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FINAL PROJECT REPORT

Development and Demonstration of Distributed Biomass CHP Microgrid Systems

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Any omissions are unintentional and the sole fault of the authors. Science advances on the shoulders of giants.

PREFACE

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

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

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

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

Development and Demonstration of Distributed Biomass CHP Microgrid Systems is the final report for Contract Number EPC-20-012 conducted by All Power Labs, Inc. The information from this project contributes to the Energy Research and Development Division's EPIC Program.

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

ABSTRACT

All Power Labs (APL) is a Berkeley, California-based small business that designs, develops, and deploys renewable energy systems that convert woody biomass into electricity, heat, and biochar to provide carbon sequestration. Biomass power is the oldest renewable energy source and a key technology for a carbon-free future without fossil fuels, particularly since it also provides on-demand power, often difficult to achieve with many renewable resources. For this project, team members upgraded the fundamental APL biomass conversion technology, developed two new product lines, improved ease of equipment deployment, integrated various technologies, and deployed multiple machines in the field. These units converted waste in distinct-use cases of an off-grid eco-village and an urban green waste recycling yard, showcasing the versatility of the innovations developed in this research project.

Keywords: Renewable energy, biomass, gasification, pyrolysis, biochar

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Background

All Power Labs (APL) has deployed hundreds of its biomass gasification units worldwide for over 15 years. In addition to generating renewable power from wood waste, a co-product of this process is biochar, a fixed carbon product that is stable for centuries, resulting in carbon-negative emissions from the system. APL is a previous recipient of three California Energy Commission (CEC) grants for research projects as well as federal awards, which provide the basis for these innovations.

The work performed during this CEC research project supports many state environmental laws, including the transition to renewable power, the responsible management of forestry waste, and the development of local manufacturing and innovation. Specifically, this work addresses the need for on-demand renewable power generation crucial for meeting the state's long-term environmental mandates, as well as immediate relief from public emergencies such as those caused by wildfires. State policy goals include decreasing greenhouse gas emissions, providing funding for various wildfire and forest resilience mechanisms, reducing the state's carbon footprint, increasing carbon sequestration, and converting existing power generation sources to renewable energy. These are all critical for California's public health, safety, economic growth, and community resiliency.

Project Purpose and Approach

The team demonstrated in-field deployment of a new product to provide a rapidly deployable, distributed system for biomass-based electricity that would connect to the power grid, serve as part of a larger microgrid configuration, or work as a stand-alone power solution as an alternative to larger, stationary, fossil-fueled powered systems. The intended audience for this work includes public agencies and private marketers in the woody biomass conversion market in need of solutions for the disposal of low- and no-value agricultural and forestry waste by-products. The project team developed several rounds of testing (including third-party measurement and validation) with innovative prototypes and in-field units under various conditions, including the following:

- Built a safer, modernized, and more resilient electricity system
- Supported California's local economies and businesses
- Advanced zero-carbon technologies for homes, businesses, and transportation
- Expanded the use of renewable energy
- Increased grid safety and reliability and decreased costs
- Implemented a more decentralized electric grid

Key Results

The project team successfully ran multiple mobile gasification units in the field during this project and developed a product that was still in its early stages upon the project's completion. The team noted several technical challenges to be addressed, and created refinements for future iterations, particularly in terms of bringing the final product closer to Underwriters Laboratories (UL) requirements and reducing the need for operator interventions. This work benefits state ratepayers, the general public, and the environment by developing on-demand renewable power that can replace ecologically problematic alternatives (such as diesel generators) and complement other renewable generation sources, including solar and wind.

Knowledge Transfer and Next Steps

The team took several actions to share project information and foster adoption of this technology including hosting public events, collaborating with strategic partners, and attending industry events to raise awareness of this work. Policy changes that could help advance this work's future success include:

- A reduction in administrative and permitting overhead for grant-funded projects.
- Increased funding for biomass-based power solutions.
- Adoption of this technology by public agencies.

Future work identified by the project team includes the development of a new gasification architecture that can be integrated into various power-production systems including diesel gensets, microturbines, linear generators, and gas up-migration systems that support hydrogen production. Various improvements are needed to the interface, diagnostics, emissions, and other subsystems to increase both ease-of-use and reliability.

CHAPTER 1: Introduction

This project's goal was to overcome significant technical barriers in biomass energy generation, which directly contributes to California's statutory energy goals by enhancing grid reliability and advancing renewable energy technologies. Renewable power will allow California's residents to have a cleaner environment, continue to advance economic and scientific innovation in the state, and ensure greater community resiliency in the face of increasing energy demand. The project team from All Power Labs (APL) built upon its proprietary gasification technology, the Power Pallet PP30 (PP30) version (v) 2.0 biomass generator. Additional objectives included achieving a new state of commercial readiness by reducing operations and maintenance (O&M), increasing feedstock flexibility, improving automation, and achieving Underwriters Laboratories (UL) requirements through development of the PP30 v3.0 biomass generator. Additionally, APL's new containerized biomass microgrid (CBM) unit would be improved to enable easier project deployments and integration with other distributed energy generation technologies by augmenting the PP30 with additional balance of systems (BOS). This work is particularly timely given California's intense challenges due to devastating drought and wildfire events, as well as the increasingly urgent need to transition to renewable energy resources.

The PP30 is a mobile biomass gasification generator that is the core product in APL's product line. The purpose of this project was to bring the PP30 from v2.0 to v3.0 and containerize it along with other BOS components to produce a microgrid-ready, on-demand, power-generation solution with reduced O&M costs, designed with an eye to future UL compliance. The PP30 processes woody waste biomass, such as nut shells and wood chips, and converts this low or no-value material into several revenue-generating streams by thermochemical processes that convert solid matter to gases that can be used to power engines. Biochar is a fixed carbon product that resembles charcoal and is used as an agricultural soil amendment, filtration medium, or as a component in industrial manufacturing processes. The carbon in biochar resists degradation and can sequester carbon from the atmosphere into soils and built products. The project team operated this novel, dispatchable, multi-modal, biomass energy microgrid to generate low-cost renewable electricity, thermal energy, and biochar with a unique scalable configuration, and demonstrated its commercial viability. This microgrid configuration is highly replicable and can be quickly scaled, providing substantial cost, reliability, and climate mitigation benefits to both California ratepayers and all state residents while advancing California's statutory energy laws.

APL has previous agreements with the California Energy Commission (CEC) and with federal agencies, which together provided the backbone for participation in the Bringing Rapid Innovation Development to Green Energy (BRIDGE) funding mechanism. The APL project team built several gasification units and deployed multiple systems in the field, testing various use cases with distinct customers.

The goals of this research project were to:

- Improve the affordability, health, equitability, and comfort of California’s communities.
- Build a safer, modernized, and more resilient electricity system.
- Support California’s local economies and businesses.
- Advance zero-carbon technologies for homes, businesses, and transportation.
- Expand the use of renewable energy.
- Increase grid safety and reliability, and decrease costs.
- Implement a more decentralized electric grid.

Success was measured by several metrics, including the following:

- Capacity factor: 25 percent
- Average and peak power output: 30 kilowatts (kW)
- Dispatchability (time to start): 10 minutes
- Annual electrical production: 219,000 kilowatt-hours (kWh)/yr
- Annual biomass consumption: 241 bone dry ton/yr
- Successful integration and operation with other distributed energy resource technologies

On-demand productive power from biomass waste can help fill gaps left by other renewable resources which typically cannot provide on-demand power (for example, solar and wind) to replace fossil fueled options such as diesel generators. Additionally, the responsible conversion of wood waste would mitigate wildfire risk.

Broadly, the primary audience for this technology includes utilities, state policy makers, and rural community leaders. This work’s scope involved deployment to two distinct customers: an off-grid eco-village with a unique renewable microgrid and urban deployment to a green waste yard. These very different market segments represent two of several possible future customers. Other users such as forestry agencies and agricultural operations have been identified as future customers for scaling opportunities. The primary benefits to all users would be more accessible renewable power generation that provides renewable heat, electrical power, and biochar. Ratepayers stand to gain from increased capacity fed to the utility grid under normal operating conditions, and by the availability of reliable backup power in public safety power shutoff events.

APL has designed, built, and deployed hundreds of gasification units worldwide for 15 years. As a previous CEC funding recipient, the project team has successfully completed several agreements that enabled the company to upgrade its personal-scale kits into a suite of small and commercial-scale machinery that converts woody biomass such as wood chips and nut shells into renewable electricity, heat, and biochar. Biochar is a fixed carbon coproduct of the chemical conversion process that can sequester carbon in the ground for centuries and is useful as an agricultural soil amendment. Since the company's founding, California has faced historic wildfires, drought, and a catastrophic beetle infestation that left tens of millions of dead and dying trees that could not be used for standard commercial products. Additionally, the state of California has passed ambitious environmental laws, including:

- California Senate Bill 1383 (Lara, Chapter 395. Short-lived climate pollutants: methane emissions: dairy and livestock: organic waste: landfills from 2016), which decreases greenhouse gas (GHG) emissions by reducing the volume of organic materials sent to landfills.
- Senate Bill 85 (Committee on Budget and Fiscal Review, Chapter 14, "Budget Act of 2020"), which provides funding for wildfire and forest-resilience proposals.
- Assembly Bill 32 (Nuñez and Pavley, Chapter 488, Air pollution: greenhouse gases: "California Global Warming Solutions Act of 2006"), which provides a framework for reducing the state's carbon footprint and increasing sequestration via biochar.
- Several policies related to the mission of the CEC, which has the statutory requirement to transition to renewable energy via Senate Bill 350 (De León and Leno, Chapter 547, "Clean Energy and Pollution Reduction Act of 2015"), as well as the Electric Program Investment Charge (EPIC) program, which funded this research project.

Private market drivers for adoption of this technology include the larger trend toward electrification, increased costs due to tipping fees for waste disposal, and the closures of California's large-scale biomass power plants.

By the beginning of this project, APL's core technology was at a technology readiness level of 9 since it had been deployed in several real-world use cases. The specific CBM configuration was a new adaptation that began at technology readiness level 5 and included the key swirl hearth component, a proprietary component that provides particularly high-quality biochar and substantially reduces the production of undesirable tar gases during the pyrolysis and gasification processes. The project team encountered several technical hurdles. Redesign of the gasifier resulted in several technical design challenges, including some that were not overcome during the project period.

Ratepayer Benefits: The development, demonstration, and deployment of APL's microgrid-enabled, biomass-based, distributed power generation solution will benefit California investor-owned utility (IOU) ratepayers by increasing grid reliability, resilience, and safety while also reducing costs. Renewable sources such as solar cannot meet peak-hour production, so on-demand solutions are a necessary complement. As an on-demand distributed energy resource, the CBM will increase the utility grid's resilience, reliability, and safety by reducing load peaks and avoiding centralized failure points and grid congestion by physically shifting generation toward centers of high electric demand, while also providing power during periods of rolling blackouts and public safety power shutoffs, which have recently impacted millions of ratepayers. As an on-demand, dispatchable resource, CBMs will mitigate the impacts of adding intermittent renewables to the grid, thereby supporting additional renewable energy deployment and reducing GHG emissions. This will decrease interruptions caused when renewables are not sufficient to meet demand. The CBM reduces costs by bringing generation closer to load, thereby reducing the need for new infrastructure, reducing the utility's need to run expensive peaking plants, and providing grid stabilization benefits that may otherwise come from more expensive sources.

Technological Advancement and Breakthroughs: This project will lead to technological advancement and breakthroughs to overcome barriers to the achievement of California's statutory energy goals by building upon the successful CEC-funded development of an innovative, biomass conversion technology using a combined cooling, heating, and power system: the PP30. The proposed work will develop a multi-modal, dispatchable, distributed energy generation microgrid solution that is both modular and scalable. Specific advancements include improving the system's capacity by expanding feedstock flexibility, reducing operator interactions for startup and shutdown, improving ease-of-utility interconnection, provisioning power by integrating inverter and battery technologies into a containerized system, and designing for UL compliance. The current generation PP30 v2.01 will be developed into a PP30 v3.0 release through various upgrades, and will be used in a CBM pilot unit that will also be developed and released. The system will deliver electricity, heat, and biochar, which can sequester carbon in agricultural soil for centuries.

Project Participants

In addition to the APL team, partners included the following site hosts:

- University of California's Hopland Research and Extension Center in Hopland, California, location of the first CBM.
- Gund Foundation's eco-village in Petaluma, California, home to the second CBM.
- Green Waste Recycle Yard (GWRY) in Richmond, California, the primary demonstration site for this project.

