15 percent O_2) during the test and observed clear correlation between the ash grate shaking and the CO increase. A different grate shaking strategy (i.e. more frequent but shorter shaking period) should be investigated to reduce this side effect. An improved mixing system would avoid this spike.

The direct biogenic CO_2 emissions were 1330 g/kWh, which is above the goal set by All Power Labs. The initial target was based on non-biogenic CO_2 emissions performance of CHP systems running on natural gas. Comparing the performance based on achieved genset efficiency, the non-biogenetic CO_2 emissions would be 685.9 g CO_2/kWh[7] for the same CHP system running on natural gas. Additional improvements in system efficiency, including gasifier efficiency can continue to reduce CO_2 emissions per kWh.

Comparing the performance based on achieved genset efficiency, the CO_2 emissions would be 685.9 g CO_2/kWh for the same CHP system running on natural gas - or 89% of the 769.9 grams/kWh target (pass). Since CO_2 emissions per kWh is effectively a measure of system efficiency, this indicates the high overall efficiency of the system. Direct biogenic CO_2 emissions levels are high due to relatively high carbon to energy ratios in biomass feedstocks (anthracite coal - 104 kg CO_2/MMBTU, wood - 94 kg CO_2/MMBTU, propane - 61 kg/MMBTU, natural gas - 53 kg CO2/MMBTU). From that data, wood releases 77 percent more direct CO_2 emissions per unit thermal energy than natural gas. Much of this carbon is still converted to CO_2 through the gasification and engine combustion process with some remaining in the biochar co-product - in fact, multiplying the target of 769.9 grams/kWh by 177% yields 1393 grams/kWh - with the measured value being 95 percent of this, which could be explained by the carbon retention in the biochar. Since the carbon in wood and other biomass was removed from the atmosphere through photosynthesis the direct emissions have limited to no net impact on increasing atmospheric CO_2 levels - depending on the source of biomass.

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[7] Natural gas: 53.07 kg/CO_2 per MMBTU or 181.1 g/CO_2 per kWh. Study system boundary: 89 kW fuel input * 181.1 g/CO_2-kWh / 23.5 kW electrical output = 685.9 grams CO_2/kWh electric.

Footnote [1] - https://www.epa.gov/sites/production/files/2015-07/documents/emission-factors_2014.pdf.

CHAPTER 3: Manufacturing and Production Readiness

Combined Cooling, Heating, and Power Power-Pallet Manufacturing Summary

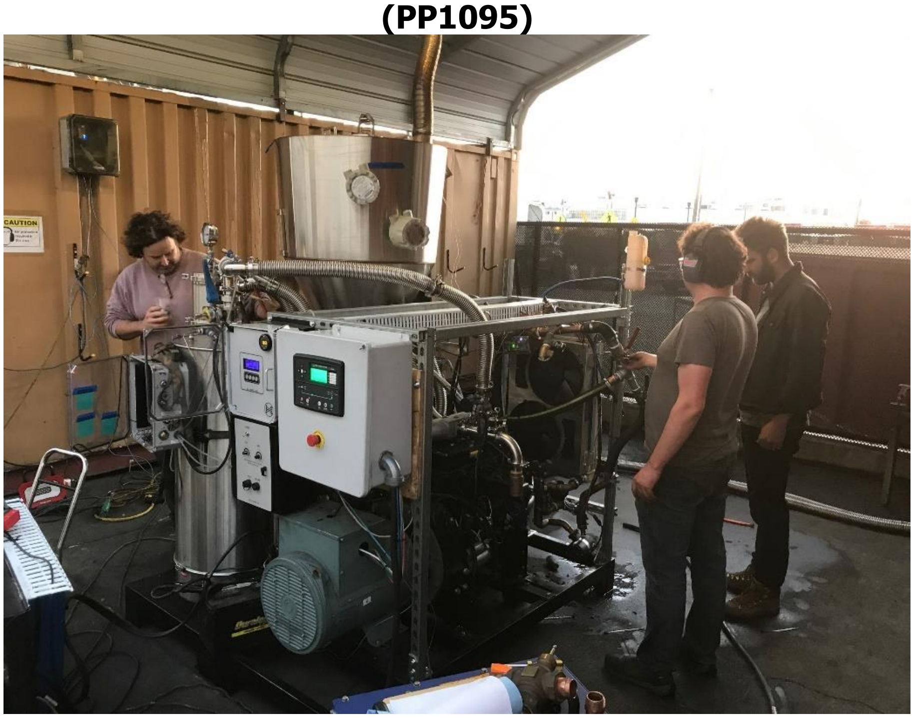
The project team decided to open up the product architecture in order to achieve many of the project requirements, which resulted in a "split skid" architecture where the gas production and the power generation are separated into unique modules. This revision improved many aspects of the product, from the design process to manufacturing, assembly, and the forward-looking outsourcing strategy. While being built in-house, each module can be assembled and tested independently, then bolted together to complete the product.

Over the course of the project, the team built four CCHP Power Pallets with this new architecture. This included two variations of prototypes, and two final versions of the CCHP Power Pallet used for final reliability and in-field pilot testing.

The team built the first CCHP Power Pallet prototype, PP1095, between September and October 2017. This machine validated the "split skid" architecture, the selected genset and configuration, and an early concept of the CHP circuit. Lessons learned from this prototype were used to inform the design of a second prototype, PP1096.

Figure 13 illustrates the early state of the CCHP Power Pallet with the location of the multiple heat exchanger modules used in the CHP thermal circuit called out.

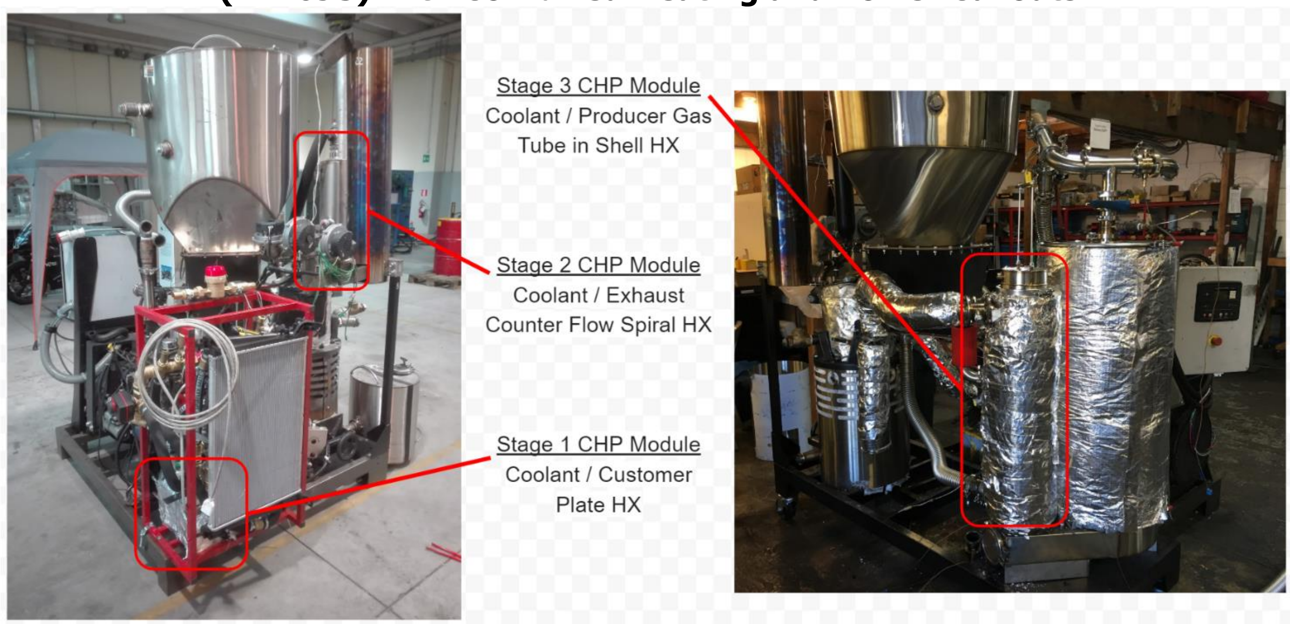
Figure 13: Combined Cooling, Heating, and Power Concept First Prototype (PP1095)



Source: All Power Labs, Inc.

Figure 14 shows the location of two locations in the CHP circuit where waste heat is being collected, and the customer interface location to access the heat. As shown in Figure 14, heat is collected at the producer gas heat exchanger and the engine exhaust. It is also worth noting that a large portion of heat is collected from the engine block which is not called out in Figure 14.

Figure 14: Combined Cooling, Heating, and Power Concept First Prototype (PP1095) with Combined Heating and Power Callouts



Source: All Power Labs, Inc.

Based on feedback from the first prototype (PP1095), the project team updated the design and built the second CCHP Power Pallet prototype, PP1096 between December 2017 and March 2018. This Power Pallet prototype represented the intended CCHP Power Pallet design for Engineering Validation Testing (EVT). The following outlines some of the feedback used to inform the second-prototype design iteration.

- Improved spacing for hardware and insulation in tight spaces.
- Placement of the magnetic pick up (MPU) needed to be relocated to get a better rotation per minute (RPM) reading.
- Frame hinges were very difficult to install.
- Better analog voltage regulator (AVR) mounting and wiring drawings needed to improve assembly.
- Better point–to-point wiring diagrams needed for improved assembly.
- CHP circuit plumbing routing needed to be refined along with improved assembly order of operations.

Figure 15 illustrates the second prototype developed and used for engineering validation testing (EVT).

Figure 15: Second Prototype (PP1096) used for Engineering Validation Testing

Source: All Power Labs, Inc.

Table 10 outlines the equipment serial numbers and configuration recorded during the assembly process of the second prototype (PP1096).

Table 10: Second Prototype (PP1096) Traveler Template Rev 21 Specification Summary

Specification	Description
PP-Skid	
APL Part No.	**820-00278 rev.01**
Skid Serial No.	**PP1106**
PP-Genset	
APL Part No.	**875-00041 rev.B**
Record ASHOK Serial Number	**JGHZ407658**
Record Compression Ratio	**10:12**
Governor Serial No.	
Generator Serial No.	
PP-Automation Assembly	
APL Part No.	**875-00025 rev.A**
PCU Serial No.	
PCU Version	3.03
PCU Code Version	1.3.4

Specification	Description
Relay Board Serial No.	1118
Relay Board Version	2.1.1
PP-Gasifier	
APL Part No.	**875-00051 rev.A**
Reactor serial No.	
Reactor Version No.	
Cowling Serial No.	
Cowling Version No.	
PP-Flare	
APL Part No.	**875-00021 rev.B - FLARE**
Gas Blower 2. Lot No.	
Air Blower Lot No.	
PP-Hopper	
APL Part No.	**875-00048 rev.A**
PP-Filter V 1.1	
APL Part No.	
CFEED	
APL Part No.	**NA**
Adsoprtion Cooler	
Adsorption Cooler APL Part Number	**TBD**
Adsorption Cooler Serial Number	**TBD**
PP-Grid Tie	
APL Part No.	**870-00064 rev.C**
Controller S/N	
Breaker Amperage (A)	100A
Contactor wiring topology	HV (L-P)
Generator frequency	**60hz**
Generator nominal output voltage	**240v**
Generator wiring topology	
Governor file name	**PP20GT_60Hz_20160127.cfg**
DSE file name	
DSE Firmware Version	
Cooling Package	
Engine Coolant CHP APL Part No.	
Engine Coolant CHP Serial Number	

Specification	Description
Exhaust CHP APL Part No.	
Exhaust CHP Serial Number	
APL Part No.	
Producer Gas CHP APL Part No	
Precomm	
Generator frequency	60 HZ
Generator nominal output voltage	110 V
Generator wiring topology	SERIES STAR
Governor file name	PP20_60Hz_20160127.cfg
MS3 Pro File Name	
MS3 Project Name	
MS3 Firmware Version	
DSE file name	n/a
DSE Firmware Version	KS_PowerPallet-v1.3.4-release.hex
PCU Code Version	n/a
Commissioning	
BASIC: 60Hz: (High Voltage 480 VAC) (18KW Continuous Peak Power)	
BASIC: 50Hz: (High Voltage 440 VAC) (16KW Continuous Peak Power)	
GT: SET VOLTAGE: 60Hz: (Continuous Max Power)	
Record Engine Timing	
Record Engine Spark Plugs Used	
AVR bias (GT only)	
Gov bias (GT only)	
Decomm	
APL Part No. (Packaging)	n/a
Record Ashok Serial Number	GAHZ418019
Record Compression Ratio	

Source: All Power Labs, Inc.

The project team built the final CCHP Power Pallet prototypes (PP1097 and PP1103) based on feedback from the second prototype, PP1096. The team built final CCHP Power Pallet PP1097 between May and June 2018, and final CCHP Power Pallet PP1103 from August 2018 and January 2019. The testing activities used from CCHP Power Pallet PP1097 were used for a combination of in-house reliability testing and in-field pilot demonstration site testing in Malibu, operating for a total of 10 months, and final CCHP Power Pallet PP1103 for high uptime reliability testing in Berkeley where it operated for three months. Figure 16 and Figure 17 illustrate the final CCHP Power Pallets, PP1097 and PP1103.

Figure 16: Final Combined Cooling, Heating, and Power Power Pallet PP1097 with Adsorption Chiller

Source: All Power Labs, Inc.

Figure 17: Final Combined Cooling, Heating, and Power Power-Pallet PP1103

Source: All Power Labs, Inc.

Combined Cooling, Heating, and Power Power-Pallet Production Readiness

Technology Readiness

Production readiness requires a minimum Technology Readiness Level (TRL) of eight which can be summarized as "Actual system completed and 'mission qualified' through test and demonstration in an operational environment."[8] During this project, the CCHP Power Pallet

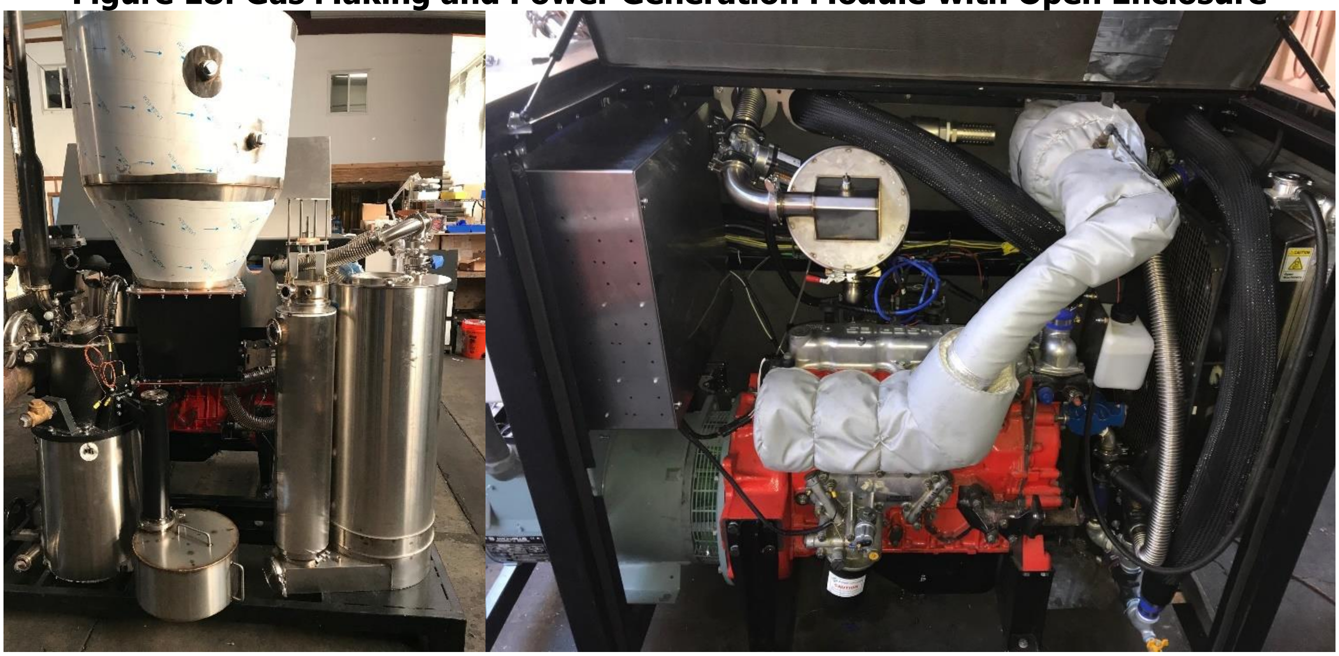
[8] "Definition Of Technology Readiness Levels" from NASA, accessed at https://esto.nasa.gov/files/trl_definitions.pdf

was able to progress from a TRL six to eight. This was in part due to a long history of manufacturing and operating Power Pallets around the world and the familiarity the team had for how to improve the technology. The improvements to system performance, reliability, and manufacturability achieved through this project were critical in reaching this readiness level. Based on this, All Power Labs is now able to work with their primary suppliers in the supply chain to increase the volume to match market demand starting in California.

Supply Chain Readiness

The key design requirement of the Power Pallet is to ensure manufacturability and production using industry-standard processes and making methods that are accessible and available around the world. As well, the design of the Power Pallet is modular to provide flexibility in designing a distributed supply chain strategy that can adapt to various market conditions and still ensure the highest quality, on-time delivery, and best overall value.

Figure 18: Gas Making and Power Generation Module with Open Enclosure



Source: All Power Labs, Inc.

The first element of a long-term strategy is to outsource the production to strategic regions for key components to begin manufacturing cost reduction activities. This leverages existing capacity and capabilities while minimizing the capital requirements to get the product to market.

The second strategy recognizes the realities and sensitivities related to control of proprietary information. All Power Labs will strengthen this by distinguishing between commodity-type materials versus innovation that makes the proposition truly unique and high value. The former will be lower risk and the latter is higher risk.

The third strategy is to set a realistic path to scale, which All Power Labs expects to accomplish by leveraging the capabilities of current supply partners that know the All Power Labs products and have experience working with for multiple years. These supply chain partners are classified into three tiers: Tier 1: full integration capabilities including existing sub-supply chain, Tier 2: core competencies with limited integration capabilities and sub-supply chain, and Tier 3: specific core competency with no integration capabilities.

Finally, the fourth strategy is a clear understanding of the specific regions representing the priority target markets, as this is a driver for the total landed cost of the product and delivery lead times. This effect is somewhat blunted by the continued evolution of logistics systems over the last decade which has made competitive delivery services for most regions in the world. All Power Labs is developing a very strong planning function, which further dulls the effect of market location as it relates to supplier selection. Nonetheless, this element will play a role in the overall supply chain strategy.

The supply chain strategy details and estimated product costs outlined below reflect the current state and planned path for the supply chain strategy, reaching a cost-optimized state, and stabilize the production of the CCHP Power Pallet.

Table 11 shows the supply chain strategy, including the partners that will be used over time across primary components.

Table 11: Combined Cooling, Heating, and Power Power-Pallet Supply Chain Strategy

		2019- Q2	2019- Q3	2019- Q4	2020	2021
Gas Making	Feed System	*APL Berkeley*	**YOCO- China**	**YOCO- China**	**YOCO- China**	**YOCO- China**
Gas Making	Gasifier	**CEMPC- Philippines**	**CEMPC- Philippines**	**CEMPC- Philippines**	**Bluesteel- Philippines**	**Bluesteel- Philippines**
Gas Making	Flare	**Wuxi Longterm Machinery- China**	**Wuxi Longterm Machinery- China**	**Wuxi Longterm Machinery- China**	**Bluesteel- Philippines**	**Bluesteel- Philippines**
Gas Making	Filter	*APL Berkeley*	*APL Berkeley*	*Bluesteel- Phillipines*	**Bluesteel- Philippines**	**Bluesteel- Philippines**
Gas Making	Final Assembly	*APL Berkeley*	*APL Berkeley*	**APL Berkeley**	**Philippines**	**Philippines**
Power Generation	Enclosure	*APL Berkeley*	*APL Berkeley*	*Ashok- India*	**Ashok- India**	**Ashok- India**
Power Generation	Genset Assembly	*Ashok- India*	*Ashok- India*	**Ashok- India**	**Ashok- India**	**Ashok- India**
Power Generation	Cooling Package	**APL Berkeley**	**APL Berkeley**	**APL Berkeley**	**Ashok- India**	**Ashok- India**
Power Generation	Exhaust System	*APL Berkeley*	*APL Berkeley*	*APL Berkeley*	**Ashok- India**	**Ashok- India**
Power Generation	Automation & Controls	*APL Berkeley*	*APL Berkeley*	*APL Berkeley*	**Ashok- India**	**Ashok- India**
Power Generation	Final Assembly	*APL Berkeley*	*APL Berkeley*	*APL Berkeley*	**Ashok- India**	**Ashok- India**

Yellow/italic: California-based; Green/bold: Low-Cost Region

Source: All Power Labs, Inc.

Table 12 outlines the current cost broken down and long-term, tops-down target broken down according to module and subsystem which relates to the overall supply chain strategy.

Table 12: Combined Cooling, Heating, and Power Power-Pallet Current and Projected Product Costing

Module	Subsystem	2019	2020
Gas Making	Gasifier	**$3,838.97**	$2,500.00
	Feed System	**$1,462.05**	$1,000.00
	Filter	**$952.22**	$1,000.00
	Flare	**$866.81**	$500.00
	Gas-Making Skid	**$486.97**	$150.00
	Sub-total	**$7,607.03**	**$5,150.00**
Power Gen	Genset	**$7,425.57**	$6,000.00
	Exhaust System	**$4,198.14**	$12,000.00
	Auxiliary Box	**$3,038.78**	
	Cooling Package	**$2,786.61**	$1,000.00
	Genset Control Sys.	**$2,694.77**	
	Automation	**$1,737.85**	$2,500.00
	Enclosure	**$1,218.73**	$1,000.00
	Power Gen Skid	**$486.97**	$150.00
	Sub-total	**$23,587.52**	**$11,850.00**
Packaging	User Kit	**$796.09**	$500.00
	Packaging	**$752.61**	$500.00
	Sub-total	**$1,548.70**	**$1,000.00**
		Grand Total	**Grand Total [TARGET]**
		$32,743.26	**$18,000.00**

Source: All Power Labs, Inc.

The key components are classified into four distinct categories: Power Generation Module, Gas Making Module, Final Assembly and Integration, and Balance of System components. Each is unique and will have a distinct supply chain strategy.

Power Generation Module

This Module is primarily composed of the engine, generator unit, control systems, and electrical/electronic components. Apart from the minor configuration to support producer gas as the fuel source, these components are readily available off the shelf from the general genset market. In addition to the numerous engine manufacturers, there are a multitude of qualified packaging houses that can provide full turnkey service. Coupled with the minimal proprietary information related to this assembly, the supply chain strategy is to outsource the full assembly to Ashok Leyland, which the project team considers a Tier 1 supplier. Ashok

Leyland is an Indian automobile company headquartered in Chennai, India and owned by the Hinduja Group. Founded in 1948, it is the second-largest commercial vehicle manufacturer in India; fourth largest manufacturer of buses in the world, and tenth largest manufacturer of trucks globally a manufacturer of commercial vehicles. They are also a manufacturer of complete genset assemblies, which are similar in scale as the CCHP Power Pallet. They provided engines for the four units used in the grant and will provide increasingly complete assemblies throughout 2019—engine/skid, engine/skid/generator/enclosure, etc. Full turnkey supply of Genset Assembly from Ashok Leyland is planned by mid-2020. Other Tier 1 suppliers will be added to the supply chain assuming on-going and significant increase in demand. The Gas Making Module is primarily composed of fabricated metal assemblies, metal hoses, miscellaneous metal hardware, and electrical components such as motors and valves. These various components are sub-grouped into Gasifier, Filter, Feed System, and Flare. While these assemblies are, by design, made from commodity materials with well-understood manufacturing processes, these also represent most of the proprietary information related to APL's technology when fully integrated into a Gas Making Module. To mitigate the potential for IP theft, it is the project team's strategy to distribute these assemblies across various suppliers and regions and to complete integration and final assembly separately. These items are planned to be outsourced in China, India, the Philippines, and the US using various suppliers that are qualified to have the necessary capacity and capabilities for specific assemblies.

Final Assembly & Integration of the Genset and Gas Making Module involves the physical assembly, configuration of the system based on customer requirements, testing and commissioning of the unit under standard test conditions, and final packaging. This requires basic equipment and infrastructure focused on material handling, electromechanical assembly, and operations of the equipment. The plan is to set up this capability within a geographic region to support local demand with strategic partners. The Berkeley facility at All Power Labs will be the initial site supporting demand in California until such time that volume within certain regions increases significantly.

Balance of Systems (BOS) are components which are integrated with the Power Pallet to provide a full system solution. Most of these components are designed and engineered by other manufacturers and are qualified and sourced by All Power Labs based on customer requirements. That said, it is also expected to standardize to certain BOS items to simplify the process. For the PIR-16010 grant, the primary BOS component is the adsorption chiller which plugs directly in the Power Pallet's thermal system. It is manufactured by Fahrenheit in Germany and supplied by Power Generation Enterprises in California.

The following information describes the production implementation plan and ramp schedule:

- 2018, four units: prototype and beta units, supports EVT/PVT testing and will be installed in APL-controlled sites. Results of these installations will inform on additional engineering improvements for future releases. Supply chain is primarily CA based.
- 2019, 20 units: pre-production units, installed at strategic customer sites with intensive involvement from APL. These include a multi-unit installation at Mendocino County and global customers in FIT and CHP markets. Results of these installations will inform the company on additional sustaining engineering improvements for future releases. Supply chain is situated in low-cost regions based for primary subassemblies, with final assembly and integration in Berkeley. BOS components to be sourced as defined by

project system requirements. Supply chain for product design improvements will be sourced in CA.

- 2020, 60 units: full release units, expansion with customer sites in California and the rest of North America and strategic global customers. Supply chain is low-cost-region-based with full power generation skids supplied by Tier 1 supplier. Gas-making assembly will be low-cost region based for primary components and final integration in Berkeley. BOS components to be sourced as defined by project system requirements. Supply chain for product design improvements will be sourced in CA.
- 2021, 120 units: full release units, expansion with customer sites globally. Supply chain is low-cost-region based with full power generation skids supplied by Tier 1 supplier. BOS components to be sourced as defined by project system requirements. Gas-making assembly will be low-cost region based for primary components and final integration in Berkeley and other market regions.
- 2022, 200 units: general release and expansion with customer sites globally. Supply chain is low-cost-region based with full power generation skids supplied by Tier 1 supplier. BOS components to be sourced as defined by project system requirements. Gas-making assembly will be low-cost region based for primary components and final integration in Berkeley and other market regions.

The following is a summary of germane patents to date:

- System and Method for Downdraft Gasification – Downdraft gasifier for producing a gaseous fuel used in an engine from carbonaceous material. CA2772537C Canada 8/29/17, CN102549115B China 12/10/14, US8764857B2 USA 7/1/14.
- Compact Genset Architecture – System and method to make compact biomass gasification power system as a complete product. US9780623B2 USA 10/3/17, US9476352B2 USA 10/25/16, US8829695B2 USA 9/9/14
- Simultaneous Pyrolysis and Comminution for Fuel Flexible Gasification and Pyrolysis – In situ size reduction of fuels during pyrolysis via low energy abrating devices. US9745516B2 USA 8/29/17
- Hybrid Fixed Kinetic Bed Gasifier for Fuel Flexible Gasification – A novel hybrid fixed-kinetic bed gasifier design to achieve the "holy grail" of a fully fuel agnostic gasifier. US9453170B2 9/27/16
- Gasifier with Controlled Biochar Removal Mechanism – A novel gasifier architecture that enables char take off prehearth for low temp biochar making. US9951279B2 4/24/18

CHAPTER 4: Performance Measurement and Verification of Combined Cooling, Heating, and Power Power-Pallet

Pilot Demonstration Site Summary

The pilot demonstration site changed several times for a combination of reasons. Originally, the pilot demonstration site was set in Santa Ana, California at Madison Materials with Regreen International Solutions as the CCHP Power Pallet operators. Due to several site challenges that could not be overcome, such as the space available for CCHP Power Pallet equipment, the pilot demonstration site moved to Ontario Agricultural Commodities (OAC) in Ontario, California in the fourth quarter 2017.

In many ways OAC was an ideal site for demonstrating the CCHP Power Pallet because of their use case and availability of feedstock, but due to a challenging regulatory process, the site was again relocated to finish the project before the grant period expired. The air quality permit ultimately became the hurdle that was unable to be overcome. All Power Labs (APL) and OAC worked extensively with the permitting agency to get the air quality permit issued. However, after 11 months of working with the air quality district and more than $10,000 in fees, there were no substantive updates from South Coast Air Quality Management District when the air quality permit will be issued. This timeframe prohibited starting the project in Ontario.

In November 2018, the Woolsey fire swept across Malibu opening up an unexpected opportunity to relocate the CCHP pilot demonstration site that would allow the project to be completed and highlight the flexibility of the CCHP Power Pallet use case. The Woolsey fire destroyed numerous houses and property, displacing many families and disrupted the power grid. A CCHP Power Pallet was already at the Skysource Ranch in Malibu since they had been awarded the Water Abundance X-Prize. The ranch hosted a family that was displaced from the fire and the CCHP Power Pallet was installed to provide the needed power, heat and cooling. David Hertz, the site host and founder of Sky Source LLC was motivated to help the displaced family and create a unique microgrid using the CCHP Power Pallet while also harvesting biomass as feedstock from the site and surrounding properties.

Figure 19 illustrates the extent of the damage caused by the Woolsey fire around the Skysource Ranch.

Figure 19: Woolsey Fire Aftermath in Malibu at Sky Source Ranch

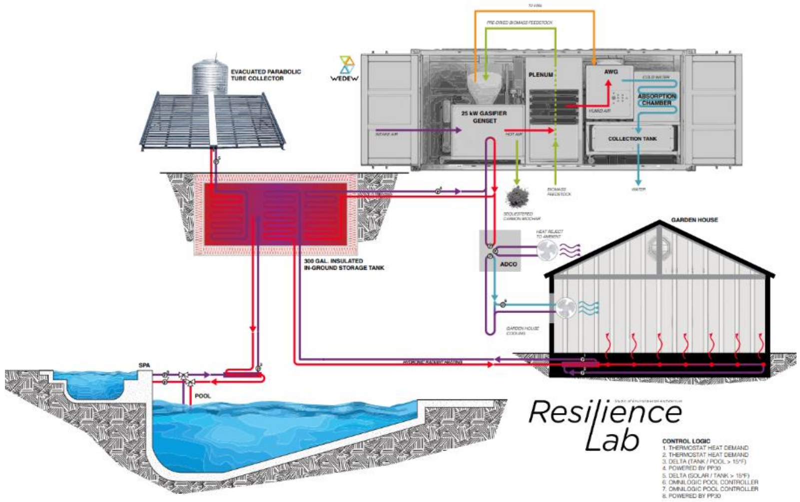
Source: All Power Labs, Inc.

Figures 20–22 illustrate the fire mitigating fuel harvesting and CCHP microgrid that was created at the Skysource Ranch to test and demonstrate the capabilities of the CCHP Power Pallet.

Figure 20: Onsite Fire Mitigation Feedstock Processing - Chipping

Source: All Power Labs, Inc.

Figure 21: Illustrated Diagram of the Combined Heat and Power Circuit and Microgrid at the Malibu Pilot Demonstration Site – Resiliency Lab Concept



Source: Skysource

Figure 22: Containerized Combined Cooling, Heating, and Power Power-Pallet at the Skysource Ranch in Malibu (Prototype PP30 in-Field)

Source: All Power Labs, Inc.

One of the two final builds of the CCHP Power Pallet, PP1097 was initially operated at the All Power Lab facility in Berkeley under a high uptime reliability operating regiment. As soon as the pilot demonstration host site in Malibu became operational, PP1097 began in field operations in a fire mitigation, micro grid use case which lasted from February 2019 through April 2019. PP1097 achieved at total of 540 hours of operation, 212 of which occurred in Malibu.

Table 13 outlines a summary of the operational performance of prototype PP1097 from bulk data. All data for 2019 reflects operations occurring in Malibu. Total system efficiency can move around easily based on variables such as load. Since the operations in Malibu had relatively low loads, the total system efficiency was lower than its designed state. When operated in a more controlled setting, 80 percent total system efficiency was measured.

Table 13: Summary of Prototype PP1097 Operational Performance

Year	SUM of Total Daily Engine Hours [hr]	SUM of Daily kWh Total [kWhe]	AVERAGE of Ag kW [kWe]	AVERAGE of HOT Run Total [kWt]	AVERAGE of COLD Run Total [kWt]	AVERAGE of Avg Feedstock	AVERAGE of System Electrical Operational Efficiency [%]	AVERAGE of Total System Operational Efficiency [%]
2019 Total	212.00	2069.90	9.45	86.04	7.83	1.07	15.51%	52.07%
Grand Total	538.51	7715.90	12.51	86.04	7.83	1.45	14.80%	52.07%

Source: All Power Labs, Inc.

The second of the two final builds of the CCHP Power Pallet, prototype PP1103, was operated exclusively at the APL facility in Berkeley, CA from February 2019 through April 2019 where it underwent a high uptime reliability operating regiment. Prototype PP1103 achieved a total of 214 hours of operations.

Table 14 outlines a summary of performance for prototype PP1103 from bulk data after three months of operations.

Table 14: Summary of PP1103 Operational Performance

Year	SUM of Total Daily Engine Hours [hr]	SUM of Daily kWh Total [kWhe]	AVERAGE of Ag kW [kWe]	AVERAGE of HOT Run Total [kWt]	AVERAGE of COLD Run Total [kWt]	AVERAGE of Avg Feedstock Consumption [kg/kWhe]	AVERAGE of System Electrical Operational Efficiency [%]	AVERAGE of Total System Operational Efficiency [%]
2019 Total	214.17	4496.50	18.86	23.49	4.31	0.92	24.31%	52.66%

Source: All Power Labs, Inc.

Both sites measured very strong fuel efficiency close to 1 kg/kWh. This means that 1 kg of biomass is converted to 1 kWh of electricity which is an improvement from the previous Power Pallet version of 1.2 kg/kwh.

Combined Cooling, Heating, and Power Power Pallet Measurement and Verification Plan

This section describes the testing and performance verification of the APL combined cooling, heating, and power system, designed to produce electricity, heat and cooling using woody biomass as the input fuel.

Study Objectives

The primary objective of this study is to quantify the performance of the APL CCHP system. The results include:

- System performance, efficiency, and energy flow.
- Gas emission rates (greenhouse gases and criteria pollutants).
- Total electricity savings (from electricity output and avoided cooling from CCHP).
- Total natural gas savings (from heat output from CCHP).
- Operation and maintenance (O&M) costs.

These results will be input data for evaluation of the system benefits through the California Energy Commission's CCHP Cost Calculator spreadsheet (CEC, 2017).

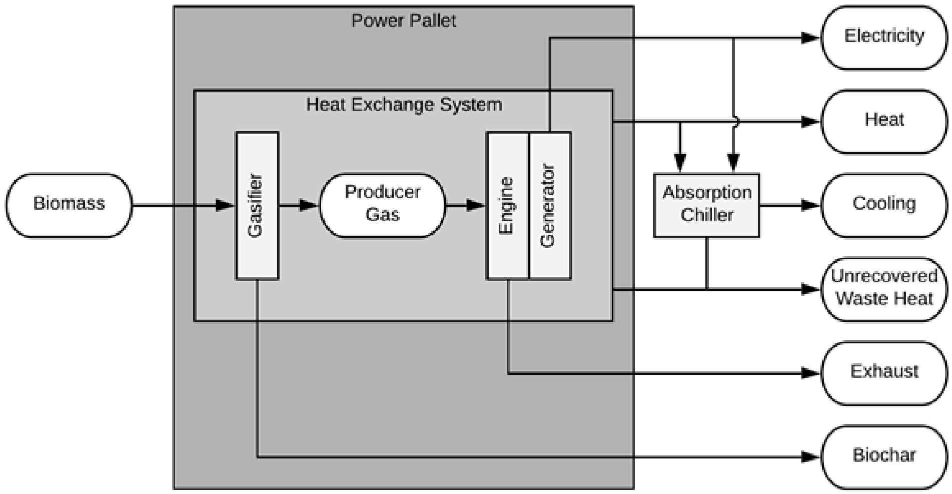
Measurement Approach

APL will install the CCHP system and instrumentation required for this MVP. Data was collected during 2018. Measurement of system performance will be conducted over two time periods:

1. For the measurement period, SERC conducted testing for one-week to measure energy and mass flows through the system. The first measurement period can take place at APL's manufacturing facility, SERC's laboratory, or the site host. The week of operating data will be used to quantify the system efficiency, energy output, and gas emission rates.
2. The monitoring period was an operational study conducted by gathering data during six-months to quantify capacity factor, O&M labor requirements, and electricity and natural gas savings.

Figure 23 illustrates the CCHP Power Pallet process diagram. The grey circles indicate measurement points.

Figure 23: Simplified Combined Cooling, Heating, and Power Power Pallet Process Diagram



Source: Schatz Energy Research Center

Methods

Evaluation of system performance was measured over two testing periods. The first test period measured system efficiency, and the second test period monitored long-term system operation, as summarized below.

1. System Efficiency Testing (conducted by SERC)
    a. Objective: The goal of this testing was to measure the system efficiency.
    b. Description: The mass and energy flows into and out of the system were measured during steady state operation of the CCHP system. Data were recorded in real time on electronic data files for two, one-hour long steady state test periods. Producer gas, biomass feedstock, and biochar samples were collected for lab analysis.
    c. Feedstock: Woody biomass feedstock.
    d. Location: Testing occurred at APL's manufacturing facility in Berkeley, California.
    e. Dates: Testing occurred on June 22 and 23, 2018.
    f. Equipment: Power Pallet CCHP serial number 1097.
2. System Operation Monitoring
    a. Objective: The goal of this testing was to evaluate the long-term system operations and maintenance requirements.
    b. Description: The total energy into and out of the system were monitored on a daily basis. Labor requirements and maintenance tasks were also monitored. Data were recorded by the system operator and analyzed by SERC.
    c. Feedstock: Walnut shells.
    d. Location: Testing occurred at the deployment site in Malibu, California.

e. Dates: Testing occurred during a three-month period from February through April, 2019. SERC conducted a site visit to verify data collection methods and instrumentation on April 29 and 30, 2019.
f. Equipment: Power Pallet CCHP serial number 1097.

During the system efficiency testing, the mass and energy flows were measured using the techniques and instruments described below. The energy values were calculated as the average during the two, hour-long steady state tests.