Engineering partners included:

- FlexFire s.r.l.s. (consulting)
- Certifi Group (emissions)
- Rad Kem (measurement and verification)
- Blue Sky Environmental (emissions)
- Soil Controls Lab/Enthalpy Lab (biochar)
- TSS Consultants (permitting)
- WeBuildMachines (automation)
- TPU Inc. (containers)

Major components were supplied by Ashok Leyland (engines), Marathon Generators, Oztek (inverters), Sol-Ark (inverters), EndurEnergy (batteries), Deep Sea Electronics (controls), and FormPak (feedstock handling).

The project team was guided by valuable insights from the project's technical advisory committee, including:

- Bryan Jenkins, University of California, Davis emeritus (gasification)
- Ray Kapahi, air permitting specialists (emissions)
- Jim McGinley, H2 Energy Group Inc. (business, renewables)
- Vi Rapp, Lawrence Berkeley National Laboratory (combustion)
- Paul Rogé, McKnight Foundation (food systems)
- Scott Turn, University of Hawaii (gasification)

Objectives

The objectives of this project included:

- Develop and release PP30 v3.0 product, an upgraded power pallet system with increased feedstock flexibility and reduced operations and maintenance costs.
- Undertake a UL review of PP30 v3.0 system in preparation for full UL certification of the product; develop a plan for listing.
- Develop a CBM pilot with bioenergy generation from PP30 v3.0 units and battery storage, with islanding and grid-tie capabilities.
- Deploy two CBM units at a disadvantaged community site for demonstration, technical and economic validation, and confirmation of appropriateness for target market applications, with third-party validation.
- Mitigate or reduce GHG and criteria pollutant (nitrogen oxides [NOx], carbon monoxide [CO], and particulate matter) emissions and wildfire risk by using a biomass, waste-to-energy system; verify through independent analyses of emissions.
- Advance the technology and knowledge of microgrids and broaden their applications, including knowledge transfer regarding microgrids and demonstration of an effective CBM use case.
- Improve the economic, health, social, and environmental conditions in disadvantaged communities including an economic benefit analysis for demonstration sites.
- Demonstrate a valid alternative to fossil-fueled, back-up generation for microgrids, including a third-party techno-economic validation of a CBM.

CHAPTER 2:
Project Approach

The project approach encompassed the development, manufacture, demonstration, and preparation for commercialization of the pilot version of the CBM.

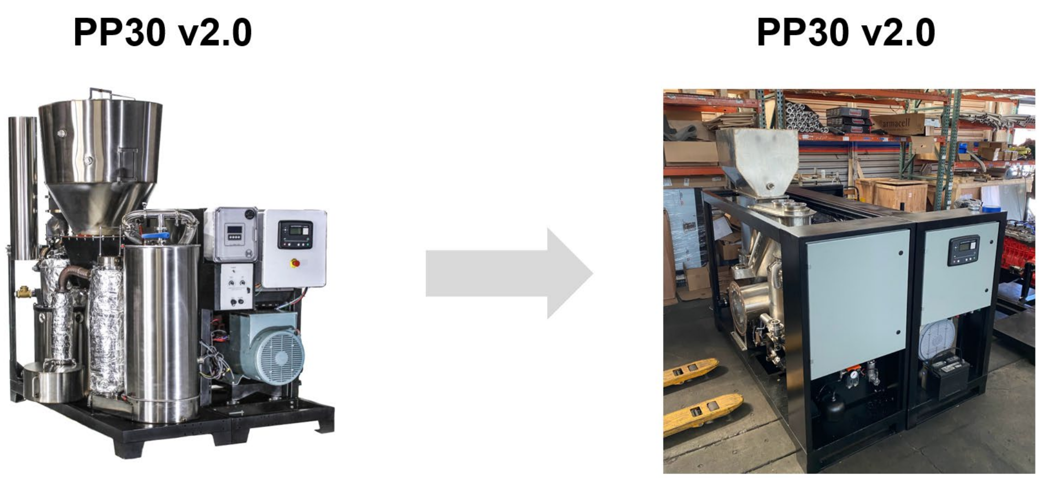
The Power Pallet

The PP30 is APL's core commercial product line, developed for more than a decade and deployed worldwide in hundreds of projects. This project was awarded as part of the CEC's BRIDGE program, which funds previously successful grant awardees.

Development

The PP30 was derived from earlier gasification kits that APL sold to clean-energy supporters. These do-it-yourself kits matured with the pairing of APL's gasifiers and internal combustion engines to provide on-demand power generation, resulting in the power pallet; the first power pallet was released in 2012 as a 10-kW back-up generator system. Figure 1 shows the generation of the power pallet (PP30 v2.0) that existed at the beginning of this project; its development was funded by previous CEC agreement PIR-16-010.

Figure 1: The Power Pallet from v2.0 to v3.0



Source: All Power Labs, 2024

The PP30 was upgraded and installed at multiple, in-field locations in the form of a CBM, a further maturation of the PP30 concept aimed at a drop-in power solution. Depending on configuration, customers can include this unit as part of off-grid, islanded operations, or connected to the utility grid, feeding power to the broader community.

Gasifier Innovation

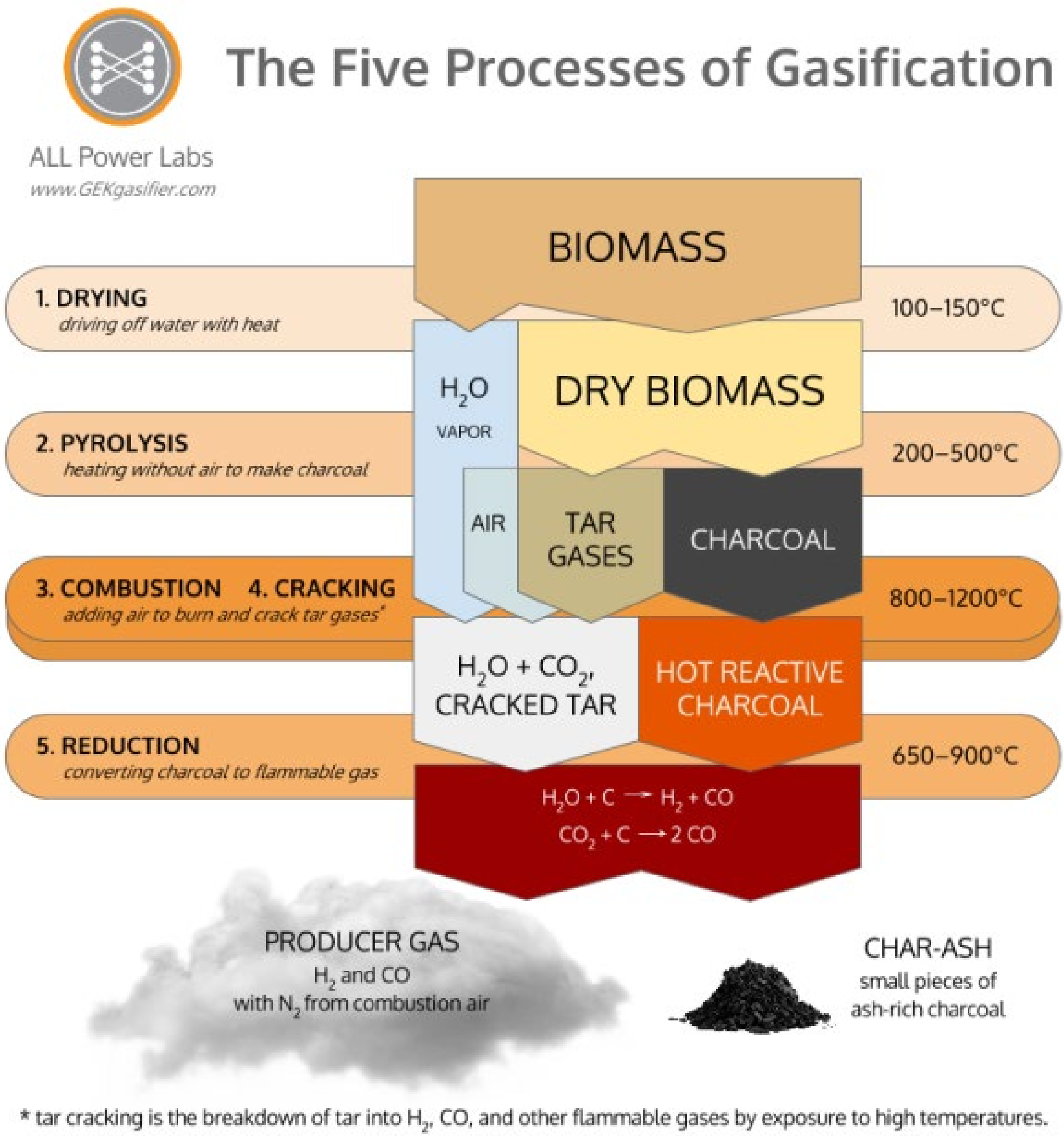
The innovation under this contract involved not only the integration of distinct CBM components, but the development of the PP30's core subsystems to make a more efficient and flexible biomass waste-processing system.

Swirl Hearth

APL was the recipient of a 2016 contract with the National Science Foundation as part of the federal government's Small Business Innovation Research program. That contract proved APL's proprietary swirl hearth technology, a component of PP30 that greatly reduces the presence of tars in the gas coming from the gasifier for reduced filtration and engine O&M, which subsequently produced very clean biochar. This current project enabled the product development of this innovative gasification architecture.

The reduction and virtual elimination of these byproducts by the swirl hearth component has several practical and ecological benefits. Biochar coming from APL's technology includes minimal polycyclic aromatic hydrocarbons (PAHs) at often undetectable levels — which results in biochar that meets some of the highest quality standards for biochar use cases. The low-tar content in the generated gases allows the baghouse filtration system in the PP30 to capture sticky tars that would otherwise adhere in the engine downstream and require regular maintenance and cleaning. Figure 2 shows the architecture of the swirl hearth and how the swirl hearth combustion annulus separates component gasses and biochar elements. By separating these components, combustion temperatures are maintained above 1,650°F (900°C) to enable the cracking of pyrolysis gases to eliminate tar compounds. The separation also prevents biomass ash from reaching high combustion temperatures that cause ash fusion or *clinkering*, which can cause increased O&M and downtimes.

Figure 2: Stages of Gasification in APL Machinery



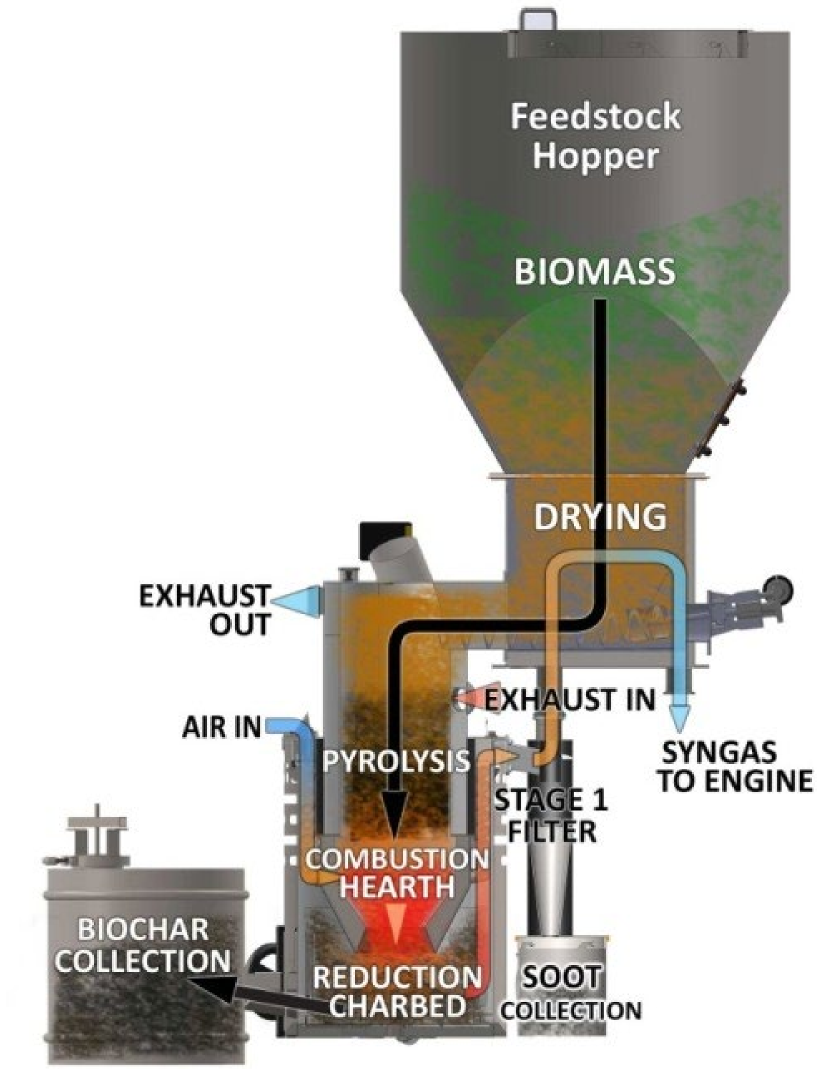
Source: All Power Labs, 2019

APL has previously integrated the swirl hearth in two sizes in other applications, but these have not had long-term, in-field deployments.

Pyrolysis Auger

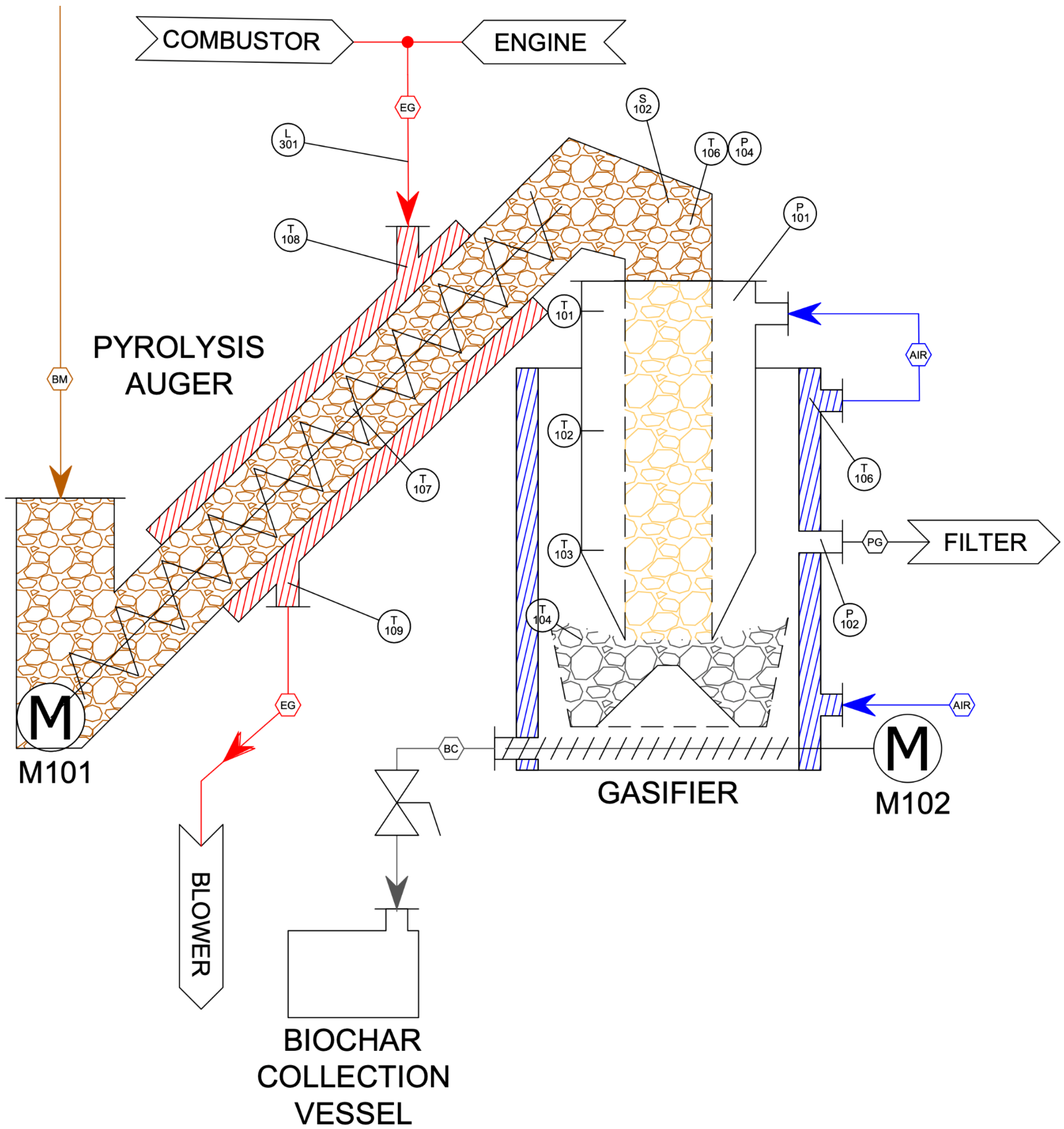
Pyrolysis is the process of splitting biomass with heat into two primary components: tar gases and charcoal (Figure 3). The PP30 v2.0 design implements the pyrolysis zone as a short vertical section (Figure 4) heated by engine exhaust. The PP30 v3.0 design implements the zone as a long diagonal section with a large diameter auger to drive the material into the gasifier. The heat can come from either combustion of the gas from the gasifier, or from engine exhaust. By supporting both sources of heat, the gasifier can run in power generation mode using engine exhaust — like the PP30 v2.0 — but also in biochar-only mode with combustor flue gas. The larger pyrolysis zone allows for more complete and more precisely controlled pyrolysis.

Figure 3: Flow of Materials in Previous Power Pallet Generations



Source: All Power Labs, 2018

Figure 4: Process Diagram Subset of the Gasifier and Pyrolysis Auger



Source: All Power Labs, 2022

Biochar Removal

The PP30 v2.0 collects biochar from the gasifier in a sealed vessel. This vessel can support 8 to 10 hours of operation before it must be changed, requiring equipment shutdown, which imposes batch mode operations of the equipment. A revised design of this offtake system added volume and valving so the biochar container can be hot swapped without equipment shutdown. This reduced operating downtime for the biochar container swap, as well as providing a longer period between changes, also coincides with average runtimes.

Combustor

The PP30 v2.0 startup process uses a flare that vents to the atmosphere to combust gases during the gasifier startup phase before gas quality is sufficient for engine operation. This flare is manually operated and only designed to support 10 to 20 minutes of operation during startup. The PP30 v3.0 released a combustor with automated mixture control, temperature monitoring, and thermal integration, which enabled the gasification system to operate in a biochar-only mode, with no time limit.

Automation and Controls

Finally, a key component of the successful deployment in this project involved overhauling the existing automation and controls subsystems for both the gas-making and power generation skid on the power pallet components.

Removing O&M operator interactions for equipment startup, shutdown, and checks was important to reduce the operator time required to manage the system; ease of use will lead to greater market adoption. One of the primary O&M simplifications included ease of startup; ignition of the PP30 v2.0 gasifier involved manually lighting charcoal with a propane torch, while the PP30 v3.0 used automated electric ignition.

Several additional automation improvements were implemented:

- Pneumatically Controlled Valves: Removed manual valve operation for hand-off from startup to engine operation
- State Machine Logic: Automated control of components (valves, ignitors) to enable automatic startup, shutdown, and switching from genset and biochar production modes
- Failure Detection (coolant level, oil level): Adding sensing and monitoring to detect failures removes pre-start checks for genset oil and coolant levels
- Remote Monitoring: Improvements to this subsystem allowed the equipment to collect and report data to the cloud for real-time visualizations to support both operations and reliability

A review of the previously conducted UL assessment (per UL 2200 Stationary Engine Generator Assemblies) of the PP30 v2.0 was conducted. Identified gaps were used to drive design changes to the automation and other systems to better align with UL requirements. An engineering review with Certifi Group was conducted to convert gaps into actionable design changes. Changes included battery charging components and the integration of unified automation cabinets

Containerized Biomass Microgrid

The CBM platform represents APL’s transition to a turnkey, renewable energy process. Previous APL products have been deployed to technicians who were more engaged with hands-on modifications and operations. In contrast, the CBM is designed to make a more passive experience, with reduced interventions and O&M and ease of transportation and installation. The CBM unit provides a pre-engineered BOS with a more streamlined user experience for the included power pallets. Figure 5 shows the first CBM (MG1001), deployed and operated at the beginning of this project at the University of California’s Hopland Research Extension Center and adopted as a baseline for operations. These CBM units included two

PP30s and a feed system that automatically delivered biomass feedstock into the top of the unit, making it suitable for less O&M. Energy storage, inverters, power distribution, and microgrid control can be optionally installed onboard the unit depending on project requirements. Table 1 describes the variations in CBM builds made during this agreement.

Figure 5: First CBM in the Field

Source: All Power Labs, 2020

Table 1: Comparison of CBM Builds

CBM Serial Number	MG1001	MG1002	MG1003
Installation Date	4/23/2021	11/6/2023	8/19/2024
Operating Period	4/24/2021 – 1/28/2022	1/16/2024 – 5/10/2024 (APL)	9/5/2024 – 10/31/2024
Site Host	Hopland Research and Extension Center	Gund Foundation	Green Waste Recycle Yard
Location	Hopland, Calif.	Petaluma, Calif.	Richmond, Calif.
PP30 Version	v2.0	v2.0+	v2.0 & v3.0
Power Use	Load Bank Demo; PG&E Interconnect with Oztek RS40 inverter approved but not installed	Off grid, electric vehicle charging, outlets, transfer switch	Load Bank Demo
Inverter	OzTek RS40/RS40-PS 40 kW nominal	Sol-Ark 30K – 30-kW nominal	None
Energy Storage	None	60 kWh EndurEnergy	None

CBM Serial Number	MG1001	MG1002	MG1003
Combined Heat and Power (CHP) Use	None	None	Drying
Feed System	Screw Conveyor with Bagflo Supersack Holder	Screw Conveyor with Bagflo Supersack Holder with Hoist	Screw Conveyor with Crate Based Storage

Source: All Power Labs, 2024

Use Cases

- On- and off-grid integration with other renewables and microgrids
- Regular use versus emergency (public safety power shutoffs, other emergency responses)
- Public and private customers including local governments, forestry agencies, and wood processors

Configuration and Balance of System

- Batteries including different types used over two deployments
- Inverters
- Grid-ready connections

Testing and Validation

The PP30 v3.0 design was tested and involved engaging with a third-party laboratory for emissions testing and for measurement and verification.

Engineering Validation Testing

The engineering validation testing subtask consisted of three distinct test plans: validating the upgraded gas-making module, validating the upgraded automation and controls module, and validating the upgraded CBM integration.

As part of the engineering improvements cited in a prior CEC project (PIR-16-010), the power pallet platform was reconfigured into a split-skid architecture where two distinct halves performed gas-making functions from woody biomass waste, and power production using the gases in an internal combustion engine. The former half is referred to as the gas-making module and testing involved the following subcomponents:

- v6.0 swirl hearth gasifier O&M improvements and UL compliance.
- v2.0 feed/drying system O&M improvements and UL compliance.
- v2.0 combustor O&M improvements and UL compliance.
- Other gas-making O&M improvements and UL compliance.

A key component of swirl hearth testing was measuring feedstock flexibility by testing four feedstocks to assess performance: sifted wood chips, wood pellets, walnut shells, and pistachio shells.

Automation and controls testing included the control-based automation architecture, reductions in operator interventions, creating and testing state machine control logic, wire harness design, mechanical safety guards, proper fusing, and support for automated valving.

CBM testing involved validation of several features: alternating current (AC) synchronization between PP30s, PP30 and electrical cabinet service access, PP30 ease of removal from CBM, validation of door clearances, and ventilation. Additionally, the team checked pass-throughs for wiring, combined heat and power (CHP) plumbing, proper operation of the feed system, and exhaust. CHP thermal-energy production, battery-bank integration, and performance were also tested. Lastly, the team investigated moisture content and feedstock consumption.

To prove proper CBM integration, the team intended to have 30 minutes of steady-state operation in the intended state that measured the function of all subsystems (swirl hearth, feed drying systems, combustor) and a pressure leak test. Following in-house engineering validation testing, the team engaged in in-house bench testing and in-field commissioning.

Bench Testing and Commissioning

Bench testing and commissioning were made up of four phases and conducted on MG1002 and MG1003 units.

- Preliminary Testing: Generation and review of necessary documentation, inspection of purchased items and the built system, proper assembly (including fabrication)
- Installation: Confirmation of proper installation of the inverter, battery bank, biomass generators, feedstock system, and the connections between these systems
- System Interconnection: Checking of electrical connections, communications links (automations and controls), and safety protocols (valves, overcurrent protections)
- Final Verification: Functional testing of subsystems and integration

Measurement and Verification Testing

The project team worked with materials scientists and engineers in the subcontractor consulting firm RadKEM to develop a measurement and verification plan (MVP) and generate a report based on testing results. This task provided independent, third-party analysis and review of performance metrics.