- Biomass input rate
  - The mass of the entire Power Pallet was monitored in real-time during the test using a large weight scale with ± 0.1 kg resolution and a recording interval less than one second. The biomass input rate is equal to the mass loss measured on the scale plus the biochar generation rate.
  - The energy content of the biomass was measured in a bomb calorimeter. The energy input rate is calculated as the product of the mass flow rate and energy content of the biomass.
- Biochar generation rate
  - Biochar was collected from two locations on the machine: the ash collection vessel and the cyclone. Biochar was collected at the end of each testing day and weighed. The mass of biochar created during the day was distributed equally across the operation time to calculate the rate of generation.
  - The energy content of both biochars were measured in a bomb calorimeter. The energy output rate is calculated as the product of the mass flow rate and energy content of the biochar.
- Electricity generation
  - Electricity power generation was monitored in real time using current transformers and voltage measurements. Electricity was measured at three locations: the total power out of the generator, the total power used by the adsorption chiller, and the net electrical output to the grid. The parasitic load of the Power Pallet was calculated by difference.
- Heating and cooling loads
  - Thermal power generation was monitored in real time by measuring the energy flow in the heating or cooling fluid. Thermal power was measured in three locations: heat output from the Power Pallet, heat input to the adsorption chiller, and cooling output of the adsorption chiller. The energy flow was calculated with two temperature measurements (supply and return temperature) and a flow rate measurement.
- Producer gas energy content
  - The energy content of the producer gas is measured by the flow rate using an orifice flow meter and composition of the gas using a gas chromatograph. The energy content of the gas was calculated using the higher heating values of the constituents measured in the gas. The energy flow rate was calculated as the product of the flow rate and energy content. Two gas samples were taken during

each test run (four samples total). The molar composition was determined by triplicate measurement on the gas chromatograph.

- Heat loss from the gasifier
  - Calculated as the difference between the energy input rate of biomass and the energy output rate of biochar and producer gas. The remaining energy is lost as heat.
- Heat loss from adsorption chiller
  - Calculated as the difference between heat and energy into the chiller and cooling out of the chiller.
- Additional heat loss
  - Additional heat loss is calculated by difference to complete the energy balance. This heat is lost through the hot exhaust gases and radiative and convective losses.
- Moisture content
  - Moisture content of biomass feedstock and biochar was measured as the mass loss after drying for 24 hours in an oven at 104 C (219.2 F).
- Emissions
  - Gas emissions from the engine exhaust were measured during the system efficiency testing using an Enerac M700 and during the system operations monitoring using a Testo 350.

Combined Cooling, Heating, and Power Power-Pallet Measurement and Verification Results

The energy properties and input rate of the woody biomass feedstock and biochar output are described in Table 15. The samples and data collected in Berkeley, California on June 22–23, 2018.

Table 15: Properties of Mass Inputs and Outputs

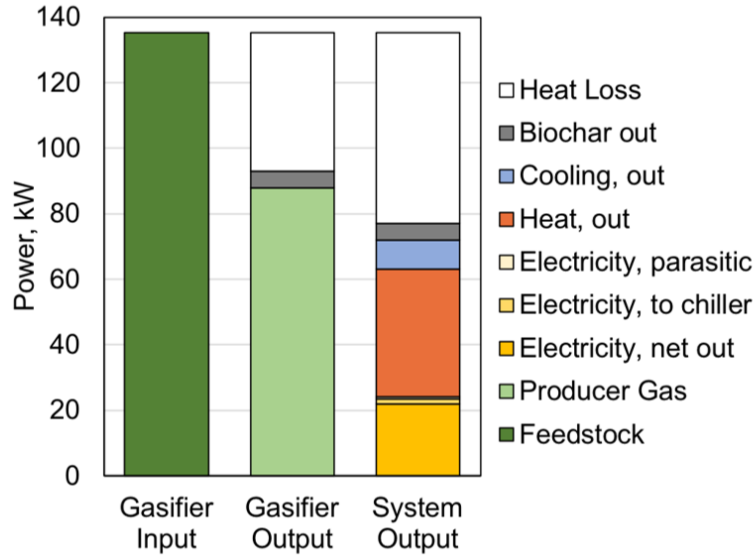
	Moisture Content, % Mass (Wet Basis)	Higher Heating Value, MJ/kg (Dry Basis)	Mass Flow Rate, kg/hr
Biomass Feedstock	11%	19.5	28.1
Biochar, Ash Collection Vessel	<1%	29.3	0.5
Biochar, Cyclone	<1%	28.7	0.2

Source: Schatz Energy Research Center

Energy and Mass Balance

The gasifier CCHP system converted 135 kW (28 kg/hr) of biomass into 89 kW of producer gas. The producer gas was used to generate a net electrical output of 22 kW and recovered 48 kW of heat. 23 kW of heat were used for a heating load and 25 kW were used by an adsorption chiller to produce 9 kW of cooling. A graphical energy balance of the machine is shown in the chart in Figure 24 and exact values on the diagram in Figure 25. Data collected in Berkeley, California on June 22–23, 2018.

Figure 24: Energy Flows of Combined Cooling, Heating, and Power System



Source: Schatz Energy Research Center

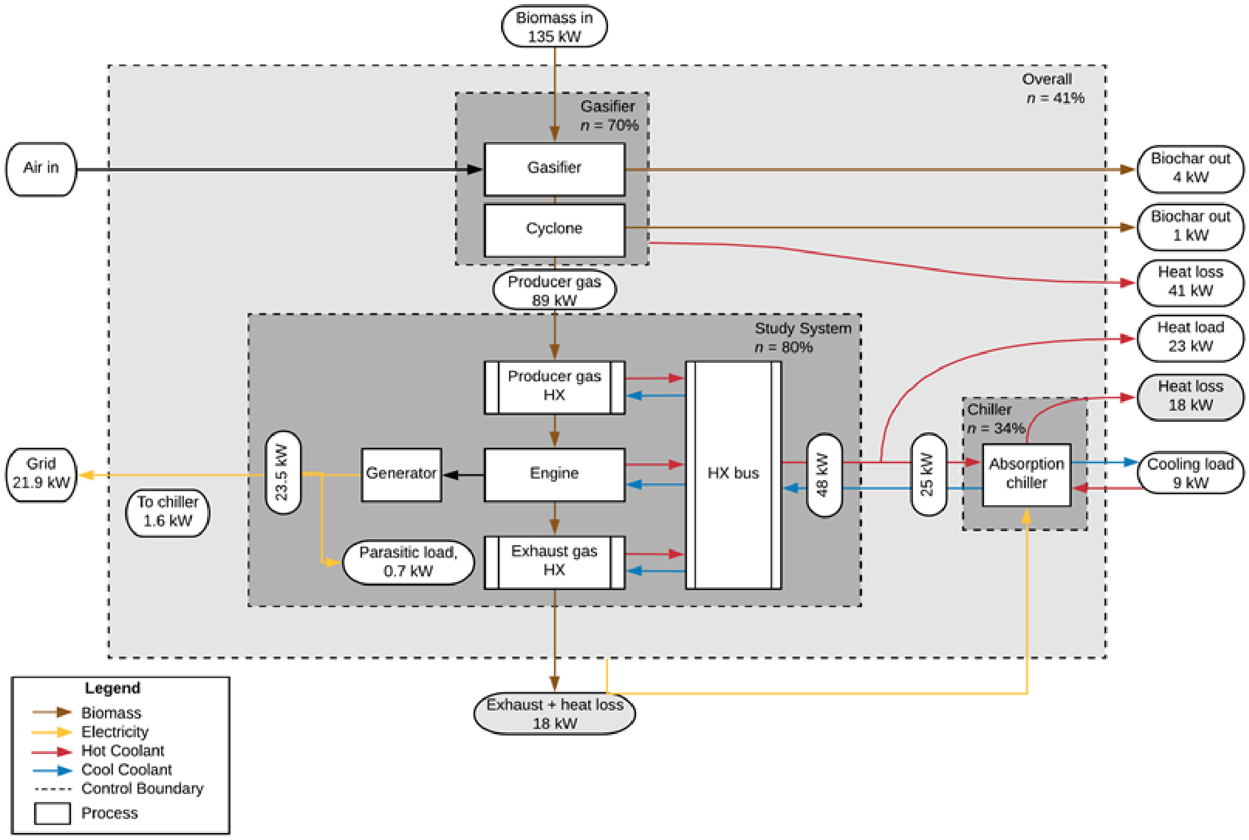
The energy content and molar composition of the producer gas is shown in Table 16, with data collected in Berkeley, California on June 22–23, 2018. The energy content of the producer gas comes primarily from carbon monoxide and methane.

Table 16: Producer Gas Energy Content and Composition

Composition	Value
H_2	0.03 % mole
CO	45.5 % mole
CH_4	3.8 % mole
C_2H_6	0.00 % mole
CO_2	0.09 % mole
O_2	10.7 % mole
N_2	39.8 % mole
Energy Flow	**Value**
Energy Content	164 kJ/mol (HHV)
Energy Content	6.82 MJ/kg (HHV)
Gas Flow Rate	0.535 mol/s
Energy Flow	87.9 kW

Source: Schatz Energy Research Center

Figure 25: Energy Balance of Biomass Gasifier Combined Cooling, Heating, and Power



Source: All Power Labs, Inc.

Efficiency

System efficiency (η) is calculated as the useful power output ($P_{useful\ output}$) divided by the fuel power input ($P_{fuel\ input}$).

$$\eta = \frac{P_{useful\ output}}{P_{fuel\ input}}$$

The efficiencies calculated at different points on the system, as outlined above, are summarized in Table 17. Data was collected in Berkeley, California on June 22–23, 2018.

Table 17: Efficiency Values

Boundary	***Description***	***Efficiency***
Study System	Producer gas to energy and heat	80%
Overall System	Biomass to electricity, heat, cooling, and biochar	44%
Gasifier	Biomass to producer gas and biochar	70%
Chiller	Heat to electricity and cooling	34%

Source: Schatz Energy Research Center

- Study System Boundary: The study system is the boundary around the engine and heat exchange system. The input energy to this system is the producer gas. The producer gas is used as the input fuel for the study system rather than the biomass because this more similarly matches a system boundary that would be drawn around a comparable natural gas system, where natural gas has already been refined from its primary source into a useable fuel for input to an engine. The useful energy output from the study system is the total heat recovered by the heat exchangers and the electrical output not minus the parasitic load.

$$\eta_{sys} = \frac{(J_{tot} - J_{para}) + P_{h,recovered}}{\dot{E}_{PG}}$$

Where
J_{tot} is the total electricity output from the generator
J_{para} is the parasitic electrical load of the gasifier system
$P_{h,recovered}$ is the thermal power output recovered by the heat exchange system
$\dot{E}_{PG}$ is the energy flow of producer gas out of the gasifier

$$\eta_{sys} = \frac{(23.5\ kW - 0.7\ kW) + 48\ kW}{89\ kW}$$

$$\eta_{sys} = 80\%$$

- Overall System Boundary: The overall system boundary is around the entire biomass CCHP system. The input energy to this system is the biomass feedstock. The useful energy output is the net electricity output, the thermal power delivered to the heat load, the thermal power for cooling, and the chemical energy in the biochar.

$$\eta_{ovl} = \frac{J_{net} + P_{h,out} + P_{c,out} + \dot{E}_{biochar}}{\dot{E}_{biomass}}$$

Where
J_{net} is the net electricity output from the system.
$P_{h,out}$ is the heat delivered to the heating load.
$P_{c,out}$ is the cooling power provided from the system.
$\dot{E}_{biochar}$ is the energy flow of biochar out of the gasifier.
$\dot{E}_{biomass}$ is the energy flow of biomass into the gasifier.

$$\eta_{ovl} = \frac{21.9\ kW + 23\ kW\ +\ 9\ kW\ +\ 5\ kW}{135\ kW}$$

$$\eta_{ovl} = 44\%$$

- Gasifier: The efficiency of the gasifier is the sum of the producer gas and biochar output divided by the biomass input.

$$\eta_{gasifier} = \frac{89\ kW\ +\ 5\ kW}{135\ kW}$$

$$\eta_{gasifier} =\ 70\%$$

- Adsorption Chiller: The efficiency of the adsorption chiller is the cooling output divided by the heat and electricity input.

$$\eta_{chl} = \frac{9\ kW}{25\ kW\ +\ 1.6\ kW}$$

$$\eta_{chl} =\ 34\%$$

Emissions

Gas emission from the CCHP system exit through the engine exhaust. Emissions were monitored during both the system efficiency and the system operations monitoring test periods (Table 18). Exhausted concentrations data was collected in Berkeley, California on June 22–23, 2018 (System Efficiency row) and in Malibu, California on April 29-30, 2019 (Operation Monitoring row).

Table 18: Measured Emissions Concentration in Exhaust Gas

Test Period	Feedstock	PP Serial #	Emissions Measuring Instrument	O_2	CO_2	CO	NOx	SOx
System Efficiency	Wood Chips	#1097	Enerac M700	0.3%	19%	3.9 ppm	3.4 ppm	3.5 ppm
Operations Monitoring	Walnut Shells	Various	Testo 350	0.10%	19%	331 ppm	270 ppm	N/A

*** Gas emissions are calculated on a dry-gas basis.**

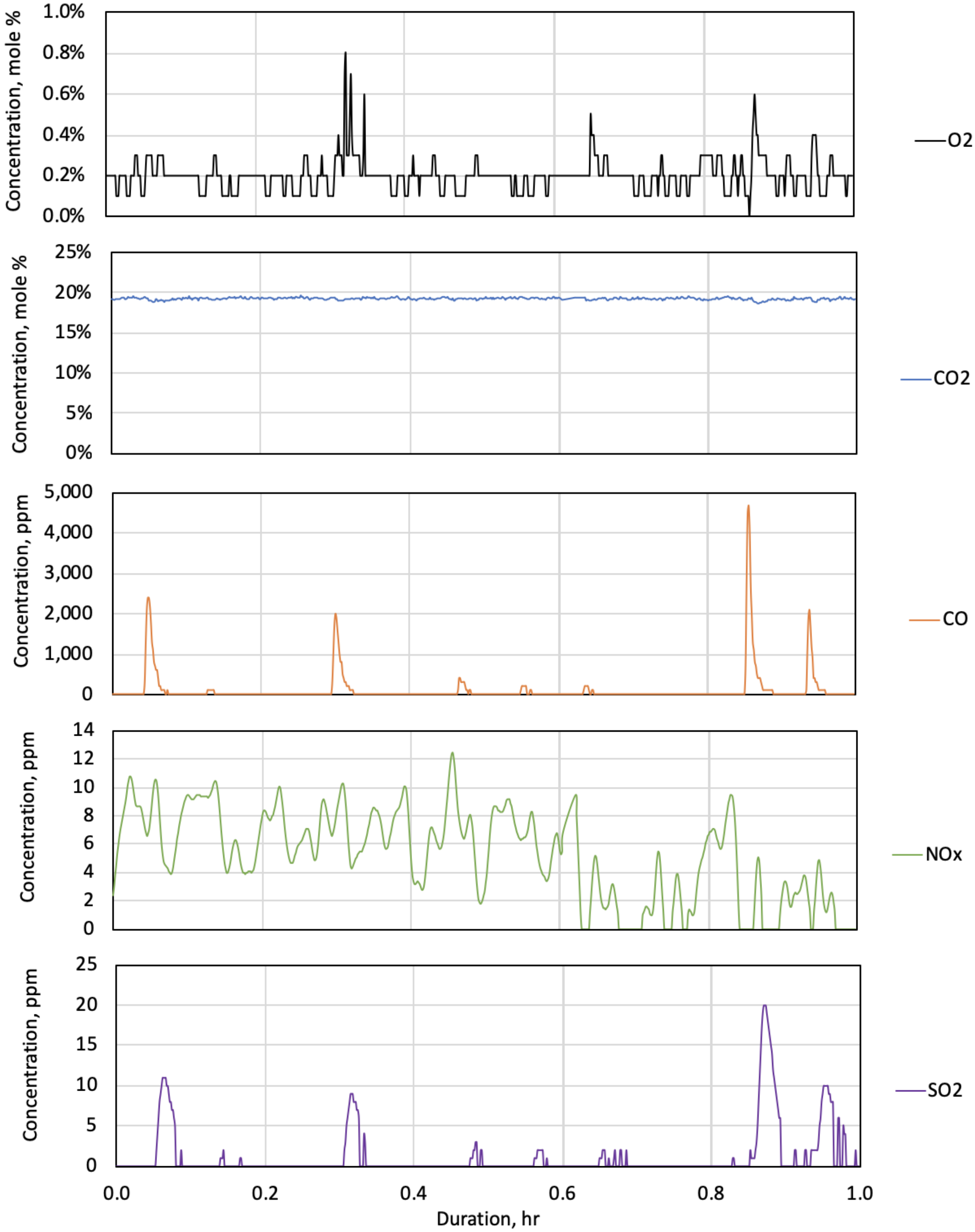
N/A indicates that sensor not available

Source: Schatz Energy Research Center

Excess oxygen and carbon dioxide emissions are similar for both test periods. Emissions of CO and NO_x varied by two orders of magnitude between the system efficiency and operations monitoring testing. The differences could be attributed to different feedstocks being used in the test periods, different gasifier systems or different instrumentation being used to measure the emissions. Additional testing would be required to resolve which variable led to the difference in emissions measurements.

A time series of the emissions profile during the system efficiency testing is shown for an hour-long steady state test show that most emissions were constant during operation, except CO and SO_2 emissions have some distinct spikes (Figure 26). Further testing is required to determine the cause of these spikes. Emission profile data was collected in Berkeley, CA on June 22-23, 2018.

Figure 26: Emissions Profile During Steady State System Efficiency Testing



Source: Schatz Energy Research Center

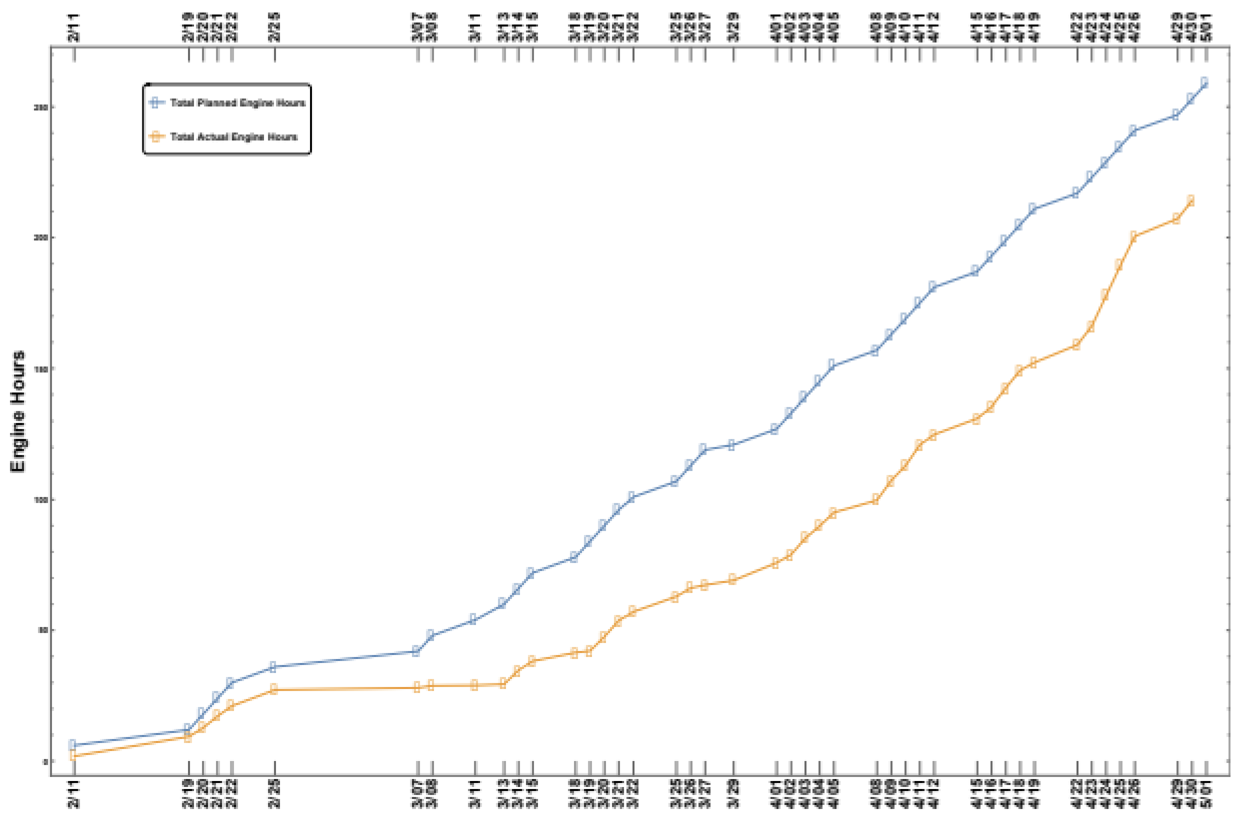
System Performance Monitoring

Monitoring of long-term system performance, operation and maintenance occurred between February and April 2019 at the CCHP deployment site in Malibu, California. This section documents the performance of the system during this testing interval.