The MVP was broken into two phases: Phase 1 focused on a single PP30 v3.0 unit to conduct the assessment of mass and energy flows, efficiency, and other performance metrics. This was conducted at APL's Berkeley site. Phase 2 focused on overall performance metrics of the CBM system, emissions, and costs. Data for Phase 2 included MG1003 operation at APL Berkeley and GWRY, and MG1002 at the Gund Foundation's Petaluma, California, location.

Extended Operations Testing

The extended operations plan created a balance of responsibilities between APL and site host GWRY, ultimately a successful partnership for long-term operations. GWRY's goal was that post-agreement, APL's machinery would remain on site and function indefinitely.

Equipment was operated at GWRY from September 5, 2024, to October 31, 2024. Handoff to staff did not occur. It was requested by the site host but was not arranged. Equipment is still present on site and expected to be integrated with site loads and operated in future projects.

CHAPTER 3: Results

Power Pallet

The power pallet is composed of two modules and several subsystems. Design and engineering changes occurred across several of these components.

Gas-Making Module

The core of APL's power pallet and the building block of the CBM is the gas-making module. A major development was to both develop a next-generation power pallet into a commercial product and test the next-generation gasifier. The PP30 v3.0 gas-making module uses APL's proprietary swirl hearth gasifier, a configuration for gasification that developed to allow a variety of biomass feedstocks and yield a clean gas to minimize downstream filtration and engine O&M. While proven functionally by the National Science Foundation, the work was performed to develop the PP30 as a commercial product and validate its performance and longer-term testing.

For the PP30 v3.0, the dual skid architecture of PP30 v2.0 was maintained to provide more space for individual components and give options to optimize the flow path of the biomass feedstock and syngas. This new architecture worked well to accomplish the design goals.

Multiple subcomponents were either developed or improved in the gas-making module:

- The new blower component provided the vacuum that drives the system during startup and biochar mode (while the genset provided vacuum during power-generation mode). The team overcame fabrication issues, iterated on rotor balancing and dimensioning, and revised other design elements with the blower to ensure that components performed over extended runs and prototype cycles.
- The new combustor burns the syngas during startup and biochar char mode. Careful material selection and manufacturing was required to ensure that the components could withstand high temperatures during operation.
- The new biochar auger that was developed to allow continuous operation had some issues with material packing and jamming when some feedstocks were used, so it was re-designed and subsequently successfully integrated into the system.

Under this project there were two major subsystem revision cycles (P1 and P2), with testing cycles carried out to inform the improvements incorporated in the revision cycles (Figure 6).

While this testing proved that the core system architecture and design were successful, it also enabled APL to identify key areas that required improvements for both performance and system longevity.

Figure 6: Photos of P1 and P2 During Assembly and Testing

P1 Assembly 1/19/23

P1 Operations (~May 2023)

PP2001 P2 Assembly

PP2001 P2 Under Test

Source: All Power Labs 2023/2024

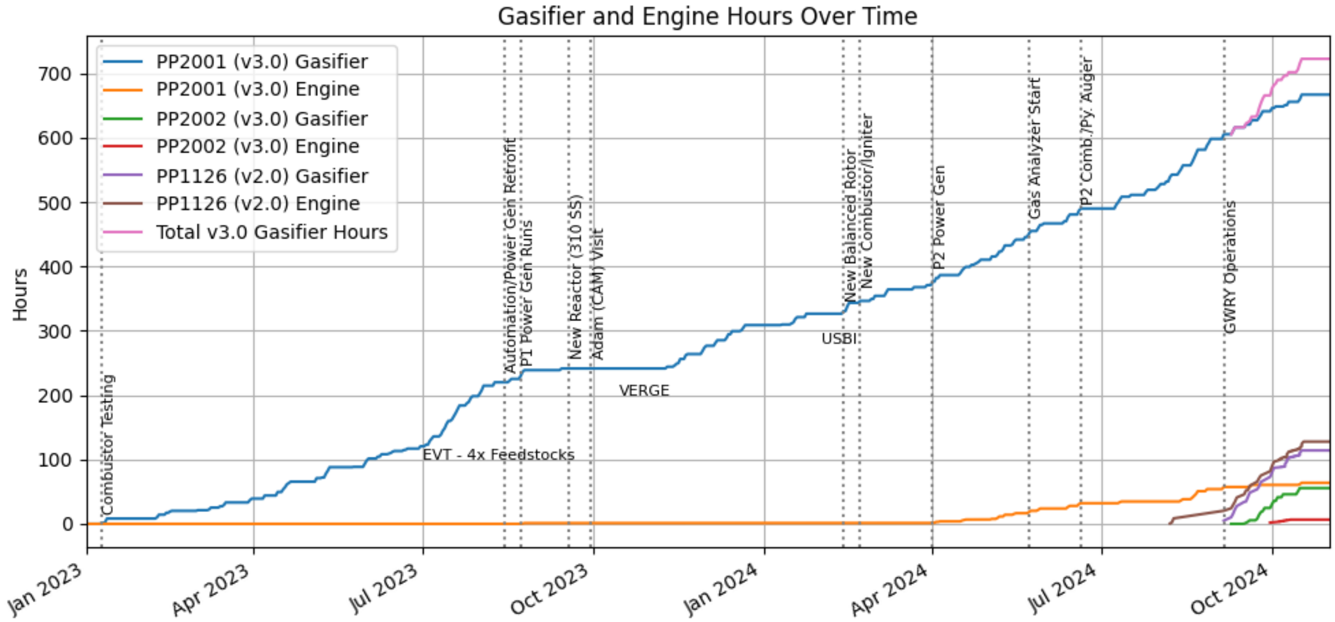
Reliability Testing Component Durability

The overall PP30 v3.0 gasification system was tested for more than 700 operating hours while primary testing occurred over unit PP2001 (Figure 7). Multiple reactors were built and tested, addressing issues found in high-temperature stainless alloy selection, gasifier igniter design, and thermal expansion.

The new combustor system was designed and built after undergoing numerous revisions. Combustor test results indicated challenges in material thermal expansion, electric igniter longevity, and ignition performance. These were addressed during build cycles.

The new blower faced challenges with rotor balancing, bearing and pulley selection, and overall integrity. Over multiple design cycles these major reliability and performance issues were addressed and improved.

Figure 7: PP30 v3.0 Cumulative Run Times and Milestones



Source: All Power Labs 2024

Material Handling

During the system's early operation, it was found that consistent, continuous syngas production in the gasifier required the stable, continuous delivery of biomass to maintain stable pyrolysis and other downstream process conditions. Feedstock flow was managed by measuring the feedstock level in the system with a rotary feedstock level switch and adding more feedstock when the level dropped. The switch's location in the system showed high temperatures during long runs that damaged the switch. To further improve the system performance, a new level of switch that could monitor feedstock head height was developed, which showed an improvement in process stability.

A new biochar auger design was tested for some runs, which leveraged a 4-inch auger design with a 55-gallon drum for biochar storage (approximately 24 hours in biochar operating mode). This was applied during some operating hours, though concerns around the potential of air leaks took this system offline when a smaller directly connected vessel was used.

Particulate Deposition

From results of the P1 design cycles including particulate deposition in tubing, the team reviewed the plumbing lengths and minimization for the gasifier to combustor length, and a second port was added to the cowling on the P2 design (so the piping was more direct).

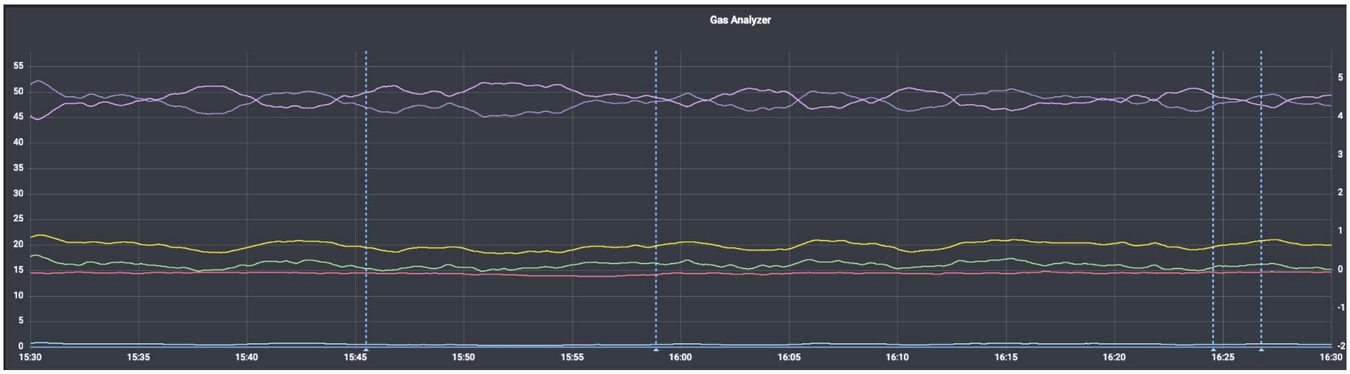
The custom high-temperature valve design was also reviewed, and potential improvements were recommended to minimize particulate build-up.

During genset operation the syngas cooling heat exchanger did not experience any jamming of its automated mechanical cleaning baffles. The deposition on this heat exchanger was a blend of particulate and tars. Given the limited maintenance required while testing, this was a good sign that gas tar contamination was low, providing a dry, non-sticky deposition that was easily cleaned.

Gas Composition

A gas analyzer was brought online on May 23, 2024, and was used during almost every subsequent run on PP2001 (Figure 8). In general, gas energy density (lower heating value) was lower than nominally expected (6.5 megajoules per cubic meter [MJ/m^3], v2.0) when the gasifier was fed with air, as planned. Higher nitrogen content was seen (Figure 8).

Figure 8: Gas Composition During Aug 22, 2024, MVP Run



Gas composition during steady state for the MVP run on August 22, 2024 from 2:00 p.m. to 4:30 p.m. was: carbon monoxide: 16.1 percent, hydrogen: 19.9 percent, methane: 0.6 percent, carbon dioxide: 14.5 percent, oxygen: 0 percent, nitrogen: 48.9 percent, and lower heating value: 4.4 MJ/m^3.

Source: All Power Labs 2024

Process Stability (Gas Composition, Temperature)

Syngas composition had outsized effects on multiple parts of the system. The first area affected was power output, where drops in fuel gas (CO/H2 [hydrogen]/CH4 [methane]) concentrations resulted in lower energy density and a subsequent increase in gas flow to maintain a given electrical power output. This increased gas drew increased air flow into the gasifier and led to run-away events, positive feedback between the generator and gasifier system. Various actions were taken to stabilize the process and gas quality including stabilizing feedstock and pyrolysis rates, grate control, and governor behavior. Figure 11 shows the temperatures in a particular run.

Other system process feedback was gathered between the pyrolysis auger and combustor/exhaust. This was traced to a feedback loop in the system where high temperatures from combustor or exhaust increased the pyrolysis rate, reducing the amount of air and oxygen drawn into the reactor, resulting in higher energy-density gas back to the combustor, in turn making it run hotter. This significant feedback was identified early on, and a flue gas bypass valve was added to better control the amount of heat introduced into the pyrolysis stage. This was proven successful in better managing the pyrolysis rate and enabling further process optimization by allowing pyrolysis temperature setpoints to be adjusted, which will additionally prove useful for biochar production and other process optimization.

Finally, in some runs, the bag-house filter media melted because the gas entering it exceeded the melt temperature of the filter material. This was also tied to run-away events during generator operation that caused high gas flows and less gas-heat exchange. Minimizing this feedback was key to stable operation. Overall, the newly independent processes provided more control flexibility. Managing feedback was also critical. Newer architectures are being considered that would minimize these interactions.

Automation and Controls

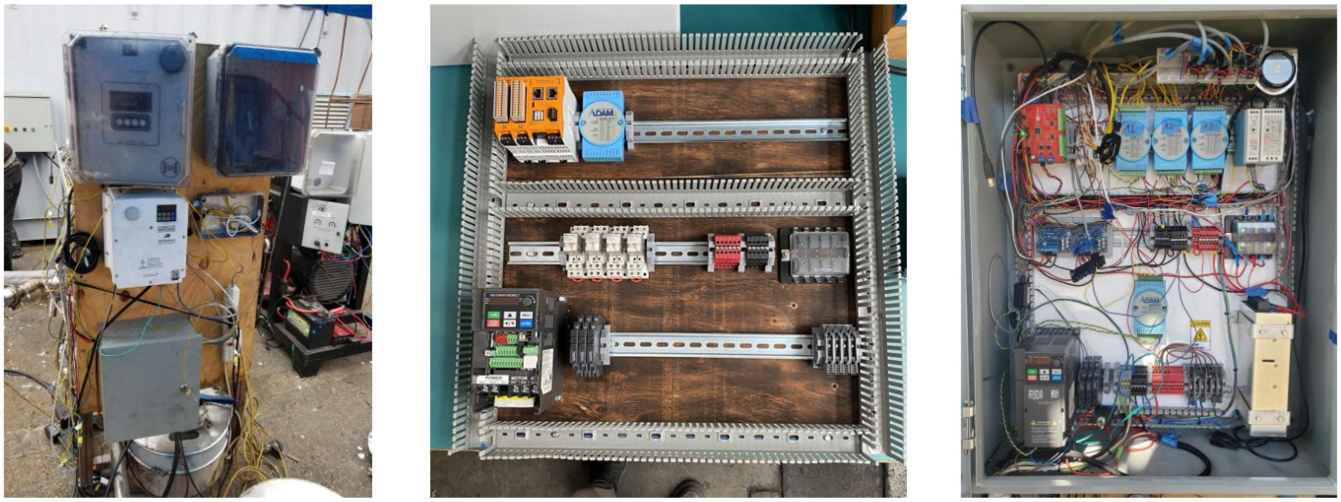
At the outset of the PP30 v3.0 automation and control design phase the team's plan was to implement a programmable logic controller-based system using off-the-shelf Siemens modules. This was considered the preferable solution at the time since it would be easier to achieve UL standards. This was scoped and quoted during the prototype phase, however, where it was found that using a single board computer (Raspberry Pi) was both flexible and fast for implementing new features. With UL certification in mind, the team did try to source a UL-listed industrial Raspberry Pi (Revolution Pi) but found that support was insufficient in that development path. The decision was made to continue implementation using a Raspberry Pi and custom-printed circuit boards. While this route required more testing to UL list the product, it was concluded that the functional benefit, control flexibility, and potential for cost reduction outweighed the extra work required.

The implemented solution enabled fast development cycles and the ability to add additional controls to the PP30 v3.0 through the prototype development cycles, and supported extensive data collection and integration from various on-board and off-board sensors for testing purposes (gas analyzer, NOx sensor, pitot tube).

State machine control (which considers historic performance) was implemented, along with communication to the genset controller (Deep Sea 8610 MK II) for the automated transition from gasifier to genset. Automated pneumatic valves under state machine control were then implemented. Various control loops were added to regulate system conditions including temperatures, feedstock flows, gas flows, and igniter temperatures.

Remote monitoring was implemented on a server using a time-series database (InfluxDB) and interactive visualization application (Grafana). Data from the equipment and the auxiliary Raspberry Pi's stream data (via JSON) to the server collected more than 250 data points, typically at 1-second intervals. Data collection with this system began in May 2023 and continued throughout the project. During deployment of MG1003, a workstation was implemented to access the user interface (Figure 12) and Grafana charts. A cell modem and IoT cellular data provider were tested successfully and provided real-time remote monitoring data as well as the ability to remotely configure the equipment. A local edge server was also installed to allow local access to data if cellular data connectivity was lost. Figure 9 and Figure 10 display some of these components and where they were situated in the machine.

Figure 9: Evolution of Gas-Making Automation Design



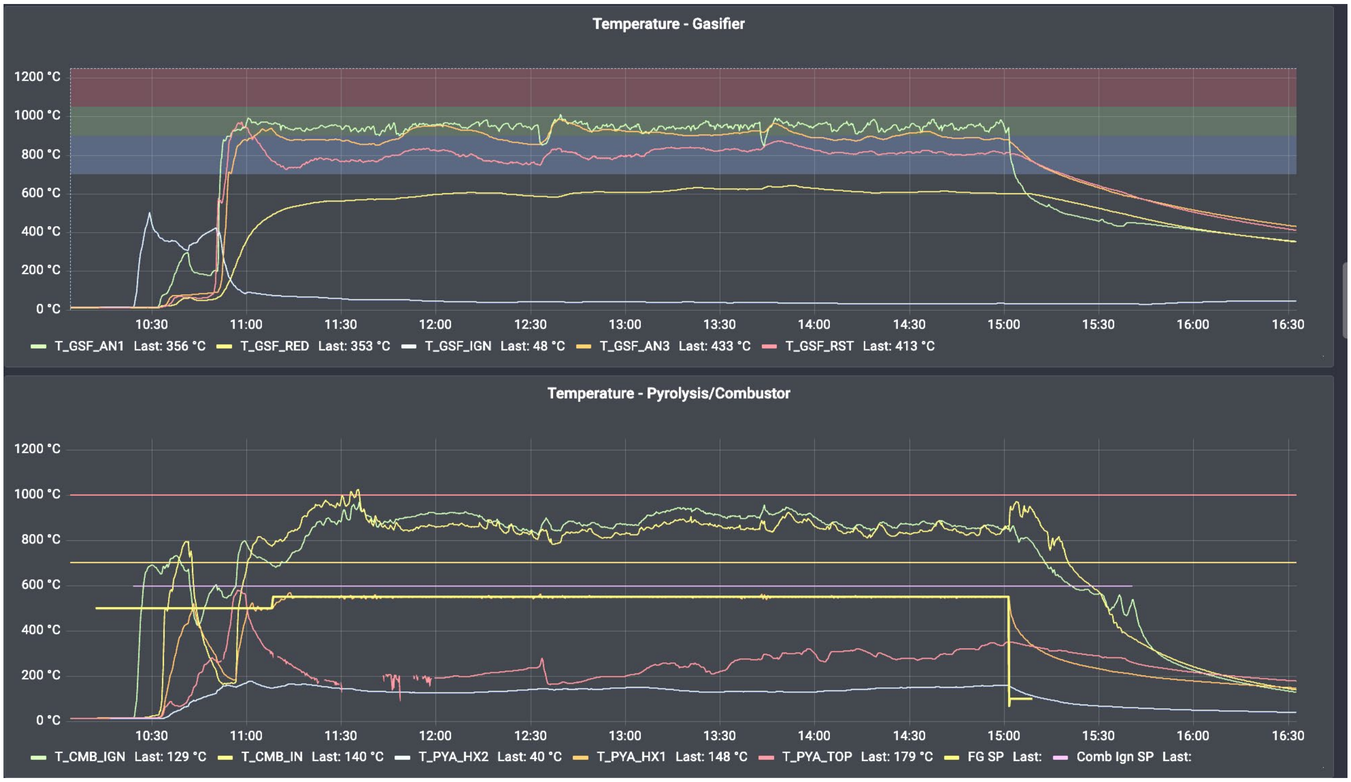
PP30 v3.0 Proto 1 | Revolution Pi | PP30 v3.0 Proto

Source: All Power Labs 2023/2024

Figure 10: Side-by-side Gas-Making and Power Gen Automation Enclosures

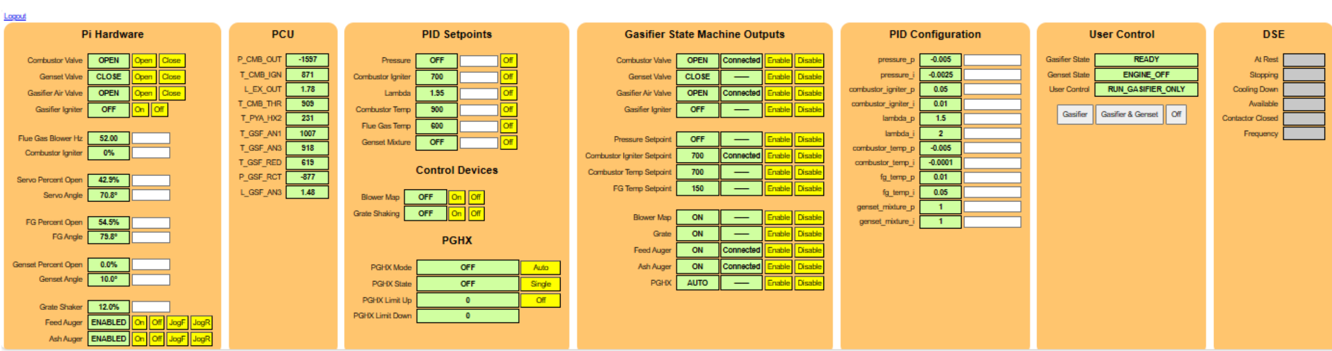
Source: All Power Labs 2024

Figure 11: Temperature Charts Collected from PP2002 at GWRY on Oct. 15, 2024, and Remotely Accessed



Source: All Power Labs 2024

Figure 12: User Interface for System Control: All Devices



Source: All Power Labs 2024

UL Gap Analysis

All Power Labs conducted a gap analysis of the PP30 v3.0 and the containerized biomass microgrid (CBM) for BRIDGE Task 2.4. This was based on a UL preliminary investigation of the PP30 v2.01, conducted and provided in 2019.

The gap analysis proved very valuable since it identified the most suitable approach to UL listing the PP30, as well as specific technical and operational issues in the equipment design.

Through consultation with a certification consulting firm, the team learned that there are multiple approaches to get UL compliance: field labeling, listing, classification, and batch certification. The team determined that the best option for early listing would be field labeling, an approach where the field evaluation body evaluates individual units and applies a field label after installation. This option is good for limited numbers in production and for updating designs.

Additionally, the gap analysis identified the main technical areas to consider as the PP30 design matures through prototyping cycles. Overall equipment layout should be considered so that electrical subsystems can be isolated from one other; components such as those for combustion can be separated from the rest of the system, and hot surfaces can be protected or isolated. For the automation systems, the need for location and the design of fail-safe circuits and valves for key systems was highlighted. Finally, the need for proper product labeling was highlighted.

Design of the control system accounted for work in the gap analysis including power supply considerations, implementation of a safety relay for core safety functions, and panel layouts that provide easy access to resettable fuses.

Overall, the report provided an excellent foundation for guiding the design of the PP30 to best align with UL listing requirements.

Feedstock Types

The completion of the engineering validation testing of the upgraded gas-making module (including the swirl hearth) included running on the four target feedstock types: walnut shells, wood chips, pellets, and pistachio shells. Additional testing on wood chips occurred at GWRY.

Biochar Testing

Syngas and biochar quality are directly impacted by gasifier performance, often with a direct relationship where improving the quality of one results in improving the quality of the other.

The swirl hearth gasifier architecture was designed to support a wider range of feedstock, so comprehensive biochar laboratory testing using standards defined by the International Biochar Initiative (IBI) was completed against the various types of biomass feedstock used during engineering validation testing, shown in Figure 13.

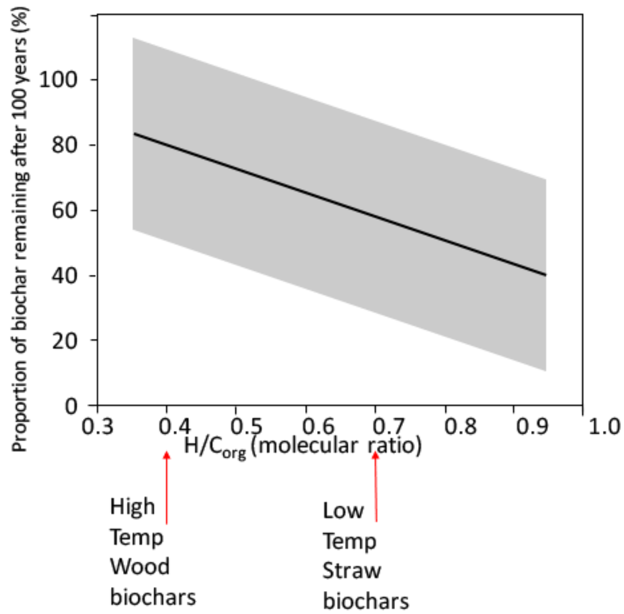
Figure 13: Biochar and Feedstock - Wood Chips, Pistachio Shells, Wood Pellets, Walnut Shells

Source: All Power Labs 2023

The following are the key test metrics and their specific relevance to biochar as a co-product of the gasification process:

- Organic Carbon: Fraction of the biomass carbon captured in the biochar. Internal target: greater than 90 percent
- Hydrogen to Carbon Ratio (H:C): A value correlated with carbon permanence or sequestration durability in soil, as shown in Figure 14 (Joseph et al., n.d.). Test results showed low H:C ratios implying greater than 80 percent of biochar carbon would remain in soils after 100 years.
- Surface Area: High surface area yields high adsorption capacities that can improve water retention capacity, filtration performance, and ability to retain nutrients in soil. Activated carbons are often considered to have surface areas greater than 500 square meters per gram (m^2/g).
- Polycyclic Aromatic Hydrocarbon (PAHs, heavy metals, dioxins, furans): PAHs of concern include 16 PAHs of concern to the United States Environmental Protection Agency (U.S. EPA 16), and a subset of 8 PAHs of concern to the European Food Safety Authority (EFSA 8). APL requirements are to meet IBI EPA 16 PAH of less than 300 milligrams/kilogram (mg/kg), and European Biochar Certificate standards of less than 6 mg/kg U.S. EPA 16 PAH and of less than 1 mg/kg EFSA 8 PAH.