Operating Hours

Between February and April 2019, the CCHP system accrued 214 hours of engine operation over 43 days of operation (Figure 27), data collected in Berkeley, California, between February and April 2019 with PP1103.

Figure 27: Planned and Actual Daily Operating Hours



Planned (blue line, circle markers) and actual (orange line, square markets) daily operating hours.

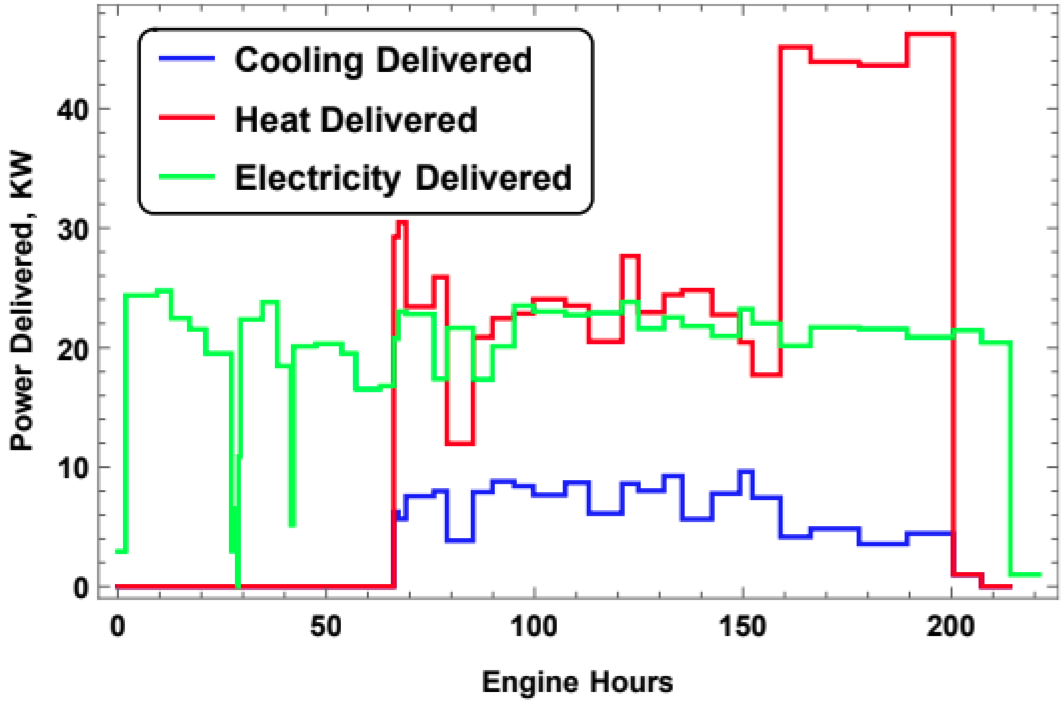
Source: Schatz Energy Research Center

Electricity

Electricity production during the monitoring period depended on the on-site load. Maximum electrical output was not typically achieved due to the constrained size and variability of the on-site load.

Cumulative electrical energy production was measured at the generator output for each operating day. The measurement is the total electrical output, not considering the parasitic load. The average power production was 21 kW with average daily loads between 3 kW and 25 kW (Figure 28). Average daily power production versus cumulative engine hours. Data collected in Berkeley, California, between February and April 2019 with PP1103.

Figure 28: Power Production Versus Engine Hours



Source: Schatz Energy Research Center

Heating and Cooling

Cumulative daily heating and cooling energy were measured during the monitoring period. Average daily cooling provided from the adsorption chiller was 7.1 kW and average daily heating provided by the CCHP system was 29 kW.

Heating and cooling data were not collected for the preliminary 60 hours of operation.

Operations and Maintenance

Operations and maintenance requirements were monitored on PP1097 to evaluate any scheduled and unscheduled maintenance events. The time required to perform the maintenance and any associated costs for replacement parts were recorded (Table 19). Unscheduled maintenance event required 15.6 hours of labor and $150 in replacement parts during the 214 hours monitoring period. This is equivalent to 4.4 minutes of labor and $0.70 of replacement parts per hour of operation.

A list of schedule maintenance events was created for the CCHP system. Schedule maintenance tasks occur at predetermine intervals depending on the cumulative hours of engine operation. The labor requirements and replacement parts for scheduled maintenance events were distributed across the operating time of the machine for analysis. Scheduled events require 4.1 minutes of labor and $2.10 of replacement parts per hour of operation under the current operations and maintenance schedule.

The maintenance requirements are expected to be reduced based on projections and operational experience from APL. A new maintenance schedule is under development but cannot be confirmed until 1,000 hours of operational data have been collected. The projected scheduled maintenance is reduced to 2.3 minutes of labor and $0.93 for replacement parts per hour of operation (Table 19), a reduction of 44 and 56 percent, respectively, when compared to the current maintenance schedule. Unscheduled maintenance requirements from data collected in Malibu, California on PP1097.

Table 19: Maintenance Requirements for Combined Cooling, Heating, and Power System

Type of Maintenance	Labor Requirement, min of labor/hr operation	Replacement Parts, $/hr operation	Downtime
Current operations of equipment			
Scheduled – current	4.1 min/hr	$2.10	7.1%
Unscheduled	4.4 min/hr	$0.70	7.3%
Total	8.7 min/hr	$2.80	14%
Projected future improvements			
Scheduled – projected	2.3 min/hr	$0.93	3.8%
Unscheduled	4.4 min/hr	$0.70	7.3%
Total	6.7 min/hr	$1.63	11%

Source: Schatz Energy Research Center

A list of the scheduled and unscheduled maintenance requirements is provided in Appendices B and C.

Startup and Shutdown Time

The time required for startup and shutdown were observed during the system operations monitoring. Startup requires 30 minutes to reach ideal reaction temperatures within the gasifier before starting the engine. Shutdown requires 20 minutes to cool down the equipment before turning off the blowers and halting gas production.

Capacity Factor

The capacity factor of the CCHP system depends on 1) the required downtime for maintenance, startup, and shutdown and 2) the net electricity output compared to the nameplate capacity.

1. The required downtime for the maintenance is 14 percent as calculated in the Operations and Maintenance section. Startup and shutdown add an additional 50 minutes of downtime per day of operation. Assuming 24 hour per day operation, the maximum operating time per day is 82.6 percent.
2. Net electricity output is 21.9 kW compared to a 25-kW nameplate capacity. The maximum fraction of electricity output is 87.6 percent.

A capacity factor is calculated separately for the electrical and thermal (heating and cooling) components of the CCHP system (Table 20). The electricals capacity factor is calculated as the product of both 1 and 2. The capacity factor of the thermal components is equal to item 1 only because the thermal output does not depend on the parasitic electrical load. Capacity factor of CCHP system is assumed a 24 hour per day planned operating schedule and calculated from data collected in Berkeley, California on June 22-23, 2018 and Malibu, California, between February and April 2019.

Table 20: Capacity Factor of Combined Cooling, Heating, and Power System

System	Capacity Factor
Electrical Output	71%
Heating and Cooling Output	81%

Source: Schatz Energy Research Center (2010)

Labor Time

Labor time is broken up into two types of labor: 1) labor for normal operation and 2) labor for maintenance tasks.

- Normal operation was observed to require approximately 25 percent of one operator’s effort. Their tasks include preparing fuel, loading biomass feedstock, system monitoring, startup, shutdown, etc. During the remaining 75 percent of the operator’s time, they are able to perform other tasks onsite not related to CCHP operation. Thus, for cost estimation, only the 25 percent operational time is included in the CCHP lifecycle cost. At an ideal site with minor improvements to CCHP operation logistics, an operator could spend as little as 10 percent of their effort operating the system.
- Maintenance tasks occur at scheduled and unscheduled intervals, as described in Operations and Maintenance section. Labor time associated with these tasks is summarized in that section and quantified using the tables in Appendix B.

Levelized Cost of Energy

The levelized cost of energy (LCOE) is calculated for the CCHP system to evaluate the cost of energy production over the lifetime of the system. Three scenarios were developed for different operating conditions and projected maintenance improvements using different assumptions, as shown in Table 21. The scenarios are:

- Scenario 1: As tested – Use basic economic and operating assumptions. Maintenance and operations data for tested version of the CCHP system.
- Scenario 2: Projected – Use basic economic assumptions. Only change is to use projected scheduled maintenance intervals as described in the Operations and Maintenance section.
- Scenario 3: Ideal – Using economic and operating assumptions that reflect a good location for CCHP use (low feedstock cost, high biochar value, low operator effort). Use projected maintenance schedule and reduce unscheduled maintenance labor and cost by 50 percent.

Table 21: Assumptions for Different Scenarios of Levelized Cost of Energy Analysis

Item	Scenario 1 As tested – current performance	Scenario 2 Projected – maintenance improvements	Scenario 3 Ideal – best operating conditions
Material Cost & Value			
Feedstock cost	$40/BDT	$40/BDT	$0/BDT
Biochar value	$1,000/tonne	$1,000/tonne	$1,500/tonne
Labor Rates and Time			
Labor rate	$20/hr	$20/hr	$20/hr
Fringe benefits	25%	25%	25%
Operator effort	25%	25%	10%
Operating days per year	365 day/yr	365 day/yr	365 day/yr
Operating hours per day	16 hr/day	16 hr/day	16 hr/day
Economic			
Discount rate	5%	5%	5%
Generator lifetime	15 yr	15 yr	15 yr
Salvage value	10% of capital	10% of capital	10% of capital
Maintenance			
Scheduled maintenance type	Current	Projected	Projected
Unscheduled maintenance	Current	Current	50% of Current

Source: Schatz Energy Research Center

For a CCHP system, the LCOE is calculated as the total net lifecycle costs of the system (TLCC) divided by the annual energy generation (Q) multiplied by the uniform cost recovery factor (UCRF). For a system with constant annual output throughout its lifetime, the LCOE is calculated following equation described by NREL:[9]

$$LCOE = \frac{TLCC}{Q} * UCRF$$

The total lifecycle cost of the system is the net present value of the capital costs, salvage value, fuel costs, revenue from biochar generation, labor cost, and replacement parts (Table

[9] Walter Short, Daniel J. Packey, and Thomas Holt, A Manual for the Economic Evaluation of Energy Efficiency and Renewable Energy Technologies PDF, NREL/TP-462-5173, March 1995.

22). In all three scenarios, operations and maintenance makes up approximately 80 percent of TLCC. Of the O&M costs, labor for normal operation is by far the largest piece. This cost breakdown shows that the focus of future developments should be to reduce labor and maintenance requirements.

A CCHP system produces heating and cooling service alongside electricity. The LCOE equation provides equal weight to electricity and the heating or cooling produced because they are all summed into the annual energy production, Q. Heating and cooling provide a different value of service than electricity and should therefore be weighted differently in the denominator of the LCOE equation. However, without a broadly accepted method for weighting the energy from electricity, heating, and cooling, three different LCOEs were calculated each with different magnitudes of Q. The LCOE is calculated for three different system outputs: electricity only; electricity and heat; or electricity, cooling, and heat. Table 23 shows the results of LCOE estimated for three scenarios.

Table 22: Net Present Value of All Categories of Total Lifecycle Costs

	Scenario 1: As tested	Scenario 2: Projected	Scenario 3: Ideal
Capital cost: Power Pallet	$73,050	$73,050	$73,050
Salvage value, chiller	$2,431	−$2431	−$2431
Capital cost, chiller (CCHP only)	$25,166	$25,166	$25,166
Salvage cost, chiller (CCHP only)	$838	−$838	−$838
Biomass fuel cost	$49,337	$51,093	$0
Revenue from biochar	$30,589	−$31,678	−$49,461
Labor cost, normal operation	$378,858	$378,858	$151,543
Labor cost, maintenance	$174,360	$141,538	$98,957
Replacement parts	$138,218	$83,102	$67,878
Total	$805,131	$717,860	$363,865

Negative values indicate revenue.

Source: Schatz Energy Research Center

Table 23: Levelized Cost of Energy Calculated for All Scenarios

	Scenario 1: As tested	Scenario 2: Projected	Scenario 3: Ideal
LCOE: *Q* = electricity only	$673	$578	$272
LCOE: *Q* = electricity & heating	$216	$184	$84
LCOE: *Q* = electricity, heating, & cooling	$303	$261	$127

Source: Schatz Energy Research Center

The LCOE for electricity only is the highest because it only considers the value of the electricity generation, not the heating or cooling. The LCOE for electricity and heat provides the lowest number because it takes includes the large amount of heat recovered without bearing the additional capital cost of the chiller. Lastly, the LCOE for the entire CCHP system includes the capital cost and salvage value of the chiller in the TLCC and has all three sources of energy output in the denominator.

The Power Pallet CCHP system provides good value for energy services in ideal operating conditions. This includes locations with biomass feedstock costs that are available at low to no cost and areas where biochar can be sold into a market. In addition, the current lifecycle cost distribution shows that the capital cost of the machine is low relative to the operating costs and indicates that the machine is available at a competitive initial price. An ideal location for this CCHP system will also have access to low cost skilled labor, for example at a location where other technical laborers are available to operate this equipment as a portion of their other work.

CHAPTER 5: Bankability Study

Bankability Summary

The bankability analysis was prepared by a third-party gasification consulting group based out of Modena Italy, Syn-gas s.r.l.s. This group was founded in 2014 by three Mechanical Engineer Ph.Ds., Giulio Allesina, Simone Pedrazzi, and Antonio Libbra from the University of Modena and Reggio Emilia, Italy specializing in research and scientific support services regarding renewable energy. Syn-gas advises companies in areas including kinetic simulation of the gasification process, biomass chemical and physical characterization for thermal treatment, biomass chemical and physical characterization for anaerobic digestion, biomass power plant design, economical evaluation of power plant NPV, biomass supply and storage, and biomass power plants bankability studies. The analysis for this report covers the design and operation of the PP30 and describes its strengths as well as recommendations for areas of improvement while considering manufacturing and market requirements.

There are several companies that produce gasification systems that were used for comparison when reviewing the bankability of the CCHP Power Pallet developed by All Power Labs. However, most at a similar scale are still at a prototype stage of development. The primary disadvantages of these existing products are high capital cost costs and high maintenance requirements compared to photovoltaic or wind systems, and a very narrow range of acceptable fuels.

All Power Labs has been developing gasification technologies for more than 10 years with an aim to directly address these challenges to enable broad use of small-scale gasification systems worldwide. This technology has evolved considerably, reaching the CCHP Power Pallet (PP30). The PP30's affordable price, compact size, fuel flexibility, and lack of tarry water byproducts represent significant advantages compared to the other options in the market. The weaknesses of the Power Pallet relate more to the lack of automation as well as considerable maintenance requirements.

Broadly speaking, the two kinds of competitors are other gasification power plants or different energy production systems such as photovoltaic solar, micro-wind turbines, and natural gas cogeneration.

Some biomass gasification competitors with products at a similar scale include:

- Senner Re2 GmbH HKA 35/45/49
- CMD ECO20X
- Entrade E5
- Volter 40 Indoor

Table 24 depicts a biomass gasification overviews and comparisons.

Table 24: Biomass Gasification Product Comparisons

	APL PP30	Spanner Re2 GmbH HKA	CMD ECO20X	Entrade E5	Volter 40 Indoor
Price (Price in USD)	≈ 74,000	≈ 260,000	≈ 100,000	> 300,000	≈ 230,000
Electrical Output	25 kW	45 kW	20 kW	50 kW	40 kW
Complexity	Medium	High	Medium	High	High
Feedstock (Moisture)	Woodchips/Shell (< 25/30%)	Woodchips (< 13%)	Woodchips (< 20%)	Woodchips/Pellet (< 13%)	Woodchips (< 18%)
System Size	Small	Big	Big	Medium	Medium

Source: All Power Labs, Inc.

Evaluation: Manufacturing

Production of the various PP30 parts takes place in different teams. Most of the gas-making system is done in Manila by the Cutting-Edge Materials Processing Corporation, a company of the MD Gruppe specialized in high precision sheet metal manufacturing. The engine is purchased from Ashok Leyland, an Indian manufacturer of commercial vehicles owned by the Hinduja Group. In the future, Ashok may have a deeper role in the power generation subsystem supply chain, however, at this time, they provide only the engine block mounted to the power generation skid. The automation is composed of a Deep Sea Electronics control module and a custom Process Control Unit (PCU) assembly. Development is currently underway to switch from this custom PCU assembly to an industrial grade programmable logic controller (PLC).

Assembly of the gas-making and power generation modules currently takes place at the All Power Labs headquarters in Berkeley, California. The in-house team has highly skilled manufacturing capabilities in sheet metal and mechanical assemblies, but the supply chain is optimized for prototyping and lower production volumes. Their supply chain group has years of experience, qualifying and setting up distributed international supply chains with strong relationships in California, China, India, and the Philippines. Such a supply chain will need to be fully used, reducing dependencies on in-house manufacturing and assembly to scale production and meet market demand.

All Power Labs' long-term strategy is to leverage its modular architecture that features two half skids—the gas-making and power generation modules—will be built up individually by the Cutting Edge and Ashok respectively, and then mounted together. Externalizing production will allow production to scale and will reduce costs while improving quality.

PP3 Evaluation: Technology

A thorough technology review of the PP30 was conducted comparing market requirements with the stated and actual measured performance of the equipment. Summaries of the findings are outlined in the next sections.

Fuel Supplying, Pre-Treatment

Balancing the business plan relies on four major factors: cost of the equipment, cost of the fuel, costs for operation and maintenance, and energy and biochar selling price.

The PP30 has proven to be very reliable when operated with fuels with a broader standard than other small-scale gasifiers on the market. Even though some fuel processing such as sifting and drying is still required, being having less restrictive fuel requirements helps enable a profitable business using less expensive fuels. A significant leap forward will derive from the design of a reactor and fuel handling system that can reduce or eliminate such fuel processing requirements.