Figure 14: H:C Ratio vs. Biochar Remaining After 100 Years



H/C$_{org}$=hydrogen to organic carbon ratio

Source: International Biochar Initiative, 2020

Sample 1 (walnut shells) was tested under non-optimal operating conditions. Sample 5 was generated under better conditions. All other samples tested at stable and continuous operating conditions.

The test results (Appendix B) indicated that the gasification process was able to handle the selected feedstock by producing biochar with similar qualities: high carbon content, high durability, high conductivity, and surface area that classified the material as quasi-activated carbon. These qualities made the biochar highly suitable for agronomic applications such as compost, industrial use such as water filtration, and as a carbon sequestration solution.

Biochar quality was directly impacted by process conditions that will require improvement across the equipment operations: startup, continuous operations, and shutdown.

Containerized Biomass Microgrid

The CBM units went through a process of design, build, commissioning, testing, deployment, and operations at two in-field locations throughout the duration of this project.

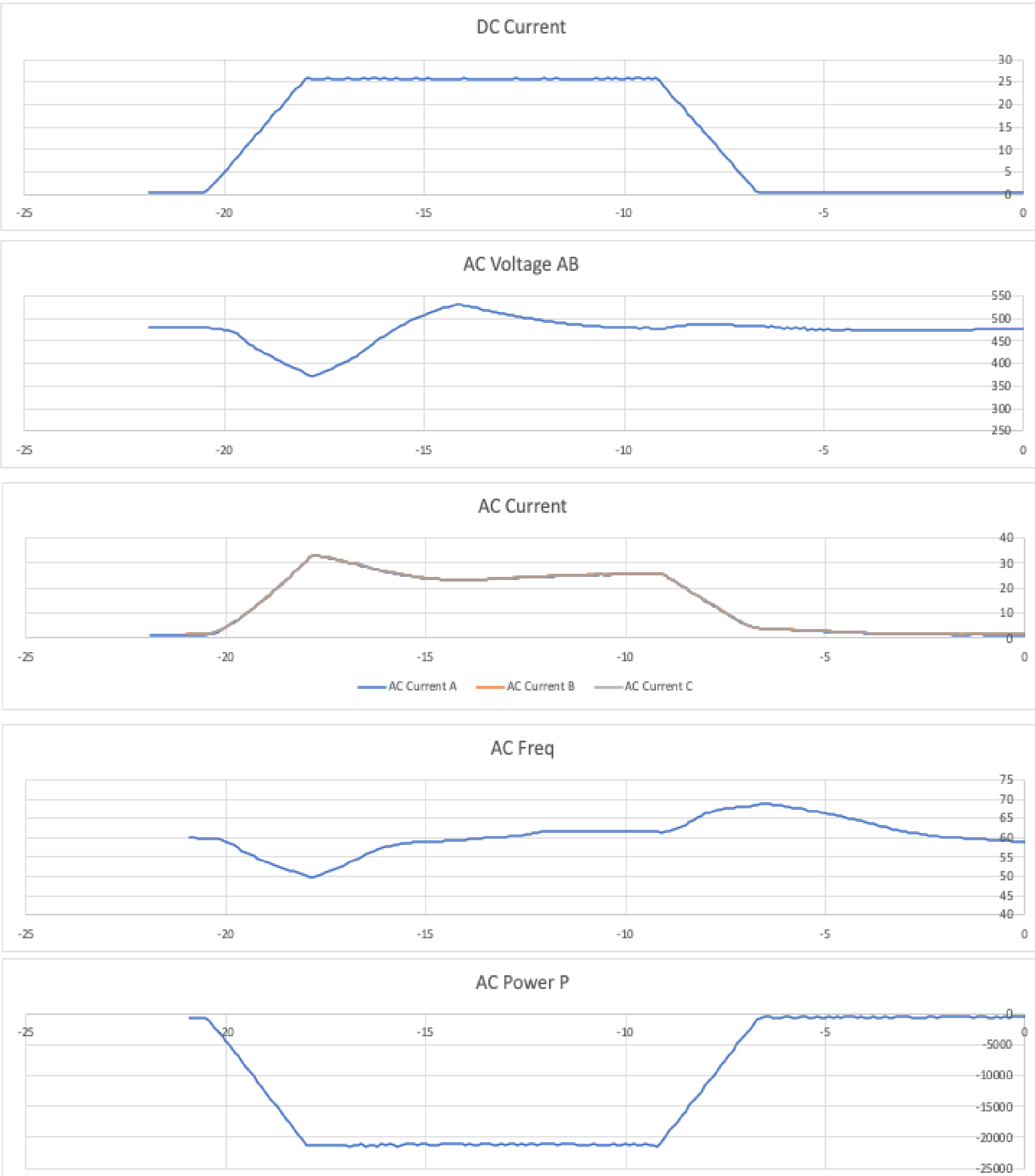
Interconnection Design and Approval

An important use case for CBM is in grid-tie configuration, where power can be fed back to the grid to increase grid reliability, resilience, and safety. The path to achieve this with CBM MG1001 was broken into three milestones: interconnection architecture design, utility approval, and field testing. The first architecture the team developed used protective relays for grid protection, per utility requirements (Figure 17). A significant amount of work was done on the design and approval of this approach, but it was ultimately deemed too high-cost and required additional commissioning and approval steps. It was concluded that by using available inverters that fully met UL 1741-SA, the project could leverage decades of photovoltaic inverter development, the utility interconnection application and timeline would be simplified, and installation costs would be lower. An architecture was designed around a 40-kW inverter and power supply from OzTek (OZpcs-RS40/RS40-PS), and a new interconnection application was submitted. The interconnection process proceeded through the Pacific Gas and Electric Company (PG&E) Fast Track Interconnection Process (Figure 16) (PG&E, 2012). The application required pending test data from the inverter manufacturer to ensure it complied with Rule 21 Phase II and Phase III requirements, which created delays, though the interconnection process itself was simplified. With this in place, the interconnection was approved by PG&E. Full interconnection implementation did not proceed due to funding limitations for other high-cost site upgrades including utility upgrades of the distribution transformer. Knowledge of the utility interconnection process was advanced during this work.

Functional testing of the OzTek components, including control communication, Rule 21 settings, and proof of grid export functionality with one PP30 were completed along with development of an initial controller and datalogging system. The dynamic response of the combined power pallet, inverter (RS40), and rectifier system (RS40-PS), showing exported AC power and the DC current between rectifier and inverter is shown in Figure 15, along with the input (PP30) AC voltage, current, and frequency. The testing showed that the system could stably deliver power using a ramp rate to full load of up to 8 kilovolt-amperes per second (kVA/s).

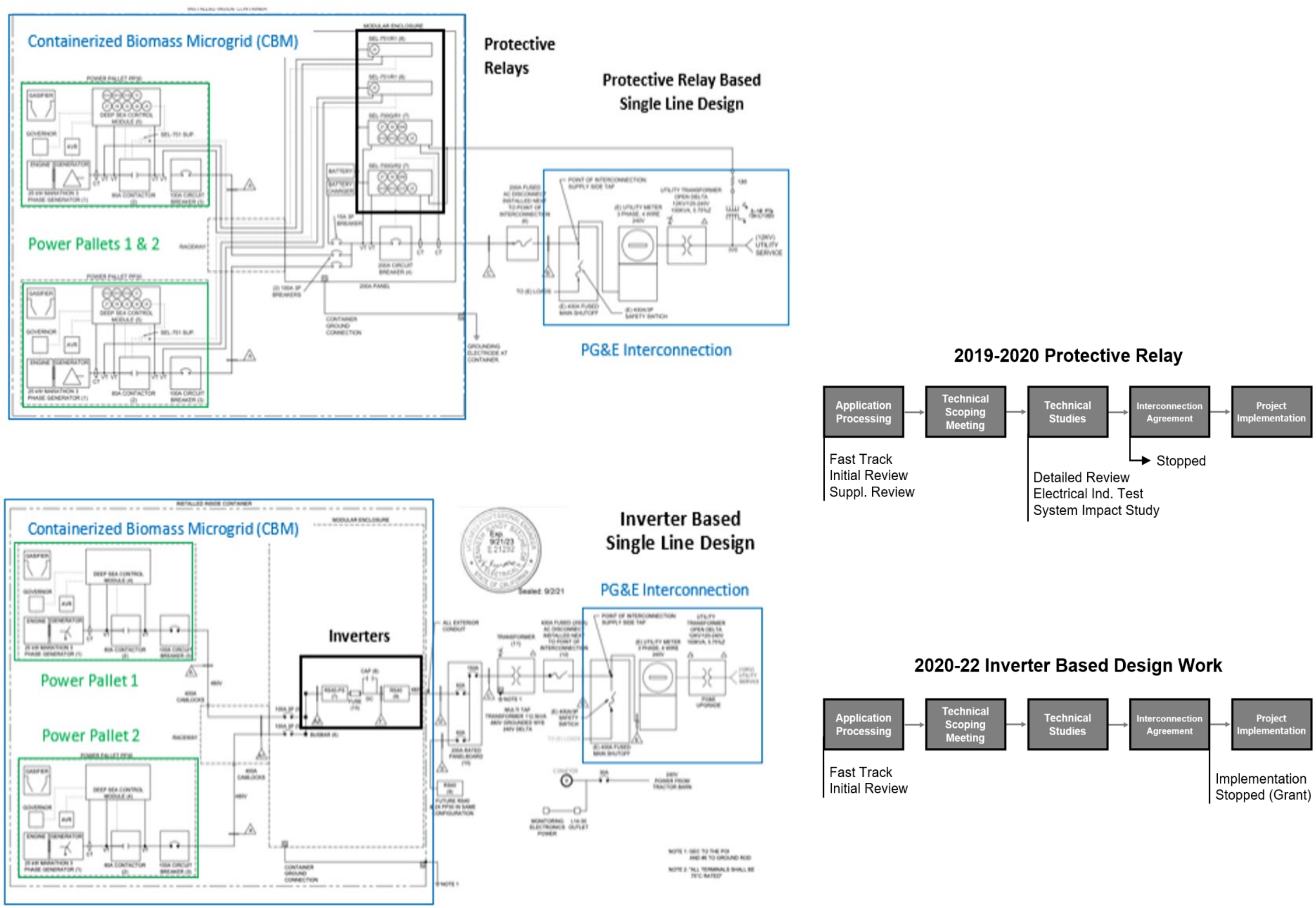
With the significant leg work of interconnection architecture done and the fast-tracked approval process understood and completed, APL was intimately familiar with the entire process and selected an inverter-based interconnection design for other CBM deployments (Figure 16), which is a more commonly used interconnection architecture.

Figure 15: Functional Test Results with 1x PP30, RS40-PS/RS40



Source: All Power Labs 2022

Figure 16: Protective Relay and Inverter-Based Interconnection Architectures



Source: All Power Labs 2022

CBM Layout and Design Improvements

APL gained knowledge of CBM systems from building and deploying three (MG1001, MG1002 & MG1003) at different sites. With the experience and data from these builds and deployments, the team learned both the technical challenges to get the equipment operational in the field and of performance for the equipment when it becomes operational.

In MG1001 and MG1002, the control electronics, balance of system (BOS), and grid-tie components were installed using a modular enclosure/rack-mount system. This layout, while modular, was less common in similar power generation applications and therefore was more difficult to configure to comply with electrical standards and codes. The electrical BOS mounting layout was therefore changed for MG1003 to an inset wall-mount style, a more common solution with which electrical contractors were more familiar: wall-mounted enclosures. The team designed a specific inset wall into the container for this purpose.

A key subsystem addressed in MG1003 to reduce costs was the improvement of the feed conveyor system. The first two CBMS, MG1001, and MG1002, used supersack holders (approximately $40,000) and a conveyor; while functional, it was an expensive solution. In MG1003 a more cost-effective solution (approximately $3,000 in materials) using off-the-shelf parts and a bulk crate system for feedstock storage was implemented.

A key subsystem addressed in MG1003 to reduce costs was the feed conveyor system. The first two CBMS used expensive supersack holders and a conveyor. MG1003 implemented a cost-effective solution using off-the-shelf parts and a bulk crate system for feedstock storage.