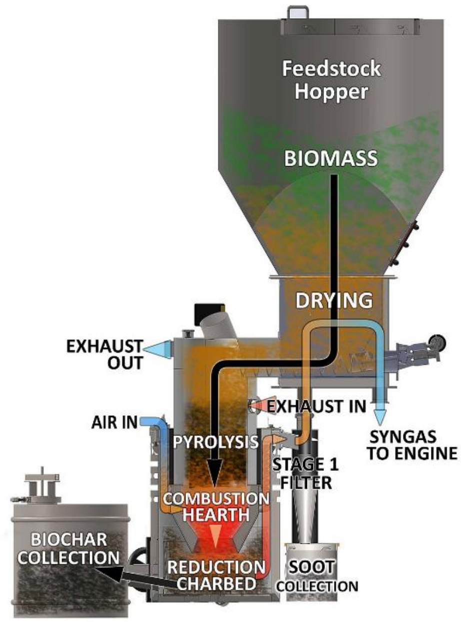
Reactor Maintenance

The analysis on O&M costs illustrate how the reactor replacement cost strongly affects the business plan. The operation for this activity is expensive both for the cost of the replaced part (the pyroreactor) and the time consumed to complete the replacement activity. It is vital to work towards the extension of the mean time to failure of this component, as well as reducing the average time required for replacing the reactor.

The mean time to failure of the pyroreactor is most affected by failure of the airlines. Possible solutions for this include using airlines with thicker metal or externalize the airlines in the form of an external heat exchanger which would separate this failure mode from the expensive reactor.

Part of the root causes that make the disconnection of the pyroreactor from the cowling a highly time-consuming operation is the way the hopper, drying bucket, pyrocoil and reactor are linked together. The O&M process for this includes removing difficult-to-access bolts that connect the assemblies together; then removing the hopper, drying bucket, and pyroreactor with a crane; and finally disconnecting the pyroreactor from the gasifier. The relationships of these assemblies can be seen in Figure 29. This operation is difficult and time intensive to perform and requires specialty tools such as a chain hoist or overhead crane.

Figure 29: Diagram of the Gasifier Component and Flows of Feedstock and Gases

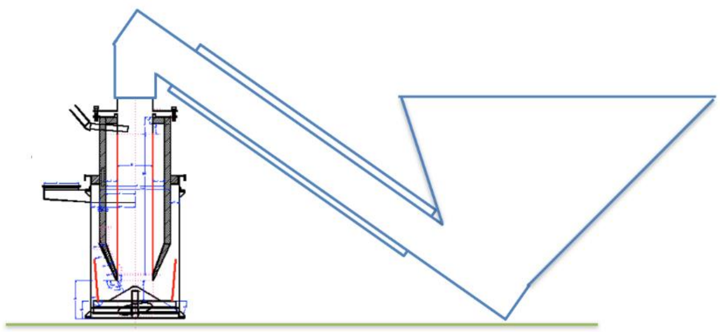


Source: All Power Labs, Inc.

These pyroreactor operation and maintenance issues relate directly with the fuel feed system. The hopper is a critical component for operating the gasifier, but the way it connects adds increased complexity in regard to replacing the pyroreactor. It is strongly recommended to remove this dependency to make the pyroreactor replacement activity more efficient.

Many advantages may derive from the adoption of an architecture similar to the one proposed in Figure 30 which would require minimal changes to the pyroreactor design. The drying bucket and pyrocoil could be replaced with a long-jacketed feeding auger and the existing hopper could be replaced with a much larger one. By independently mounting these, this proposed architecture simplifies the process for replacing the pyroreactor. An additional advantage would be having a lower refilling port height.

Figure 30: Alternative Hopper Feed System and Gasifier Layout



Source: All Power Labs, Inc.

The Power Pallet product roadmap documentation referenced for this bankability study outlines plans to introduce a new reactor architecture. The new reactor—called the swirl hearth—requires an external gas–air heat exchanger. This will partially solve the issues reported in this section. Nevertheless, it is important to suggest that the transition to the new architecture should be taken into consideration in order to enable other critical improvements such as the larger and lower fuel hopper, increased diameter fuel auger, and separate pyrolysis stage in the auger, all of which are expected to improve fuel handling.

Continuous Feeding: Issues and Hidden Costs

The PP30 continues to adopt the peculiar hopper–reactor–filtration–engine relationship that was originally designed for batch operations. Over the years, an add-on continuous feeding (C-feed) system was added to the system. It is a knife valve that opens and closes the hopper based on the fuel height in the hopper monitored using two paddle level sensors. There are two major issues with the current solution:

From the economical point of view the machine, even when it is sold with the C-feed system, it is not self-sustainable and still requires a conveyor belt or fuel auger to keep the PP30 fed. This is a hidden cost that is usually overlooked in a business plan, it is not standardized, and the cost may vary depending on the specific solution chosen by each customer. From the technical point of view, when a fuel storage and a feeding system is added, useless redundancies outlined below are created.

Primary hopper → fuel auger → PP30 hopper → reactor.

Consequently, the PP30 hopper can be removed from the high uptime use cases but kept available in the case that batch operations are needed.

Interviews with persons involved in the reliability program (ROPP) at APL highlighted that the last hopper design is more likely to create bridging and rat-hole events. Therefore, this is a further reason to remove the hopper. Additionally, some of the present design decisions are outmoded and based on legacy concerns, for example, the current design uses a stainless-steel hopper linked to an iron drying bucket.

In long runs, the drying bucket has shown preferential condensation of tars and moisture within the jacket. That space is incredibly hard to clean, while the use of iron increases the chance of rusting and deterioration of this component. The latest configuration the of drying bucket receives the air coming from the producer gas heat exchanger (PGHX) before going to the engine. This substantially reduces the risk of fouling however the thermal exchange between the air and the biomass is substantially lower than the previous configuration. Future versions of this part should be redesigned or removed.

The fuel auger that moves the fuel from the drying bucket to the reactor has a diameter of 75 mm (diameter of the bore hole between drying bucket and reactor). This is just barely sufficient to process the variety of fuels that the PP30 was designed for. The small auger relies on the heat of the drying bucket to partially prevent dangerous bridging phenomena. A larger auger will solve both the issues with fuels with higher tendency to create bridging (such as chipped vine prunings), while it frees the system from being dependent on the drying bucket.

Lastly: the current C-feed system was tested for a limited amount of time, most of it done on a hopper design different from the current one.

Therefore, for reliability improvement and cost reduction points of view, it is strongly suggested to discontinue the current hopper–drying bucket–12V fuel auger design. Focusing the design cycle on the reactor will help to improve its reliability. The market offers several off the shelf solutions from a fuel storage tank to the reactor.

Filtration: Issues and Hidden Costs

One of the primary variables affecting bankability of the PP30 has to do with the amount of reliability data and measured operation and maintenance costs, with gas filtration representing a key area of missing information. Nonetheless, calculations described in this work illustrate that O&M significantly impacts the possible profitability in any business plan. To change this, two issues must be addressed about filtration and operation and maintenance.

The filtration strategy has undergone multiple changes in recent years. For this reason, the technology is far from collecting enough running time to have reliable data about the real cost of operation and maintenance for the filtration system. In addition, despite many improvements, filtration still requires excessive effort from the operator in order to maintain optimal operating conditions. Outlined are additional observations and recommendations related to the gas filtration system.

The cyclone vessel is difficult to assemble and is too bulky. It is not provided with automatic char discharge, so it constantly emptying it to maintain operations. This maintenance activity alone is enough to discourage possible customers to purchase a PP30 for continuous use. Furthermore, this emptying operation can only be safely done after the reactor cools down; this means that the cyclone alone causes the longest down time during long runs. The cyclone must include an automatic char disposal system with maintenance interval of at least one week for high uptime applications.

The PGHX has the fundamental role of cool down and controlling gas temperature before going through the filter media. The combination of this PGHX with a bag house filtration solution has proven to be an effective solution for cleaning the gas before entering the engine with reduced risk of tar fouling. On the other hand, the current design of the PGHX produces a significant pressure drop if not constantly cleaned. For this reason, an automatic system based on sliding baffles was implemented. The cleaning mechanisms showed several issues, such as a high tendency to get stuck. The control switch requires a more robust design but despite this, the PGHX still requires heavy maintenance. It is strongly suggested to update the design of the PGHX to have a gas-in-the-tubes heat exchanger taking advantage of the well-established knowledge for cleaning heat exchangers.

The filter bags require more operational data as well as reliable regeneration mechanism.

Engine: Supply Chain and Performance Issues

For the PP30 release, All Power Labs decided to discontinue the use of 3.0L General Motors (GM) engines due to the end of the production of this engine decided by GM. Indian manufacturer Ashok Leyland (A-L) was chosen as the primary engine supplier.

Pro of this choice are:

- A-L is can make 3.8L engines with 12:1, 16:1, and 17:1 compression ratios. These ratios allow higher efficiency in the biomass-to-power conversion rate (GM engine compression ratios ranged from 8.3 to 10.5:1 depending on the piston type).
- A-L has larger displacement compared to the 3.0 L of the GM engine. This assures higher power production reaching 25kW, compared to 18kW with the GM.
- A-L has an existing joint venture with the company Advantek that supplies engine engine control units (ECUs). Advantek showed the capability to produce customized ECUs with specific working parameters optimized for producer gas use.
- A-L manufacturing capability goes beyond the engine supply. A-L is able to deliver the whole power generation sub-system composed of: engine, generator, wiring, engine CHP, case and soundproofing.

Unfortunately, these advantages need to be balanced looking at few critical cons:

- While higher efficiency is a desired feature, addressing planned and unplanned maintenance activities is more important to focus resources on to meeting market expectations.
- Preliminary tests on A-L engines showed lower tolerance to tar deposits compared to GM engines.
- A-L supply chain is not easily accessible around the world. This fact will increase difficulties in engine O&M when spare parts are needed. Not having easy access to engine spare parts will discourage customers from using this project.

The experience with GM showed that the Vortec series has low efficiency and old architectures (for example, ignition is still controlled by a distributor), on the other hand they have proven to be highly resistant to tar deposits and particulate matter. GM - PSI produces a 4.3 6 cyl engine with a retail price between USD$5,000–6,000. This engine is also well known internationally, so spare parts can be easily sourced, and maintenance costs are low. Therefore, it is suggested to adopt this engine for the PP30.

Automation and Remote Monitoring

This architecture is not suitable for long-term application and remote monitoring is not possible. In addition, Underwriters Laboratories (UL) and Conformité Européenne (CE) standards require a specific electronic arrangement for alarms and safety that work with a supplementary battery. A more robust PLC architecture will be adequate to control the gasifier. The PLC will be programmed using standard languages and will be able to easily add features. The PLC will be coupled with a human interface module (HMI) suitable for a smart monitoring of gasifier parameters. The PLC is able to record alarms and warnings, and it will be equipped with a remote monitoring expansion. The PLC can be supplied using a supplementary battery to satisfy standards requirements.

Safety

Gasification systems for power generation can be dangerous if not operated properly. Careless handling or unsafe design can lead to fires, explosions, and the release of poison[10]. For these reasons, safety should be considered during the designing and operation and maintenance of a system like the PP30.

The operation manual has not yet been updated for the PP30. For the purposes of this report, a previously written operations manual for the PP20 will be reviewed. This manual can currently be found on the APL website. While the operation manual will need to be updated for the PP30, the PP20 operation manual will be sufficient to comprehend the safety of the product.

Safety recommendations present in the manual refer mostly to the proper sealing of the power plant. This addresses risks of carbon monoxide leakage and the unplanned mixing of air in the gas stream. Carbon monoxide is one of the main constituents of producer gas, with a percentage usually between 20 and 30 percent. It is a combustible gas and therefore it is useful for the energy production, with a heating value of 12.5 MJ/Nm^3, but it is also a very toxic and dangerous gas. The PP30 operates under a vacuum, so in case of imperfect sealing in the machine, the producer gas will not be released in the environment. However, after shut-down and even after the machine has cooled down, the system will still be rich in carbon monoxide and therefore it is necessary to ensure adequate ventilation during maintenance operation, having a blower turned on to draw the gas away not approach the system with open flames or sparks.

Working under vacuum is an advantage for the carbon monoxide containment but enables unplanned mixing of air in the system. If air enters in a place where temperatures are higher than the auto-ignition point or in the presence of sparks or smoldering embers, it can cause internal fires or an expansion event. For this reason, it is critical to maintain good sealing of the machine before every start up.

The manual explains thoroughly these precautions and describes a leak testing procedure.

There are three other areas of safety that need to be included including:

- Hot surfaces
- Moving parts
- Electrical hazard

[10] FAO 1986. Wood gas as engine fuel. FAO Forestry Department, 1986. ISBN 92-5-102436-7

With the PP30, the engine is inside an enclosure that protects the operator from the hot parts of the engine and its moving parts. It also reduces the noise level of the engine below 80 db from any angle at 3-ft and below 72 db from any angle at 21 ft for the operator safety. Concerning the hot surfaces, most of these are covered with insulation, but it is insufficient for preventing injury or burns. According the product roadmap, the next version of the PP30 will include an enclosure around the gas making container as well, which will cover most of the remaining hot surfaces, including the gasifier, reactor, filter, and all the other hot parts except for the flare and the exhaust pipe. These two components will be put behind two metal shields to prevent the operator from getting a burn if touched accidentally.

Regarding the power electronics, the operation manual needs to state that it can be maintained or modified only by a qualified electrician.

Economic Analysis

A simplified economic analysis to assess the investment from a possible customer of the PP30 is necessary to understand if this machine could really be a source of income. Otherwise, it is not credible that it will be sold even if it is a renewable and carbon negative source of energy. Different scenarios were considered in the modelling of a financial worksheet to find the solutions that can make the PP30 an added value for a company, such as a project with varying possible costs and revenues.

Conclusion

The PP30 has the potential to be a profitable product, both for All Power Labs and for potential customers. However, some changes are mandatory to cut the operation and maintenance costs and increase the machine automation and reliability, otherwise the economic losses of an installation would overcome the benefits. Addressing these observations in combination with the low installation cost of the machine compared to similar products would result in huge potential for the market, especially in the case of renewable energy subsidies. Furthermore, biomass gasification systems have two main advantages over competing technologies: they are on-demand like natural gas cogeneration, while being renewable like solar and wind. Unlike the latter two, biomass gasification is not only carbon neutral, but carbon negative. Accounting for the entire life cycle of the plant material that became wood, in the gasification process not all the carbon dioxide the plant has converted is released back into the atmosphere during its energy exploitation, allowing for some amount to be sequestered directly into the soil as biochar. Furthermore, the forms of biochar from the PP30 system have a high recalcitrance index, ensuring a centuries-long half-life for the carbon product. This means that additive and multiplicative carbon sequestration effects can be realized in agricultural or forestry applications over generations.

CHAPTER 6: Technology/Knowledge/Market Transfer Activities

APL's primary product line is the Power Pallet and virtually all business, educational, and outreach activities have culminated in the release of this iteration of the technology. Internally and among the community of biomass gasification enthusiasts who followed APL, the release of the PP30 with CCHP was a significant event and several existing avenues were leveraged to broadcast this new iteration of the units as well as some unique opportunities that were explored on this project.

APL holds a monthly free open house to showcase their products and projects. These are informal events that anyone can attend to ask questions or listen to a brief lecture and then enjoy snacks baked in an oven powered by the Power Pallet gensets. The open house event that debuted the PP30 was by far the most active one in 2018, with approximately 50 attendees, including possible partners, old acquaintances, curious members of the community, and individuals related to policy making. Impromptu visitors and partners in other grant funding opportunities have also had the PP30 showcased and during the life of this project, multiple school trips visited APL's campus with both domestic and foreign secondary and tertiary students coming to learn about renewable energy and engineering. The PP30 was the showcase of all these informal community events as showed in Figure 31 and Figure 32.

Figure 31: Combined Cooling, Heating, and Power Power Pallet Open House June 2018

Source: All Power Labs, Inc.

Figure 32: Lecture at the Combined Cooling, Heating, and Power Power-Pallet Open House June 2018

Source: All Power Labs, Inc.

All Power Labs also communicates with the academic community and has a strong relationship with the Renewable and Appropriate Energy Laboratory (RAEL) at the University of California, Berkeley (Dan Kammen, its director, is on the APL Board of Directors). APL provides data to RAEL that they use with their interactions with key decision makers. This allows information to disseminate to a higher-value audience. Additionally, work performed by the Schatz Energy Research Center (SERC) can be incorporated into future publications. SERC researchers attempted to get a paper published during the life of this grant but could not accomplish this while balancing their other responsibilities.

A third venue for outreach was publicity generated by the Water Abundance XPRIZE and the decision to situate the PP30 in Malibu with APL's XPRIZE partners Skysource. Being co-recipients of this $1.5 million award gave All Power Labs international publicity and although the actual machine that was responsible for winning it was distinct from the CCHP unit that was funded in this opportunity, both are the outcome of CEC funding to scale up the PP30. The CCHP unit, installed at Skysource Ranch, Malibu, provided energy following the 2018 Woolsey wildfires and received national attention with a news segment from CBS featuring the microgrid at the ranch. APL has an Italian branch of the company composed of world experts in gasification associated with the University of Modena. Giulio Allesina of this subsidiary will present to the European academic community on the XPRIZE unit and its value in the biomass gasification space.

Figure 33: The Water Abundance XPRIZE Team

Source: XPRIZE (2018)

Lastly, disaster relief after the Woolsey fire, other state agencies received information about the technology. In particular, the California Department of Forestry and Fire Protection (CAL FIRE) was on hand to coordinate efforts with an in-the-field, first-hand demonstration of the this technology for possible future funding opportunities and scaling.

Figure 36 illustrates the CAL FIRE team that was stationed at the Skysource Ranch in Malibu which was the staging ground for combating the Woolsey fire.

Figure 34: CAL FIRE Team at Skysource Ranch post-Woolsey Fire

Source: All Power Labs, Inc.

Figures 35 and 36 show two groups are students who came to APL's headquarters in 2018 to review the technology. Figure 37 depicts the project team demonstrating the PP30 for industry members at the VERGE industry conference focusing on renewable energy in 2018.

Figure 35: Laguna Creek School (Elk Grove, California) Students Learning About the Combined Cooling, Heating, and Power Power-Pallet

Source: All Power Labs, Inc.

Figure 36: Students Visiting From France to Learn About the Combined Cooling, Heating, and Power Power-Pallet

Source: All Power Labs, Inc.

Figure 37: The PP30 Combined with Skysource Technology at VERGE Oakland

Source: All Power Labs, Inc.

CHAPTER 7: Conclusions/Recommendations

Conclusions

This project was largely successful at meeting the requirements of the funding agency and has led to further opportunities for scaling and reproducing this success in new use cases. The solicitation goal of 80 percent total system efficiency was ambitious, and the project team was able to meet that in a controlled environment. The second field-tested unit was able to realize practical offsets of natural gas and complemented the electrical and gas grids. The biggest roadblocks to complete success were non-technical challenges that hinder R&D and testing of new technologies. The permitting process was onerous, expensive, and protracted, representing the largest hurdle related to market penetration. Additionally, although the final CCHP Power Pallet prototypes use a relatively fuel-flexible and cost-effective gasifier, there remain challenges with fuel handling and processing that will make widespread adoption of biomass for energy challenging.

Next Steps

Funding for this project has allowed APL to create a safer, more efficient and powerful small-scale gasifier. Additionally, the company has been able to continue this work on a scaled-up commercial-sized version of the technology. Broadening the use cases for biomass is a critical component for reaching a tipping point of customers. The fact that the PP30 was deployed in a novel use case has given the project team insight into how it could be used for disaster relief and the development of modular PP-based machinery. The prospects of new use cases and new derivations of the technology will also ensure that CEC funds see maximal return on investment.

Although the initial intent for this project assumed a light industrial use case, shifting to a disaster relief residential setting still offset natural gas and grid electricity in a reproducible way. APL and Skysource are interested in pursuing further funding and development of microgrid solutions that will meet additional real-world applications. Additionally, the two companies have also discussed creating hybrid, multi-modal disaster relief machines that incorporate electricity production, heating and cooling, waste disposal, water generation, battery storage, grind connection, and possibly integration with further renewables. This broadens the horizons for thinking about resiliency for long-term, stable deployments that support the natural gas and utility grids as well as intermittent, short-term scenarios such as forestry clean-up work or relief after catastrophic disaster events.

Broadly speaking, the internal challenges in this project can be split into three categories: technology challenges, market readiness, and regulatory challenges. These intersecting factors form a useful framework for thinking about how future projects can be more successful and what the roadmap for small-scale gasifiers looks like.

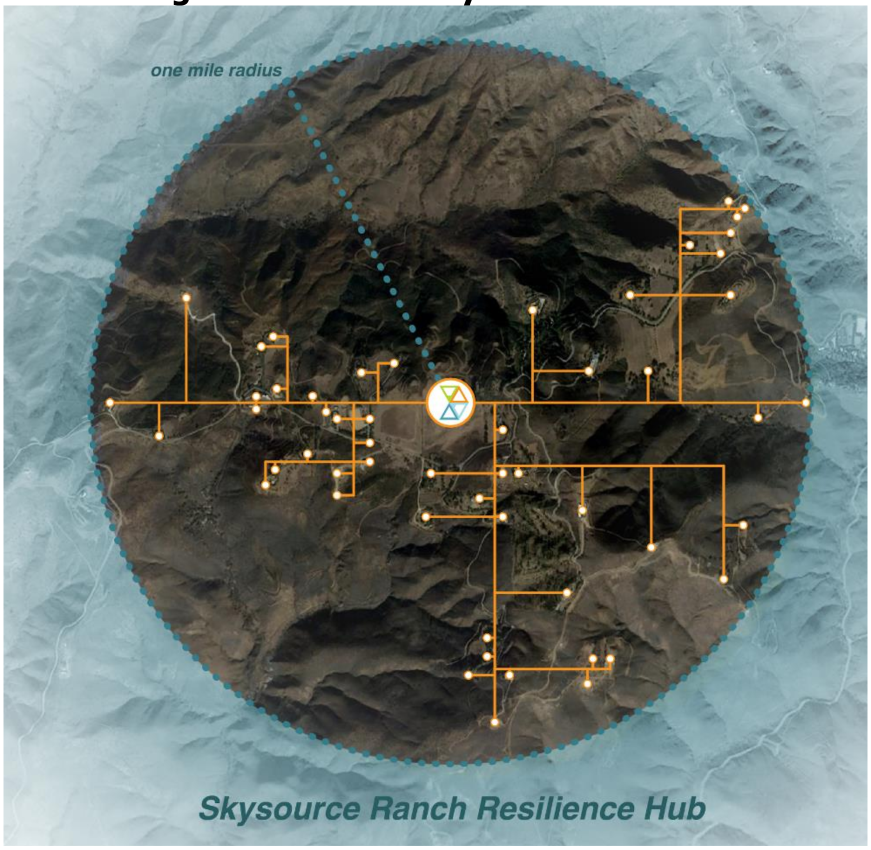
In terms of the technology, improving fuel flexibility (such as widening acceptable feedstocks, reducing pre-processing) is a fundamental challenge of all biomass processing solutions: there are theoretical limits to how effectively a machine can move solid fuels with different characteristics. APL has already made inroads in widening feedstocks and will continue to revise the gas-making architecture to this end.

Creating more mature and passive systems that have user-friendly interfaces and that can meet the expectations of contemporary customers (for example. improved automation and user-friendly interfaces) is another major requirement for large-scale adoption. Finally, finding solutions for reduced operation and maintenance will ultimately make biomass a more attractive option. In addition to the previous two challenges, finding ways to make the labor more economically viable will involve maximizing all value streams of the technology (such as using biochar or possibly participation in carbon credit schemes) and also having robust balance of systems to support the Power Pallet itself.

The final major hurdle in APL's domestic deployment projects has been external to the company and its technology: getting successful grid connection. By working on the Skysource site and leveraging that team's existing expertise with renewables, the APL project team was able to strategize new solutions for electrical interconnection, such as feeding a battery bank that itself feeds into the grid. This three-stage model (gasifiers to batteries to utility grid) can act as a buffer for varying electrical loads and has the potential to ease the interconnection approval process.

Figure 38 is a conceptual schematic diagram of the Resiliency Hub. Skysource aims for the development to support the surrounding area, with neighbors in this relatively inaccessible valley in Malibu able to share resources centered around an APL/Skysource combined unit. This model was put into practice by necessity during the Woolsey fire but would be far more efficient and effective if done deliberately as part of a mitigation and relief program with a relevant agency such as CAL FIRE.

Figure 38: Resiliency Hub Schematic



Source: Skysource

Recommendations

Having identified possible new use cases and customers, narrowing in on the next round of sustaining engineering improvements of the technology, and comprehending the external forces that complicate widespread deployment, the project team is confident that there is more work to be done that can provide additional benefits to California taxpayers from government funding agencies and ratepayers connected to the grid. Future funding can be used for improving the technology further in areas such as fuel flexibility and operation and maintenance cost reduction as well as further market development, deploying to use cases outside the scope of this funding opportunity, such as disaster relief and microgrid development. This would not only open the market to *more* customers but new types of customers such as government procurement contracts for CAL FIRE relief or even IOUs themselves that desire redundancy in the event of catastrophe that destroys grid infrastructure.

Additionally, it is vital to provide education about biomass processing and to lobby for institutional change that will better support and use this type of technology. The external pressures and inefficiencies of institutions made this work far more difficult, costly, and fraught than it needed to be. If an air quality permit for two of these units costs $10,000 and takes more than eight months to be issued when it is prepared by an engineering firm, that will make it impossible for market adoption. Existing entities that comprehend the need for biomass gasification as an energy solution will have to help educate decision makers at relevant agencies to reduce the overhead required for even the simplest deployments. For instance, there is not yet a category under Underwriters Laboratories (UL) for gasification technologies. There needs to be mechanisms to enable state-funded R&D and short-term experimental projects that can spur further innovation in this space. Comparing biomass to solar, it took a generation of engineers, technicians, investors, and companies pushing for adoption before risk-averse regulatory agencies, governments, and utilities accepted it; today, it is such a known entity that there is no controversy in permitting a solar project.

Ultimately, the internal and external problems can be ameliorated by further acceptance of biomass. As with solar, there must be a critical mass of first adopters that leads to a market tipping point for widespread adoption. Additionally, unlike solar or geothermal, the underlying science of combustion and real-world applications of biomass gasifiers for almost a century provide a rich knowledge base that can allow this renewable technology to rapidly scale and complement other renewables, fossil fuels, and nuclear power. There is no single electricity production or heating and cooling silver bullet that is appropriate for all use cases, so to meet existing needs—to say nothing of what the energy landscape will look like in 20, 50, or 100 years—it is vital to invest in further research, public outreach, and business market activities to encourage the adoption of biomass processing to phase out dependence on limited fossil fuels and natural gas.

CHAPTER 8: Benefits to Ratepayers

Importance and Benefits to Ratepayers

Biomass gasification power generation provides ratepayers with a new energy option, one that is on demand and renewable, but not weather dependent. This project, built entirely of technology designed and manufactured in California, demonstrates a cost-effective way to address the light industrial and commercial market's dependencies for natural gas powered CCHP equipment, as well as a myriad of issues associated with climate change, including drought, wildfires, and the need for more renewable energy. This project illustrates the viability of mobile gasification systems to fit into this market while avoiding the use natural gas while sourcing the fuel from fire remediation efforts, as well as demonstrate how this technology also provides the potential for significant reduction of harmful emissions compared to the use of grid electricity and natural gas fueled equipment.

In addition, the carbon sequestration potential of the biochar is particularly groundbreaking because very few technologies exist that can essentially sequester atmospheric carbon, which is what the CCHP Power Pallet can do when paired with the natural forest ecosystem—an innovative and groundbreaking "BECCS" (bio-energy with carbon capture and storage) technology. When introduced back into California's soils results in a carbon negative energy solution, something that separates this technology from almost any other energy option. The biochar produced from this energy technology enables the sequestration of carbon that would otherwise have been released into the atmosphere. Furthermore, by combining the production of electricity, heat, and cooling with the production of the biochar byproduct, the climate impact increases by orders of magnitude.

Energy Offset and Economic Value

The CCHP system reduced energy demand in California through four mechanisms:

1. Electricity Offset – Electricity demand is directly offset by electricity generation from the CCHP Power Pallet.
2. Cooling Offset – Electricity demand is offset by the cooling service provided by the CCHP Power Pallet that would otherwise come from electric-powered air conditioners.
3. Heating Offset – Natural gas demand for heating is directly offset by the heating service provided by the CCHP Power Pallet that would otherwise come from natural gas-fired boilers.
4. Natural Gas Electricity Offset – Natural gas consumption in utility-scale power plants is reduced by generation of electricity from the CCHP Power Pallet system. A portion of the electricity demand provided by the CCHP Power Pallet offsets natural gas fired power plants in the state.

The reduced energy demand from each mechanism is summarized in for a single PP30 CCHP unit. The assumptions and calculation methods are described in detail further and Table 25 shows the energy demand reduction using a CCHP PP unit.

Table 25: Reduced Annual Energy Demand Resulting from One PP30 Combined Cooling, Heating, and Power Unit

Mechanism	Energy Offset	Economic Value	Avoided Emissions
1. Electricity Offset	158 MWh/yr	$28,130/yr	38 tonnes CO_2e/yr
2. Cooling Offset	22.2 MWh/yr	$3,950/yr	5 tonnes CO_2e/yr
3. Heating Offset	7,100 therm/yr	$7,670/yr	38 tonnes CO_2e/yr
Natural Gas Electricity Offset	6,100 therm/yr	$2,630/yr	0 [a]

[a] Avoided emissions from natural gas power plants is captured uner mechanism 1.

Source: All Power Labs, Inc.

1. Electricity Offset

A CCHP Power Pallet will offset 158 MWh of statewide electricity per year, equivalent to an average annual load of 18 kW. This is calculated based on the 25-kW nameplate capacity operating 24 hours per day at the measured electricity capacity factor of 72 percent.

The economic value of the offset electric energy is based on the average California residential electricity price of $0.1776 per kWh for investor-owned utilities (IOUs) in 2016, as suggested by the CEC in Attachment 13 of this grant funding opportunity[11]. With this value, the CCHP system will offset $28,130 per year of residential electricity at the site host.

2. Cooling Offset

The CCHP system provides 9 kW of cooling from the adsorption chiller for space conditioning when it is operating. The adsorption chiller operates at an 83 percent capacity factor, which includes system downtime for startup, shutdown, and maintenance. The adsorption chiller is assumed to offset a conventional air conditioner using a compression cycle with a coefficient of performance of 2.9 (equivalent to an energy efficiency ratio (EER) of 10). The conventional air conditioner would use 22.2 MWh per year, which is offset by the CCHP.

The economic value of the offset electric energy is based on the average California residential electricity price of $0.1776 per kWh for investor-owned utilities (IOUs) in 2016, as suggested by the CEC in Attachment 13 of this grant funding opportunity. With this value, the CCHP system will offset $3,950 per year of residential electricity at the site host.

3. Heating Offset

The CCHP system provides 5,000 therms of heat per year for onsite heating loads. Heat is recovered at the at an 83 percent capacity factor, which includes downtime for startup, shutdown, and maintenance. The heat from the CCHP is assumed to offset a conventional natural gas furnace with an 80 percent annual fuel utilization efficiency (AFUE). The conventional furnace would consume 7,100 therms to provide the same quantity of heat as the CCHP system.

The economic value of the offset natural gas consumption is based on the average California residential natural gas price of $10.80 per MMBTU, as suggested by the CEC in Attachment 13

[11] [CEC] California Energy Commission. (2016). Attachment-13 Guidelines for Cost and Benefit Calculations. GFO 16-503.

of this grant funding opportunity. With this value, the CCHP system will offset $7,670 per year of natural gas at the site host.

4. Natural Gas Electricity Offset

The electricity provided by the CCHP system offsets electricity that would otherwise be provided by California's average electricity grid mixture. The most recent data from the CEC indicates that natural gas electricity generation constitutes 43.4 percent of California's grid mix[12] with an average heat rate of 7,809 BTU/kWh[13] (equivalent to an efficiency of 43.7 percent). Using these values, the electricity produced by the CCHP system will offset 7,100 therms of natural gas per year that would have otherwise been consumed for utility-scale power production.

The economic value of the offset natural gas consumption is based on the average burner tip price of natural gas for California IOUs. This average burner tip price for the California IOUs is $4.29 per MMBTU in 2019 as modeled by the CEC in the mid-demand scenario[14]. With this value, the CCHP system will offset $2,630 per year of natural gas that would have been used to generate a fraction of the offset electricity.

Greenhouse Gas Emissions Offset

Emissions reductions from the CCHP system stem from avoided emissions from offsetting other forms of energy consumption such as natural gas and electricity. Overall, one CCHP unit will avoid 81 metric tonnes (89 tons US) of CO2e emissions in California. The carbon intensity of electricity used in California is 0.24 tonne (.26 tones) carbon dioxide equivalent per MWh_e[15]. For the 180 MWh of electricity offset from the generation and avoided air conditioning load provided by the CCHP system, this equates to 43 tonnes (47.4 tons) of avoided CO2e per year per CCHP unit. By offsetting natural gas use for heating, which has a carbon intensity of 5.3 kg CO2 per therm[16], the CCHP system avoids 38 tonnes of carbon dioxide emissions.

The carbon dioxide emissions resulting from using biomass would occur in similar magnitudes whether or not it used in the biomass gasifier system. When the biomass is used in the gasifier, the carbon contained in the feedstock is either emitted as carbon dioxide in the

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[12] [CEC] California Energy Commission. (2017). Total System Electric Generation. Retrieved 10 May 2019 from https://www.energy.ca.gov/almanac/electricity_data/total_system_power.html

[13] Nyberg, Michael. (2018). Thermal Efficiency of Natural Gas-Fired Generation in California: 2018 Update. California Energy Commission. CEC-200-2018-011. Retrieved 10 May 2019 from http://efiling.energy.ca.gov/getdocument.aspx?tn=225588

[14] [CEC] California Energy Commission. (2019). 2019 IEPR Forecast – Preliminary Model in Microsoft Excel. Retrieved 10 May 2019 from https://www.energy.ca.gov/assessments/ng_burner_tip.html

[15] [CARB] California Air Resources Board. (2018). California Greenhouse Gas Emissions from 2000 – 2016: Trends of emissions and other indicators. Retrieved 10 May 2019 from https://www.arb.ca.gov/cc/inventory/pubs/reports/2000_2016/ghg_inventory_trends_00-16.pdf

[16] {EIA] U.S. Energy Information Agency. (2016). Carbon Dioxide Emissions Coefficients. Retrieved 10 May 2019 from https://www.eia.gov/environment/emissions/co2_vol_mass.php

exhaust stack[17] or sequestered as biochar following the reaction. If the biomass were not used in the gasifier, it would be control burned at a forestry site, left to decay naturally, or consumed in a wildfire. All of these counterfactual pathways result in the same fate of the original biomass carbon: it is either emitted as carbon dioxide or sequestered as a recalcitrant form of carbon in the soil. While pile burns and wildfire emissions have notably higher criteria pollutant emission factors than a controlled gasification process, the general carbon balance will be nearly identical, where the majority of carbon is emitted to the air as carbon dioxide with a small fraction (2–10 percent) remaining in a stable, solid form. For this reason, the direct emissions of greenhouse gases from gasification of biomass are ignored because they are the same in the CCHP use case compared to the business-as-usual reference case (not using the biomass for energy).

When deployed at scale, the CCHP Power Pallet will also result in job creation across multiple sectors, including manufacturing, feedstock supply chain (harvesting, processing, transportation), equipment operation, construction, and project development. Additional benefits Commercial-scale biomass power generation systems offer California ratepayers includes:

- Greater Reliability, Clean Energy: On-demand, non-weather dependent, renewable energy can be used to provide local capacity in hard to serve areas, while reducing peak demand. This dispatchable power can be moved to the grid locations where it can promote the greatest reliability benefits and generate power at times of peak loading.
- Energy security: The CCHP Power Pallet develops a native Californian renewable resource and reduces the need for electricity imports from other states that generate power using coal.
- Lower Cost: The CCHP Power Pallet's reduction of wildfire risk lowers the costs associated with wildfire damage to ratepayer-supported infrastructure, such as transmission lines and remote substations while producing groundbreakingly-cheap bioenergy to help mitigate climate change. This is especially important considering that on average, California ratepayers pay 154 percent of the national average for electricity, as of October 2018.[18]
- Increased Safety: By creating a market demand for forestry biomass waste, the CCHP Power Pallet will increase safety by creating an economic driver to support forest thinning, thus reducing the risk of catastrophic wildfire and damage/destruction of CA's IOU owned transmission lines.
- Public health: The CCHP Power Pallet substantially lowers criteria pollutant emissions and reduces wildfire danger, with its associated adverse public health impacts.
- Economic development: The CCHP Power Pallet's creation of demand for forest biomass waste derived from California's unprecedented tree die-off economically support

[17] Carbon exits the exhaust stack in other forms (e.g. carbon monoxide and unburned hydrocarbons), but their quantities are several orders of magnitude less than the carbon dioxide emissions (5-50 ppm versus 15-20%) and are therefore not consequential to this analysis.

[18] "Electric Power Monthly" from the U. S. Energy Information Administration https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_5_6_a, accessed January 3, 2019

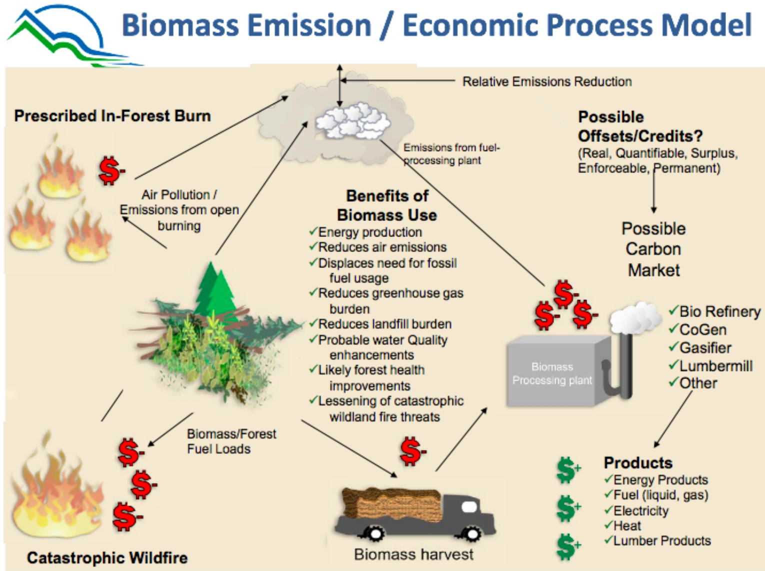
thinning operations and secondary markets such as mills. In addition, the CCHP Power Pallet project creates American manufacturing jobs.