To ensure the correct relative moisture content (between 10 percent and 15 percent) of biomass feedstock, the CBM system has a drying stage that uses ambient air to dry the biomass or heat from the PP30 CHP loop. Future work will look at integrating this drying system with the product to reduce manual interactions and staging.

CBM Procurement and Manufacturing

The container for MG1002 was delivered in the third quarter of 2021. The container for MG1003 was delivered in the second quarter of 2023. The remaining parts for MG1002 were also delivered in the second quarter of 2023, and the subsystems for CBM were manufactured and installed in the container in the third quarter of 2023. Parts for MG1003 were ordered in the fourth quarter of 2023, and subsystems were manufactured in the first and second quarters of 2024.

CBM In-House Commissioning

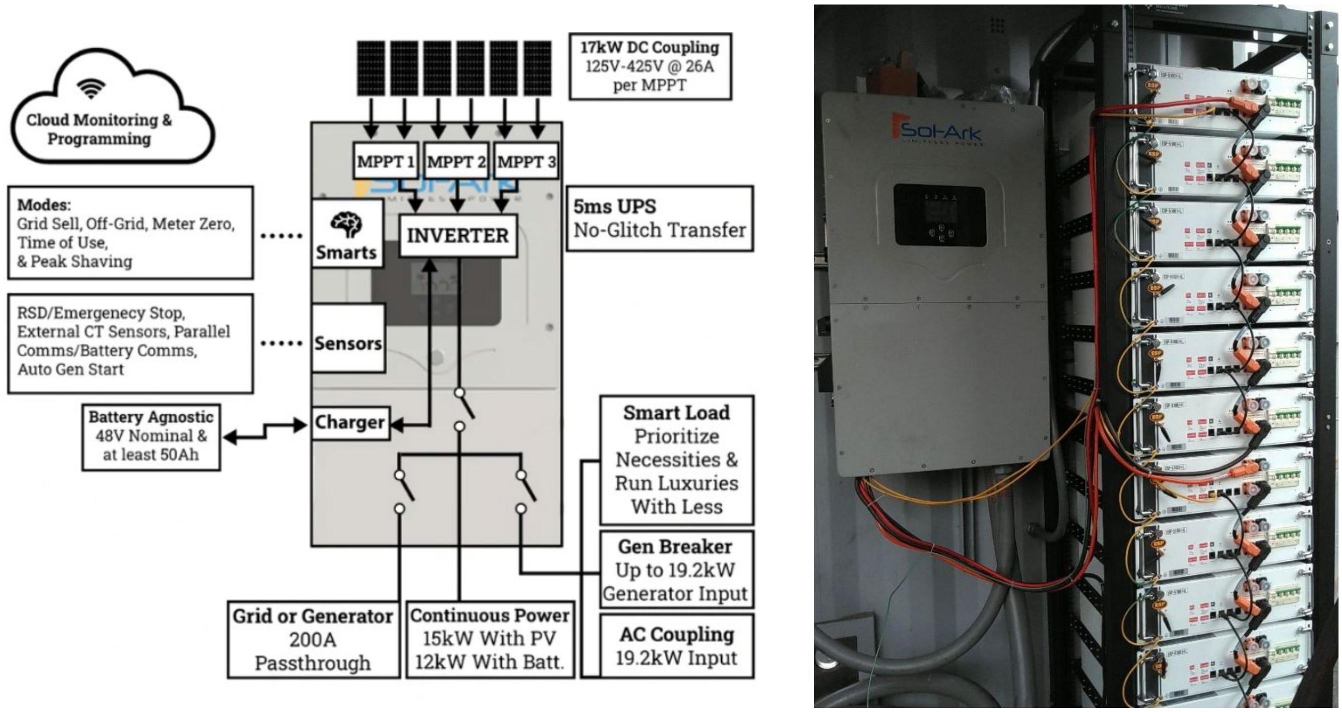
In-house commissioning occurred at APL headquarters in both 2023 and 2024.

MG1002

Most of the commissioning of the mechanical and gasification subsystems, including the power pallets, was straightforward and went as planned. There were, however, some component issues that required equipment relocation in the container. The team addressed those as they arose.

Testing and in-house commissioning of the battery and inverter system took considerable effort due to equipment shipping errors and running a nonstandard configuration (generator on grid input). After much work, the team achieved 20 kW of charging load and 4 kW of output load simultaneously, with the final configuration limiting the battery charge rate to avoid overloading the system (Figure 17).

Figure 17: Sol-Ark 30 K Inverter and EndurEnergy Battery Rack Installed in MG1002



Source: Sol-Ark and All Power Labs

MG1003

CBM MG1003 was assembled and commissioned in July 2024 and August of 2024. The new, lower-cost biomass feed-system design worked as planned. The new inset wall layout worked. A CHP loop was implemented and used for feedstock drying with MG1003. Power pallets PP1126 (PP30 v2.0) and PP2002 (PP30 v3.0) were installed.

PP30/CBM Demonstration and Extended Operation

Demonstration and extended operations occurred at the GWRY site in 2024.

Feedstock

An important early step prior to each CBM deployment was a site visit by the APL team to evaluate numerous factors to ensure success, including the availability and characteristics (size, composition, and moisture content) of the feedstock.

Both Gund (MG1002) and GWRY (MG1003) primarily use wood chips for feedstock. However, Gund had challenges processing (sifting and drying) the wood chips so instead ran the equipment on walnut shells temporarily and later switched back to wood chips.

An initial sample of feedstock from GWRY was contaminated with rocks, so the APL team chose to pre-qualify the GWRY feedstock by testing it at APL in Berkeley. This was found to be helpful to ensure the quality and consistency of the material, identify any issues, and help customers make any changes to address those issues prior to onsite deployment and operation. Supersacks are commonly used in bulk material handling and were chosen for feedstock deliveries, storage, and the feed system (Figure 18, Figure 19).

Figure 18: Feedstock Supersacks Arriving at APL Headquarters

Source: All Power Labs 2024

Figure 19: Bulk Feedstock at GWRY

Source: All Power Labs, 2023

Site Preparation

The Gund site in Petaluma, California included a barn and other buildings to be retrofitted in a workshop supported by the CBM. APL's partner at the Gund Foundation completed this as planned and the installation was completed without issue.

The GWRY site preparation in Richmond, California required coordinating timing with an outgoing tenant to ensure adequate space for the CBM in the planned location (Figure 20). GWRY staff had a small bobcat vehicle with pallet forks available for use both during construction and during project operations.

Figure 20: CBM Site Location

Source: All Power Labs, 2023

Transportation and Site Installation

Shipping containers are ubiquitous for moving goods and equipment; the methods and means for transporting them are well established. However, it was found that when the CBM systems were transported using the more common roll-off type trucks, the loading and unloading could cause issues (for example, dropping from the truck bed) and also required additional heavy equipment like cranes for final positioning of MG1001. When looking into this issue the team learned of side-loader trucks that reduce container movement, can position the unit with just the side-loader if adjacent to the truck, and can work in tighter spaces. This type of transport truck is now the preferred method for moving CBM systems and was used for MG1002 and MG1003 (Figure 21).

Figure 21: Side-Lifter Moving MG1003; MG1003 Initial Installation at GWRY

Source: All Power Labs, 2024

Operator Training

Training at the Gund site with MG1002 took place over three days, with training days taking five to six hours each. Training consisted of an overview of the unit components and their functions, dry running the unit demonstration and practice, demonstrations of running the unit, followed by practice in running the unit and troubleshooting.

As some trainees were pulled away for short periods of time during training for regular farm duties, training took longer than expected to ensure everyone understood all steps and common issues. A complete set of standard operating procedures and operations manuals were provided.

MG1003 at GWRY was run by APL staff during the project. GWRY staff have been trained to use it, but continued operations will depend on agreements between individual parties.

Site Commissioning

MG1002 was fully commissioned at the Gund site in February 2024 (Figure 22) and now functions as an off-grid power source for the Blue Marble Acres regenerative farm. The batteries provide 60 kWh of backup power, which is approximately two days of off-grid use, while the generators can recharge this amount in approximately one hour. Electric loads are expected to grow as additional infrastructure is installed.

MG1003 was commissioned at the GWRY site in September 2024 (Figure 23).

Figure 22: MG1003 Installation at GWRY

Source: All Power Labs, 2024

Figure 23: PP2002 Installed in MG1003

Source: All Power Labs, 2024

Extended Operation

Bringing the PP30 v3.0 engine online faced unexpected challenges. Often a small amount of propane-automated "dual fuel" was required to ride through process variability while operating PP2001. Various adjustments were tested including spark timing, spark-plug types, and process adjustments. Minimizing gas flow variations (for example, by minimizing governor rates of change) was most successful in stabilizing the process. Further work is required.

To functionally test MG1002 electrical power distribution and genset synchronization with PP1126, the PP2002 genset was run on propane. The PP2002 gasifier was brought online separately (Table 2).

Table 2: Cumulative Testing Run Hours

	2023	2024	Total
PP2001 (v3.0)	309 (Gasifier) ~8 (Engine)	289 (Gasifier) 52.8 (Engine)	597 (Gasifier) 60.8 (Engine)
PP2002 (v3.0)	n/a	63.05 (Gasifier) 9.2 (Engine - Propane)	63.05 (Gasifier) 9.2 (Engine - Propane)
PP1126 (v2.0)	n/a	144 (Gasifier) 131 (Engine)	144 (Gasifier) 131 (Engine)

Source: All Power Labs

PP1126 O&M

The operator found minor issues with the mismatch of parts with the generator synchronization, and a small part of the producer gas heat exchanger failed; however, both were easily resolved through routine troubleshooting.

PP2002 O&M

At approximately 15 hours runtime the Pyro Auger connections sheared. The woodchips had required additional torque to drive through, and the auger was using a lighter shaft, a connection design intended to improve feedstock flow but may have instead reduced strength. Increases to maximum motor current addressed feedstock binding; this excess applied torque that should be managed more carefully in the future. This was repaired at APL Berkeley with a new attachment design, reinstalled, and worked successfully. Table 3 summarizes the operation hours of the power pallets installed in the CBM onsite at GWRY.

Table 3: Operating Hours for Equipment at GWRY

	PP1126	PP2002
Period	9/5/24 - 10/31/24	9/5/24 - 10/31/24
Labor Hours for Daily Operations	8.81	Insufficient hours to calculate accurately
Labor Hours for Maintenance	1.25	--
Labor Hours for Repair/Troubleshooting	3.88	--
Total O&M Hours	5.13	--
Engine Hours	130.47	--
O&M Hour/Engine Hour	4.06%	--

Source: All Power Labs, 2024

During operations at GWRY, state machine control continued to be iterated to reduce operator interactions. The electric gasifier igniter used, which significantly reduced manual interactions with the equipment. Other control strategies were explored, and the team succeeded in progressing through several startup states without operator interactions (Figure 24).

Figure 24: APL-Designed Feed System Working Well on Site

Source: All Power Labs 2024

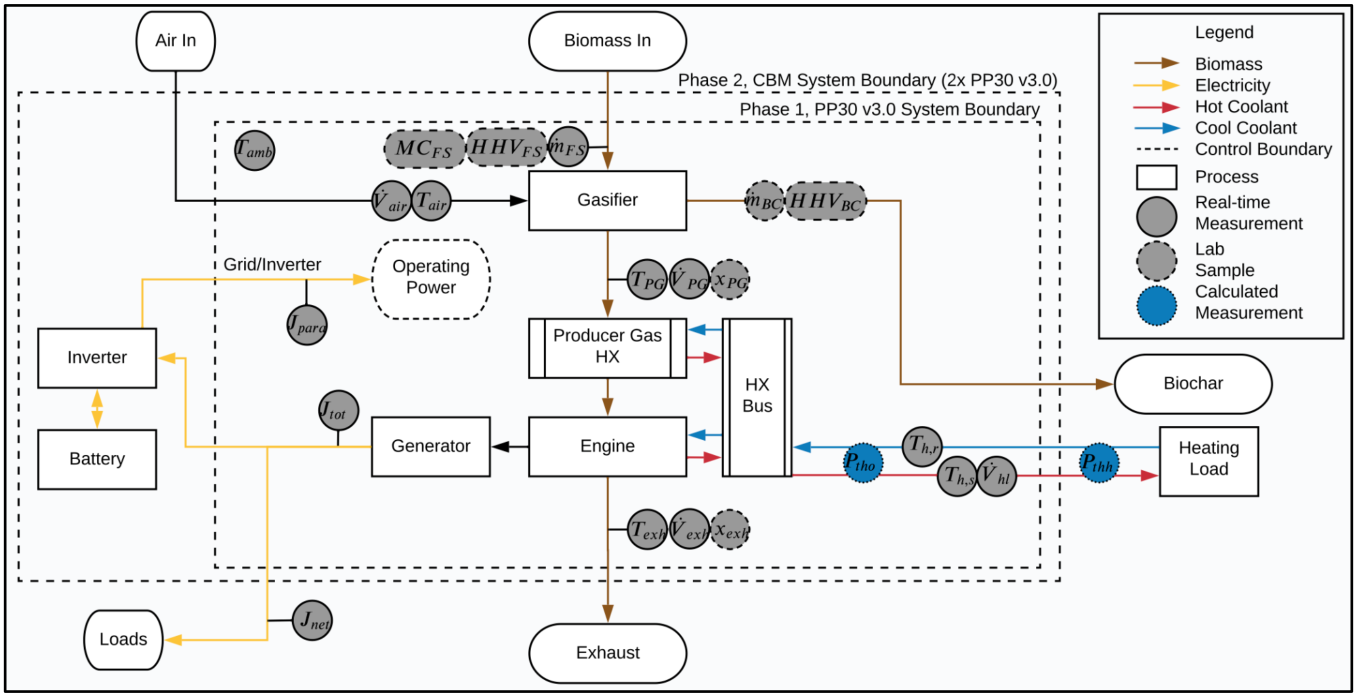
Measurement and Verification Report

A measurement and verification report was provided by RadKEM, Inc., an independent third-party that analyzed performance metrics for the biomass gasifier (Figure 25). Testing was conducted over two periods with more than 480 hours run time with 289.5 steady-state operational hours from January 1, 2024 to August 29, 2024 (Figure 26).