- Environmental benefits: The broader societal impacts extend beyond pure business concern into ecological preservation and innovation as well. The thinning operations supported by the CCHP Power Pallet not only improve forest health and mitigate wildfire danger, but they have also been shown to provide watershed benefits and increase the availability of water for rivers and streams.
- Advances state policy goals on Climate Change: The CCHP Power Pallet is not only a power generation technology but has the co-product of biochar that can be used as a highly valuable and effective soil amendment. Its potential in areas such as increased soil fertility, removal of toxins from food, and remediation of fallow and degraded land can provide a huge benefit to American agriculture as well as simply providing a healthier environment for all Californians. Biomass gasification results in net carbon negative emissions, through the sequestration of carbon from the production of biochar.

The benefits of using forest residues from high fire risk regions with the CCHP Power Pallet are very intertwined where a single activity such as forest thinning and removal of high fire risk forest biomass directly impacts the health and safety of California residences and the reliability of utilities. Utilization of biomass materials make forest fires less common and less extreme, producing less harmful emissions as well as reduced damage to property and utilities. By using this biomass for forest products and the production of distributed renewable energy, economic benefits are created to support these activities and produce jobs. And with the added benefit of biochar production, can result in a carbon negative outcome, contributing directly to reversing climate change, not just slowing it down. Some of these benefits are illustrated in this figure developed by the Placer County Air Quality District.[19] Figure 39 depicts a biomass economics model developed by Placer County Air Pollution Control Districts (APCD).

[19] From the presentation "Air Quality Issues and Opportunities – Placer County Forest Resource Sustainability Initiatives" by Tom Christofk, Air Pollution Control Officer, Placer County Air Pollution at the Control District Community Scale Bioenergy Conference (December 14, 2012).

Figure 39: Biomass Emissions / Economic Process Model



Source: Placer County APCD

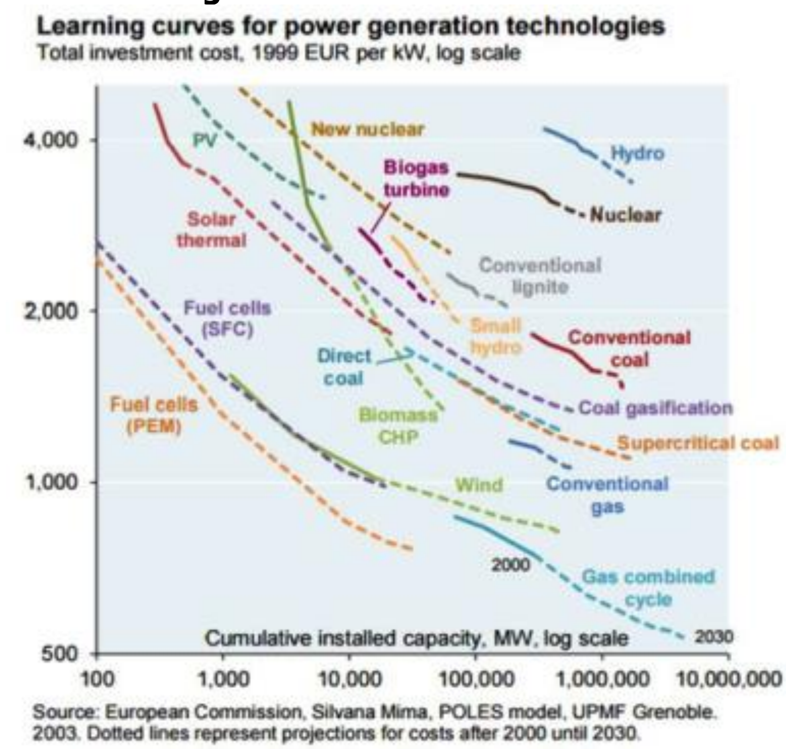
There are different use cases in which the CCHP Power Pallet can be applied to where some have a higher value proposition and provide more benefit than others. To maximize the benefits of the CCHP Power Pallet, the best use case intersects with the agriculture, forestry, and the urban green waste management sectors utilizing waste streams rather than virgin material. Extending on this, by partnering with a company that already has a biomass supply chain which they are able to produce useful products from, and as a result produces a biomass waste stream suitable for the CCHP Power Pallet, the benefits are compounded. The facilities of these companies often already have much of the biomass processing equipment that would be required for a CCHP Power Pallet project. This in return minimizes the capital investment to bring a CCHP Power Pallet project online, and often have the loads and the interconnection that are well suited for the CCHP Power Pallet scale. This significantly reduces the barrier of entry to initiate a CCHP Power Pallet project. Such a project is the most cost optimized for bringing a project online with the primary expense being the CCHP Power Pallet equipment itself at an estimated price of $73,050, plus the cost of the adsorption cooler, permitting, interconnection and integration which are variable depending on the project and jurisdiction.

When deployed at scale, the model indicates significant benefits across the triple bottom line, including production of renewable energy, emissions reduction, job creation, carbon sequestration, and managed forest land, all at an LCOE that is very competitive with alternative energy sources. The climate impact is especially compelling and worth highlighting. During this unique and unprecedented time of climate change, the combination or renewable energy production, GHG reductions, and biochar production enables this technology to be a carbon negative solution. This separates the value proposition of this technology from the alternatives converting the dependency on natural gas into a climate mitigation solution.

While this project did experience significant regulatory challenges, it sets the groundwork for future studies and projects using the CCHP Power Pallet. This technology continues to represent a value proposition that benefits California's triple bottom line. Since the value proposition for this technology addresses so many benefits to California, it is critical to continue developing the CCHP Power Pallet so that it becomes a viable technology and energy option that can be used across California, both in areas needing more reliable natural gas alternatives, but also areas hardest hit by climate change.

As illustrated in the figure 40,[20] biomass energy, in comparison to other power generation technologies has experienced a relatively rapid learning curve. Even though biomass energy is considered a new technology, compared to other power generation technologies, minimal investment will help continue to mature this technology, deploy at scale, and reap the multitude of benefits this technology can contribute to California.

Figure 40: Learning Curve for Power Generation Technologies



Source: European Commission

[20] "Deep de-carbonisation of electricity grids" by Peter Lang (November 29, 2015), available at https://judithcurry.com/2015/11/29/deep-de-carbonisation-of-electricity-grids/ and accessed on February 2, 2019

LIST OF ACRONYMS

Term	Definition
AAC	Atmospheric Analysis & Consulting, Inc.
AB	Assembly Bill: legislation from the California legislature
APL	All Power Labs, Inc.
BAAQMD	Bay Area Air Quality Management District
BACT	Best Available Control Technology: industry best practices within a given field or technology
BDT	Bone Dry Tons: standard measure for weighing biomass without including water
BioMAT	Bioenergy Market Adjusting Tariff: a feed-in tariff scheme in California for biomass-produced energy
CEC	California Energy Commission
CHP	Combined Heat and Power
CPUC	California Public Utilities Commission: regulatory body overseeing utilities
DBH	Diameter at Breast Height
DFx	Design for x
DOE	Department of Energy: federal agency for energy policy and funding priorities
DVT	Design Validation Test
ECU	Engine Control Unit
EPA	Environmental Protection Agency: federal agency for ecological concerns
EPIC	Electric Program Investment Charge
EVT	Engineering Validation Test
FIT	Feed in Tariff: an economic arrangement where a utility pays for on-demand energy from outside sources
GHG	Greenhouse Gas
GWRY	Green Waste Recycle Yard
HAP	Hazardous Air Pollutant
IOU	Investor Owned Utilities
LCOE	Levelized Cost of Energy: a measure of lifetime costs divided by energy production

Term	Definition
KWe	Kilowatt Electric
NEM	Net Energy Metering: an economic arrangement where a utility gives credit for energy produced by outside sources
OLTT	Online Tar Test: a method for measuring tar gases given off in gasification
PCU	Process Control Unit: electronic device for monitoring and automation of plant processes
PG&E	Pacific Gas & Electric: an IOU concentrated in Northern California
PLC	Programmable Logic Controller: industrial computer adapted for the control of manufacturing processes
PM	Particulate Matter: microscopic liquid or solid pieces suspended in gas
PP	Power Pallet
ROC	Reactive Organic Compounds: a subset of volatile organic compounds
ROI	Return on Investment: ratio between the net profit and cost of investment
SAM	Serviceable Available Market: part of the total addressable market (TAM) that can actually be reached
SD	Standing Dead (trees): trees which are no longer living but have yet to be felled, a class of dead forestry mass
TAC	Technical Advisory Committee
Triple bottom line	Accounting framework that takes into account environmental, financial, and social goals.
TRL	Technology Readiness Level: a measure of maturity for a new technology
VFD	Variable-Frequency Drive: adjustable-speed drive used to control AC motor speed and torque
VOC	Volatile Organic Compound: a large class of organic materials, some of which are toxic
WTE	Waste-to-energy: process of energy recovery from agricultural, forestry, industrial, or municipal waste

APPENDIX A: Additional Engineering Validation Testing Data

Data Collection Devices

Data were collected with the following equipment

Instrument

1. Badger meter 1: Series 380 BTU impeller 1.5 inch (customer fluid flow and temperature)
2. Badger meters 2 and 3: Series 380 BTU impeller 1 inch (internal coolant flow and Temperatures)
3. Optima Pallet Scale: OP-900B-02 (fuel consumption)
4. Shark Power Meter: Shark 100 (AdCo electric power consumption)
5. PP30 DSE (Net Power Pallet electric output)
6. Mengo data acquisition system (data collection)

The Badger meters were used to measure temperature and flow rate as illustrated in Figure A.1. Each meter measured two different temperatures across a heat exchanger and one liquid flow rate.

The optima pallet scale was used to measure fuel consumption in real time. The pallet scale was installed under the gas making skid.

The shark power meter was used to measure real time electric power from the grid consumed by the AdCo.

The PP30 DSE was used to measure the real time electric power export to the grid.

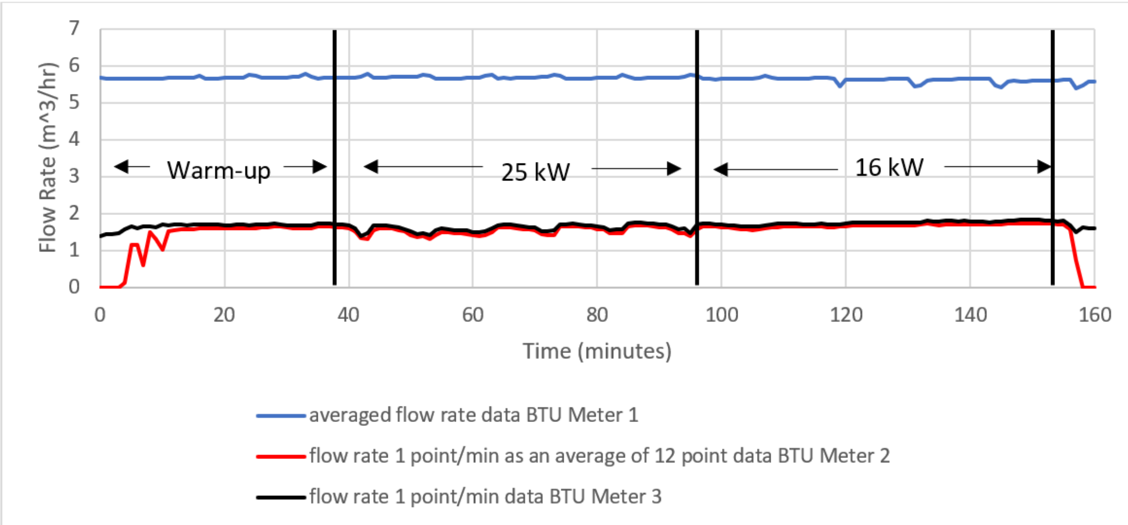
The mengo data acquisition system was used to collect and report all data in real time.

Analysis

Chapter 2 illustrates the process flow diagram (PFD) REV 03 for the engine cooling and CHP package on the PPv1.5. With instrumentation for the PIR-16-010 grant added.

Figure A-1 is a plot of the engine coolant and customer flow rate with respect to time.

Figure A-1: Engine Coolant and Customer Flow Rate

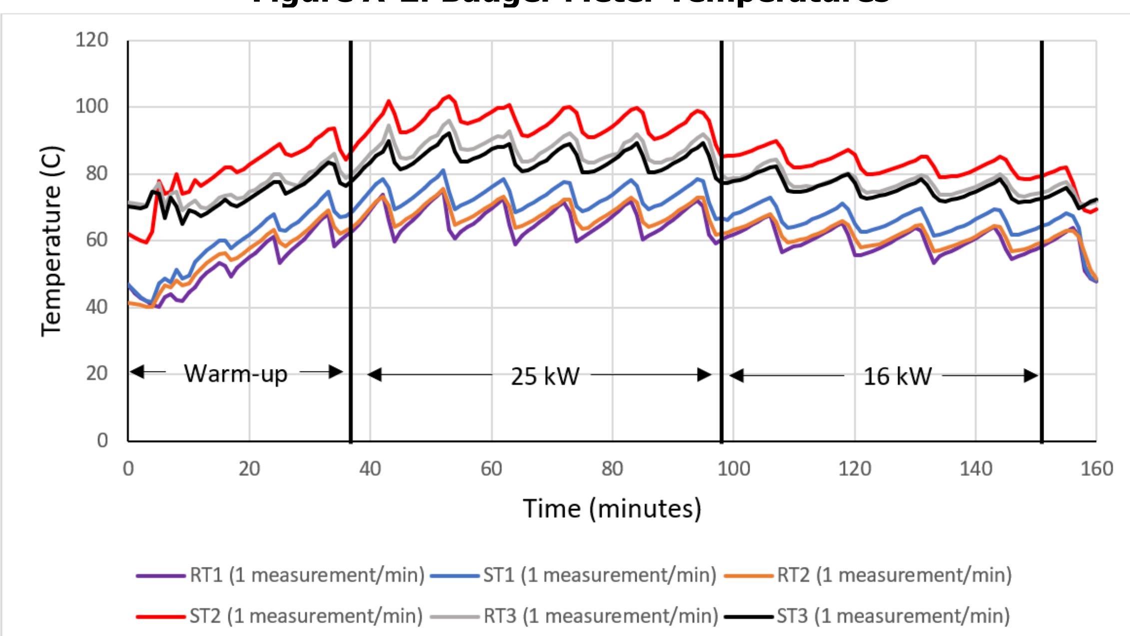


Source: All Power Labs, Inc.

The coolant flow rate measurements were taken every 1/12 of a minute by Badger meters 1 and 2. In order to report numbers every minute, 12 flow rate measurements were averaged and reported for each minute as shown in Figure A-1. Badger meter 3 collected measurements every minute and are directly shown in Figure A-1.

Figure A-2 is a plot of the different badger meter temperatures with the relative positions illustrated in Figure A-1.

Figure A-2: Badger Meter Temperatures



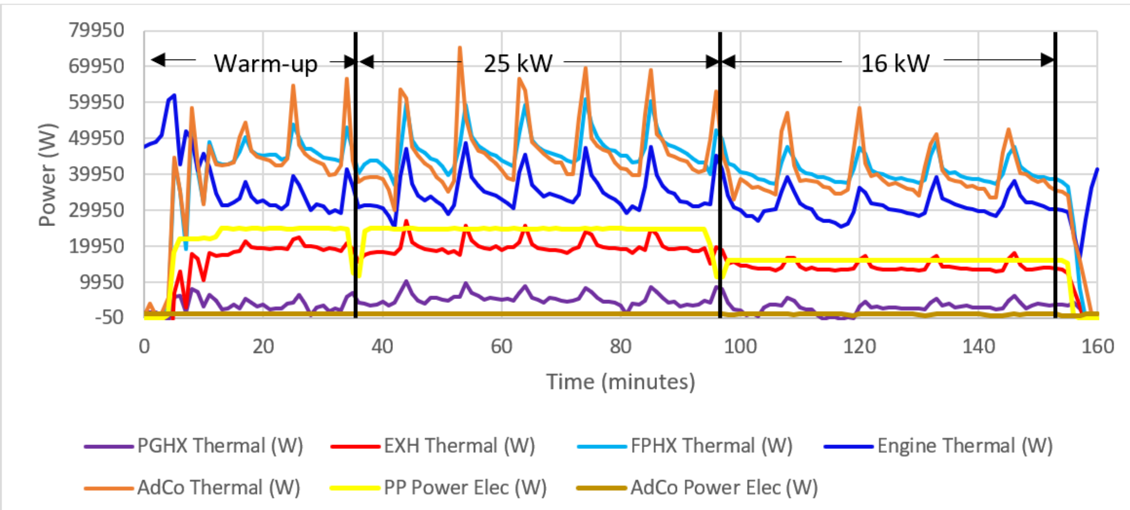
Source: All Power Labs, Inc.

Temperature measurements were collected every minute by badger meters 1, 2, and 3 for each temperature and directly shown in Figure A-2. The following probes Surrounded each heat exchanger in order of upstream to downstream prob.

1. Engine: RT3 and RT2
2. PG HX: ST3 and RT3
3. EX HX: ST2 and ST3
4. FP HX: RT2 and ST2
5. AdCo: ST1 and RT1

Figure A-3 is a plot of the thermal and electric power.

Figure A-3: Thermal and Electric Power



Source: All Power Labs, Inc.

Thermal power for the engine, PG HX, EX HX, FP HX, and AdCo were calculated by

$$P_{th} = \frac{dV}{dt} \rho C_p \, \Delta T$$

Where dV/dt is the volume flow rate, ρ is the density of water at 80 C, $C_p$is the specific heat of water at 80 C, and $\Delta T$is the difference in temperature of the output and the input of the heat exchanger.

The electric power measurements where collected every 10 second for both the power pallet and the AdCo electric consumption. These measurements were averaged every minute and reported in Figure A-3.

Table A-1: Average Thermal and Electrical Power @ 25 kW

AdCo Power	PP Power	PG HX Thermal Average	EX HX Thermal Average	FP HX Thermal Average	Engine Thermal Average	Customer Thermal Average
-1195.0	24902.2	-5397.5	19975.6	-46917.8	34940.1	46367.1

All units in watts.

Source: All Power Labs, Inc.

Table A.1 gives the average power for each thermal heat exchanger and electrical power for the power pallet and AdCo.

The power was averaged over the one hour testing period shown in Figure A-3.

The negative signs for the PG HX and FP HX indicate that thermal energy is leaving the coolant loop. The negative sign for the AdCo power indicates that electric power was consumed.

Table A-2: Average Thermal and Electrical Power @ 16 kW

AdCo Power	PP Power	PG HX Thermal Average	EX HX Thermal Average	FP HX Thermal Average	Engine Thermal Average	AdCo Thermal Average
-1126.6	16145.6	-3015.2	14289.0	-40422.0	31088.0	39442.1

All units in watts.

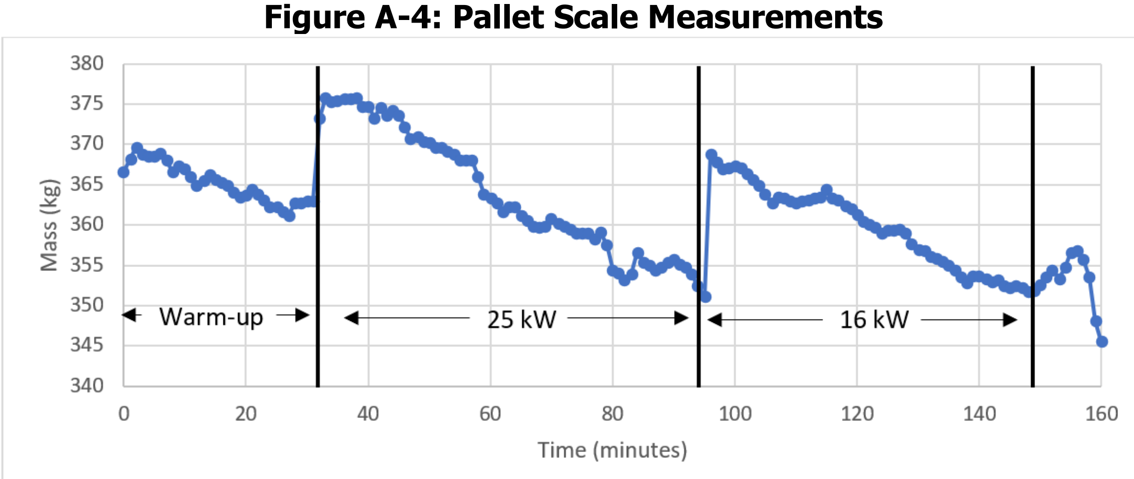
Source: All Power Labs, Inc.

Table A-2 gives the average power for each thermal heat exchanger and electrical power for the power pallet and AdCo.

The power was averaged over the one hour testing period shown in Figure A-3.

Figure A-4 provides pallet scale measurements of change in mass over time.

Figure A-4: Pallet Scale Measurements



Source: All Power Labs, Inc.

The pallet scale measured mass approximately 12.5 times every second. Each point shown in Figure A-4 represents an average of 750 points.

The change in mass was found by measuring the difference between the stable high value after refueling and the stable low value just before refueling. During the fueling process the operator may add some temporary additional mass or subtract mass for a short time in order to refuel the machine. It is for this reason that the maximum and minimum were not used but rather the steady maximum and minimum.

Heat fraction and efficiency results from the best scenario.

Table A-3: Best Scenario Heat Fraction Results

Fraction of energy contribution with respect to Producer Gas	PG HX	EX HX	FP HX	Engine HX	AdCo
@ 25 kW	-0.0857	0.317	-0.745	0.555	0.736
@ 16 kW	-0.0718	0.340	-0.963	0.740	0.939

Source: All Power Labs, Inc.

Table A.4: Best Scenario Efficiency Results

Efficiencies with respect to Producer Gas	Electrical and Metered Thermal Energy	Overall Efficiency Elec+AdCo	Engine Efficiency	Genset Efficiency
@ 25 kW	70074.3	111%	0.430	0.395
@ 16 kW	54461.1	130%	0.418	0.385

Source: All Power Labs, Inc.

Heat fraction and efficiency results from the intermediate scenario

Table A-5: Intermediate Scenario Heat Fraction Results

Fraction of energy contribution with respect to Producer Gas	PG HX	EX HX	FP HX	Engine HX	AdCo
@ 25 kW	-0.0558	0.207	-0.485	0.361	0.479
@ 16 kW	-0.0451	0.214	-0.606	0.466	0.591

Source: All Power Labs, Inc.

Table A-6: Intermediate Efficiency Results

Efficiencies with respect to Producer Gas	Electrical and Metered Thermal Energy	Overall Efficiency Elec+AdCo	Engine Efficiency	Genset Efficiency
@ 25 kW	70074.3	72%	0.280	0.257
@ 16 kW	54461.1	82%	0.263	0.242

Source: All Power Labs, Inc.

Results from the worst scenario

Table A-7: Worst Scenario Heat Fraction Results

Fraction of energy contribution with respect to Producer Gas	PG HX	EX HX	FP HX	Engine HX	AdCo
@ 25 kW	-0.0418	0.155	-0.363	0.270	0.359
@ 16 kW	-0.0328	0.156	-0.440	0.339	0.430

Source: All Power Labs, Inc.

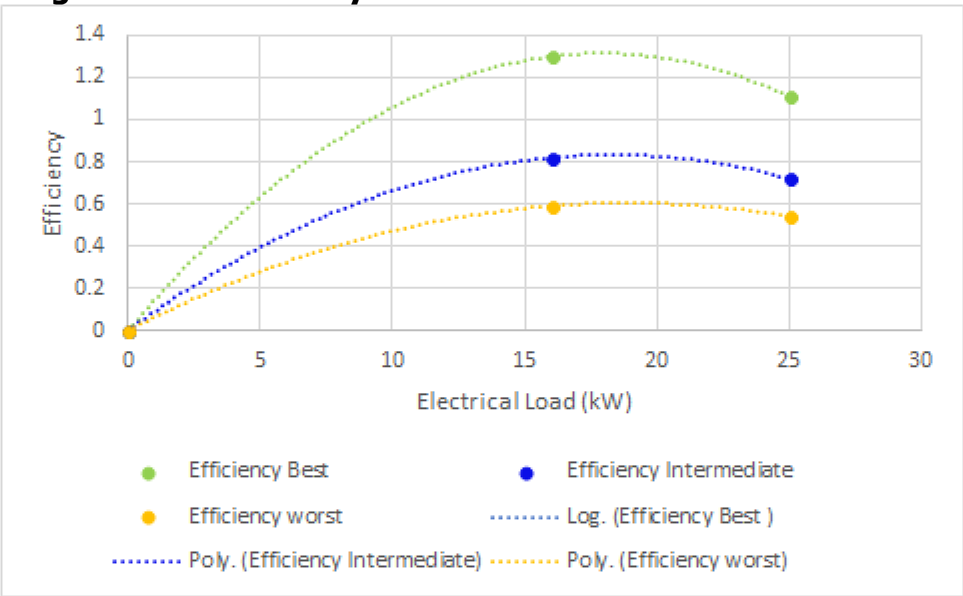
Table A-8: Worst Scenario Efficiency Results

Efficiencies with respect to Producer Gas	Electrical and Metered Thermal Energy	Overall Efficiency Elec+AdCo	Engine Efficiency	Genset Efficiency
@ 25 kW	70074.3	54%	0.210	0.193
@ 16 kW	54461.1	59%	0.191	0.176

Source: All Power Labs, Inc.

Figure A-5 is a plot of efficiency vs electrical load for each scenario.

Figure A-5: Efficiency vs Electrical Load for Each Scenario



Source: All Power Labs, Inc.

As discussed in the CHP module discussion section, the amount of variability between the three scenarios is significant leading to efficiencies below 60 percent and above 100 percent.

The heat fraction of the engine CHP module was determined by

$$E_{cool} = \frac{P_{th,ENG}}{P_{PG}}$$

Where $P_{th,ENG}$ is the thermal power produced by the engine and P_{PG} is the calculated heat rate of the producer gas.

The heat fraction of the engine exhaust CHP module was determined by

$$E_{EHX} = \frac{P_{th,EXH}}{P_{PG}}$$

where $P_{th,EXH}$ is the thermal energy contribution from the exhaust heat exchanger to the engine coolant loop.

The heat fraction of the producer gas CHP module was determined by

$$E_{PG} = \frac{P_{th,PG}}{P_{PG}}$$

where $P_{th,PG}$ is the thermal energy contribution from the PG heat exchanger to the engine coolant loop.

The heat fraction consumed by the AdCo module was determined by

$$E_{AdCo} = \frac{P_{th,AdCo}}{P_{PG}}$$

Where $P_{th,AdCo}$ is the thermal power output of the customer loop and assumed to be consumed by the adsorption cooling module.

The study system efficiency was determined by

$\eta_{calc} = \frac{P_{AdCo,elec}+P_{elec}+P_{th,ENG}+P_{th,EXHX}+P_{th,PG}}{P_{PG}} = \frac{P_{th,AdCo}}{P_{PG}}$.

where $P_{AdCo,elec}$ is the electric power consumed by the AdCo.

The genset engine efficiency was determined by

$$\eta_{genset,elec} = \frac{P_{elec}}{P_{PG}}$$

Where $P_{elec}$is the electric power produced by the genset and $P_{PG}$is the calculated heat rate of the producer gas.

The AL engine efficiency was determined by

$\eta_{AL,elec} = \eta_{genset,elec}/\eta_{gen,Mar}$.

Determining the COP from Charts Provided by Fahrenheit

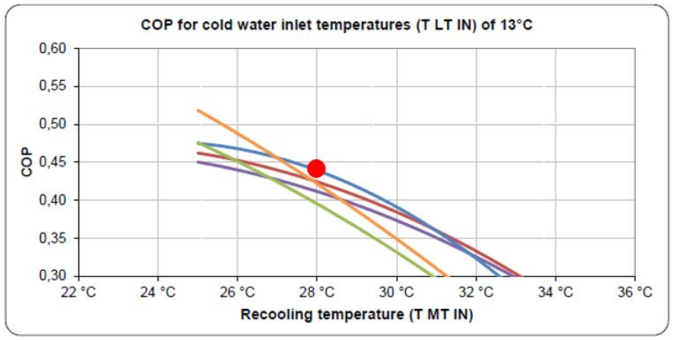
Table A-9 provides information collected on June 22, 2018 to determine the COP using charts provided by Fahrenheit.

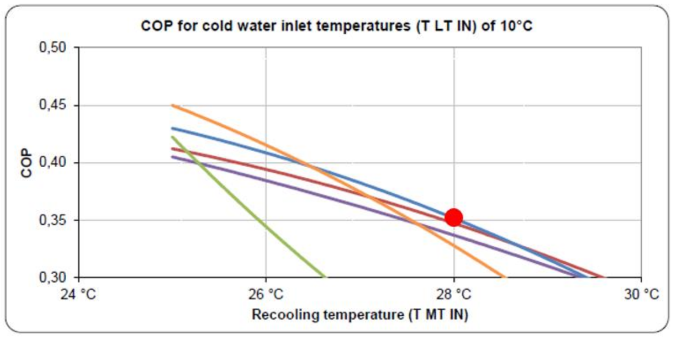
Table A-9: Required Temperatures for COP Determination

COP	Temperature
T LT in	10.9 C
T MT in	28 C
T HT in	75 C

Source: All Power Labs, Inc.

Figure A-6: COP Chart from Fahrenheit eCoo 2.0 Operating Manual





The T HT in is illustrated by the blue curve in the Figure to the top and the red dot was placed using data from Table 1 describing the conditions observed on June 22, 2018.

The T LT in was 51.6 F (10.9 C) which is in between the two charts shown in the Figure to the top. Linear interpolation must be used to determine the COP.

Source: All Power Labs, Inc.

Using linear interpolation the COP is computed to be

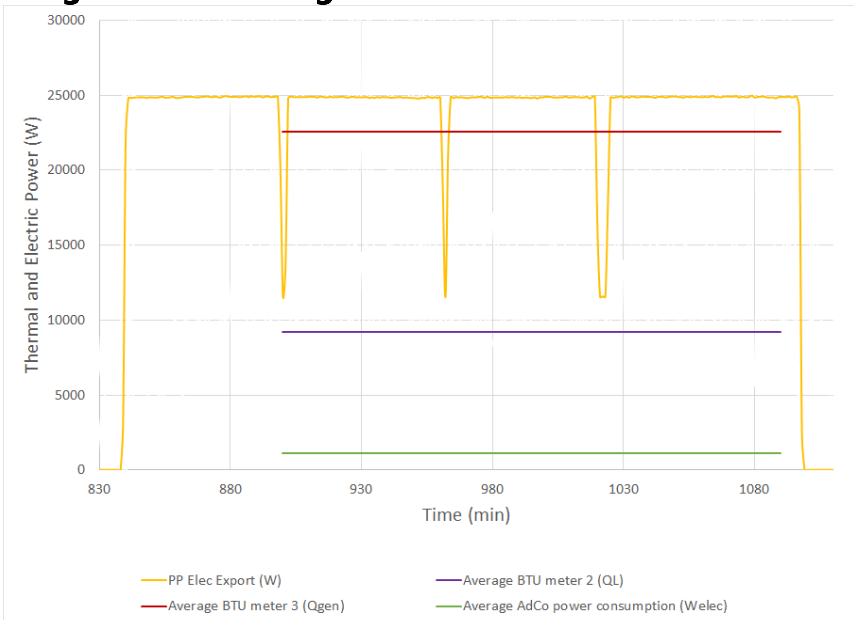
$$COP_R = 0.36+(10.9-10)(0.44-0.36/13-10) = 0.384$$

Calculating the COP from Collected Data

The COP_R is defined by equation 1 below

$$COP_R = \text{Desired output/Required input} = \text{Cooling effect/Work input} = Q_L/(Q_{gen}+ W_{elec})$$

Figure A-7: Average Thermal and Electrical Power



Source: All Power Labs, Inc.

Figure A-7 provides the averaged thermal and electrical values needed to calculate COP. Using equation 1, the COP is calculated to be

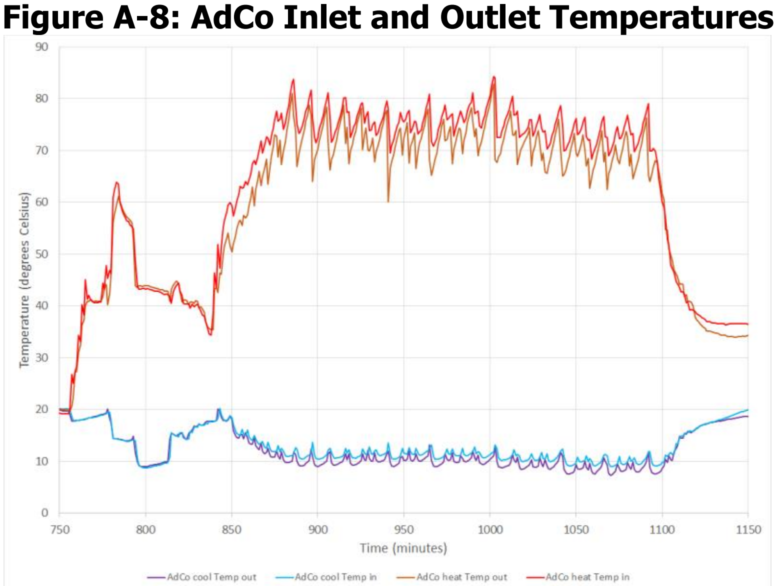
$$COP_R = Q_L/(Q_{gen} + W_{elec}) = 9209/(22594+1100) = 0.389$$

Adsorption Cooler Capacity

The adsorption cooler capacity provides a sense of the amount of energy that the adsorption cooler can remove from a space to be cooled

Figure A-8 provides temperature data collected on June 22, 2018. The plot given reflects the measured temperature AdCo inlets and outlets for the high temperature and low temperature circuits.

Figure A-8: AdCo Inlet and Outlet Temperatures



Source: All Power Labs, Inc.

Table A-10 provides average inlet and outlet temperatures for the high and low temperature circuits.

Table A-10: Average High and Low Inlet and Outlet Temperatures

Source	Temperature
T Hi in ave	75.0 C
T Hi out ave	71.3 C
T Low in ave	10.9 C
T Low out ave	9.6 C

Source: All Power Labs, Inc.

Using the badger meter data, the amount of energy that can be absorbed by the low temperature circuit was determined to be 9.2 kW.

The following values are common in practice to describe the capability of a refrigeration system.

- 9.2 kW of refrigeration
- 552 kJ/min of refrigeration
- 2.6 ton of refrigeration

A system running with the cooling capacity described above can typically provide cooling to a 180 m^2 residence space.

APPENDIX B: Scheduled Maintenance Tasks

Part	Maintenance Type [a]	Maintenance Interval, engine hours: Current	Maintenance Interval, engine hours: Projected [b]	Maintenance Time, min. [c]	Part Cost
Shake filter bag	Clean	10	100	10	
Replace polishing filter	Replace	30	210	10	$28
Clean governor	Normal cleaning	40	200	15	$28
Cyclone	Clean insides	100	250	5	
Filter gaskets	Check/replace	100	250	10	$20
Replace filter bag	Replace	100	500	15	$30
Graphite paste PRY-COW	Check/replace: 50%	125	250	5 (15)	$5
Cyclone collection gasket	Check/replace: 50%	125	250	5 (15)	$5
O_2 sensor	Check/calibrate	125	125	30	
Air intake check valve	Clean	125	125	10	
CYC-IHX gas line	Clean	125	125	15	
Ash auger tube	Add grease	125	125	10	$1
Grate shake tube	Add grease	125	125	10	$1
Airlines	Remove soot	125	125	30	
Clean governor	Deep cleaning	200	400	35	
Governor bearings	Replace	200	400	30	$10
Blower	Check/replace: 50%	200	200	5 (15)	$30
Graphite paste, grate door	Check/replace: 50%	250	250	5 (10)	$5
Cyclone sani gasket	Check/replace: 50%	250	250	5 (5)	$6
Pryoreactor gasket	Check/replace: 50%	250	250	5 (5)	$10
Ash can gasket	Check/replace: 50%	250	250	5 (5)	$6
Pressure sensors	Calibrate	250	250	5	
Spark plugs	Check/clean	250	250	30	
Pyroreactor surface	Clean/inspect	250	250	5	

		Maintenance Interval, engine hours			
Part	**Maintenance Type [a]**	**Current**	**Projected [b]**	**Maintenance Time, min. [c]**	**Part Cost**
Gasifier grate	Purge/inspect	250	250	15	
Gear shaft bolts	Tighten nuts	250	250	5	
Fuel auger hardware	Tighten shaft collar	250	250	10	
Graphite paste PYR-CYC	Check/replace: 50%	500	500	5 (10)	$5
Graphite paste PYR-DRK	Check/replace: 50%	500	500	5 (10)	$5
Engine coolant	Replace	500	500	30	$50
Engine oil	Replace	500	500	20	$50
Engine oil filter	Replace	500	500	15	$50
ACV lid gasket	Check/replace: 50%	500	500	5 (5)	$5
Battery terminals	Check/clean	500	500	10	
Oxygen sensor	Replace	500	500	15	$70
Pyroreactor	Major assembly	625	625	60	
Spark plugs	Check/replace: 50%	900	900	10 (20)	$50
Gas cowling assembly	Check/replace: 50%	1000	1000	10 (30)	
Radiator	Flush	1000	1000	60	

Source: Schatz Energy Research Center

APPENDIX C: Unscheduled Maintenance Tasks

Part	Maintenance Type	Maintenance Time, min.	Replacement Part Cost
Gas Blower	Replace	45	$30
PG Filter	Fix: filter off flange	20	
O_2 Sensor	Fixed electronic issue	5	
PG HX	Replace with new version	300	
PG HX	Fixed	360	
Filter Bag	Fixed: came loose from housing	15	
Spark Plugs	Fixed	30	$50
Engine	Cleaned cylinders	60	
O_2 Sensor	Replace	30	$70
Air Intake	Fixed: pour in alcohol while cranking	20	
Air Intake	Fixed: pour in alcohol while cranking	20	
Coolant Fan	Fixed		
Fuel Air Mixer	Fixed	30	
Total		935	$150

From data collected during 214 hours of operation in Malibu, CA.

Source: Schatz Energy Research Center