For Phase 1 operations on PP2001, data collected on August 22, 2024, showed that:

- The combined heat and power production was 56.1 percent of overall efficiency with 1.48 kilograms per hour (kg/hr) of char production at 8.99 kW, and 67.9 percent efficiency for conversion of producer gas to net electricity and heat (see Appendix A).
- Calorimetry testing by Kinetica, Inc., of as-delivered walnut shells indicated that the high heating value was 20.127 megajoules per kilogram (MJ/kg) and walnut-shell biochar was 27.8 MJ/kg. Using the 15.4 kg/hr feedstock rate, this equated to 85.9 kW of available energy. Appendix A includes calculations for deriving available energy.

Figure 25: Simplified Schematic of Components for MVP



Source: All Power Labs

Figure 26: PP2001 During MVP Phase 1 Testing Aug 27, 2024

Source: All Power Labs, 2024

Based on APL's analysis, during PP30 v3.0 testing on August 22, 2024, a Testo 350 emissions analyzer and a 3-way catalyst were used on the engine exhaust. A sweep across mixtures to optimize emissions was not conducted and a fixed lambda setpoint of 1.02 was used. Table 4 shows data from 3:09 p.m. to 3:29 p.m.

Table 4: Emissions Data

	SJAVPD Gasifier Genset	U.S. EPA, <500 HP Landfill Gas	Results
CO	<75 ppm CO	<610 ppm CO	944 ppm (155% of U.S. EPA) (1,259% of SJVAPCD)
NOx	<9 ppm NOx	<150 ppm NOx	11 ppm (7.4% of U.S. EPA) (123.6% of SJVAPCD)

HP=horsepower; ppm=parts per million; SJVAPCD=San Joaquin Valley Air Pollution Control District

Source: All Power Labs

Further optimization of emissions control is needed. A nitrogen oxide sensor was tested and shown to be robust over approximately 200 hours of gasifier/genset operation. This sensor can allow dynamic adjustment of mixture to optimize emissions performance to find a balance between NOx and CO conversion. This sensor can allow continuous emissions monitoring of NOx emissions.

CHAPTER 4: Conclusion

Overall, the project team was successful in creating an updated PP30 system, integrating it into the CBM product, and developing the derived Charpallet technology. Work performed during this project has implications for several industries and organizations and provided the project team with a renewed focus for future work.

Key Implications

There are key implications and outcomes for several groups:

- Commercial Markets and Consumers: Two new product lines are closer to wide market adoption by meeting long-term customer needs.
- Utilities: There are few options for on-demand renewable generation so a reliable power option in events such as public safety power shutoffs or wildfires would support the utility grid.
- Consumers: California ratepayers have some of the highest electricity costs in the United States. Distributed, renewable generation can reduce these costs and avoid public safety power shutoffs in emergencies such as wildfires. There are also public health and safety implications.
- State Policy: Several state agencies could benefit from this work including forestry agencies with the need to remove more than 100 million dead trees in California, rural and tribal communities in need of power self-sufficiency, and emergency response services that require on-demand power.

Benefits and Importance

Several groups will benefit from this technology. One is future communities in need of drop-in biomass solutions for resiliency (such as the pilot urban-waste processing facility in this project), especially since large biomass plants have closed statewide over the past two decades and limited locations exist for the handling of agricultural and forest residues (Mayhead and Tittmann, 2012). Both the state and California residents would benefit from advancing clean energy solutions for the state’s ambitious clean energy mandates.

This project created an easily deployable product to advance greater market adoption. Equipment operations and maintenance overhead were major impediments to adoption, even by those seeking solutions. The next-generation power pallet made significant strides in automation, monitoring, and reduced operations and maintenance costs. One unexpected benefit was the creation of the derived Charpallet technology for customers that do not need electricity but are instead interested in converting biomass into biochar; this opens a large market segment, particularly for agricultural and forest communities. Finally, the project team was able to use biochar as a carbon sequestration vehicle in new situations, which could lead to multiple end products (Schmidt and Wilson, 2014).

Market Opportunities

The possible application of biochar as a building material has huge potential, particularly with recent federal prioritization of American manufacturing and infrastructure. Related to this, the broader industry and public transition to clean energy has only expanded during this contract and the possibility of rural communities using biomass power for electric vehicle charging stations is a market that is growing exponentially.

Knowledge Transfer Activities

The project team engaged in a variety of knowledge transfer events for various audiences. APL's informal open houses and high school student tours introduced a less technical group to this technology. Being one of the host sites for San Francisco Climate Week, April 26, 2024, allowed the team to share the project's success with many individuals. Industry events such as the VERGE 23 Sustainability Conference, the 2024 North American Biochar Conference in Sacramento, and the World Ag Expo 2024 in Tulare, provided the opportunity to directly communicate with more specialized and technical audiences with deeper understanding of industry needs. Finally, the ability to connect with academics who applied and tested biochar produced during this project will boost awareness of the material's value in new infrastructure applications. The project team was encouraged by the interest from researchers in biochar samples, which were provided to multiple researchers at the United States Department of Agriculture and at the University of California, Davis.

Lessons Learned and Future Development Opportunities

As explained in Chapter 3, even though there were substantial design and engineering challenges the project team was able to find several solutions to these issues. Additional work remains to enable both longer run times and consistent syngas output quality.

Power Pallet v3.0

The power pallet was the core of APL's technology and the building block of the CBM.

Much progress was made in developing the Power Pallet v3.0, including proving the new swirl hearth gasifier architecture and ancillary systems; but further improvements and product development are required to achieve extended run times to make this technology suitable for field deployments.

To achieve longer run times, the team identified key areas to the PP30 v3.0 that need further work.

The first area was the overall temperature control of the system, including the swirl hearth, which was needed to both optimize the syngas gas-making process and prevent high temperatures within the gasifier that could damage components. Some methods of managing temperature initially explored were exhaust gas recirculation in internal combustion engines and steam injection. Improvements to gasifier component robustness could include insulation, ceramics, and alternative high-temperature alloys.

The power pallet incorporates several heat exchangers that use heat generated in some processes of gasification to improve overall system efficiency. The team identified improvements to the layouts of the heat exchangers and their design, which would improve gas quality and system performance. Additionally, the team identified a heat exchange arrangement that makes the system independent of engine exhaust to run the gasification process, which can make the gasifier more agnostic to the end-use integration and potentially allows it to support other applications like diesel engines (low-exhaust temperatures), syngas upgrading to hydrogen or other fuels (no exhaust return), and other possibilities.

The filtration system was put under relatively limited operating hours when power generation was in operation; however, observations were that deposits contained comparatively low amounts of tar, and the producer gas-heat exchanger required no servicing. The gas analyzer gas sampling train showed soot in the water bubbler, but no tar deposition. This provided the evidence that one of the main objectives of the swirl hearth architecture — to reduce gas tar content — had been achieved.

Significant improvements to the automation system were completed, but the extended runs revealed that additional control features for startup and operation were needed. While the automation architecture was designed with UL listing in mind, further work will be required to fully develop the system with these new components to both improve robustness and meet UL requirements.

In cases where biochar is sold on the carbon removal market, digital monitoring and verification are important. Adding on-board feedstock and biochar weighing will improve verification by providing verifiable data from system operation.

To improve feedstock flexibility, on-board automated drying would reduce external pre-processing and make operation significantly simpler.

Containerized Biomass Microgrid

The CBM represents an essential development in the deployment of APL technology. By combining feed systems with electrical offtake components, the CBM allows flexible deployments that match each site's needs without additional work for the host site. Deployment can be rapid, with a site coming online in as little as two days. Through the two CBM deployments performed in this project, much was learned about the challenges with CBM including design, delivery, setup, and operations. This learning brings the CBM design in line with standard industry practices for electrical BOS and delivery and will set the foundation for mass deployment of the technology at diverse sites, both reducing overall costs and allowing greater flexibility in energy use.

Recommendations and Next Steps

The project team has identified several internal next steps, including:

- Continued development of gasification technology to improve usability and reliability. Primary technical areas to resolve include the following:
    - Continued deployment and in-field validation of the PP30 v3.0 and Charpallet systems.
    - Improved user interfaces.
    - Continued system automation and diagnostics to minimize operator engagement.
    - Continued development of remote monitoring and control, including cellular data connectivity for ease of installation, mobility, and security.
- Develop a flexible, renewable biomass fuel-generation solution that can be paired with widely used distributed energy resources such as diesel and gas generators, microturbines, and others that rely predominantly on fossil fuels by decoupling thermal heat return from the engine's gas system.
- Identify funding for electric vehicle charging applications from public and private sources.
- Continue improving genset emissions performance to achieve targets. Performance optimizations can include increasing total catalyst volume, catalyst operating temperature, and mixture control.
- Continue improving combustor emissions performance, which may include improved oxidation performance, intentionally reducing gas-energy density through exhaust gas recirculation.

Recommendations for industry and public agencies include:

- A reduction in administrative overhead for deployment of similar projects, such as a more streamlined permitting process for short-term and grant-funded work (securing a permit can be so time-consuming that it endangers a project's success).
- Further funding for biomass research so it can develop to the levels of other clean energy technologies such as solar and wind.
- Adoption of biomass conversion technologies for public agencies and utilities in areas of distributed energy generation, forestry maintenance and wildfire mitigation, and disaster response.
- Support of biomass carbon-removal pathways to address historic carbon emissions and reduce long-term climate impacts.
- Support the integration of biomass power with other distributed-energy generation technologies (batteries, solar) to create unique microgrid solutions for both customers and use cases.

GLOSSARY AND LIST OF ACRONYMS

Term	Definition
AC	alternating current
APL	All Power Labs
BOS	balance of system
BRIDGE	Bringing Rapid Innovation Development to Green Energy program
CBM	containerized Biomass Microgrid
CEC	California Energy Commission
CHP	combined heat and power
CO	carbon monoxide
CO/H2/CH4	carbon monoxide/hydrogen/methane
EBC	European Biochar Certificate
EFSA	European Food Safety Authority
EPIC	Electric Program Investment Charge
GHG	greenhouse gas
GWRY	Green Waste Recycle Yard
H:C	hydrogen to carbon ratio
H/C_{org}	hydrogen to organic carbon ratio
HP	horsepower
IBI	International Biochar Initiative
IOU	investor-owned utility
kg	kilogram
kg/hr	kilograms per hour
kVA/s	kilovolt-amperes per
kW	kilowatt
kWh/yr	kilowatt-hours per year
m^2/g	square meters per gram
mg/kg	milligrams per kilogram
MG1001, MG1002, MG1003	serial numbers for specific CBM units
MJ/kg	megajoules per kilogram
MJ/m^3	megajoules per cubic meter
MVP	measurement and verification plan

Term	Definition
NO_x	nitrogen oxides
O&M	operations and maintenance
PAH	polycyclic aromatic hydrocarbon (includes heavy metals, dioxins, furans)
PG&E	Pacific Gas and Electric Company
PM	particulate matter
PP1126, PP2001, PP2002	serial numbers for specific power pallet units
PP30	Power Pallet, 30 kW model
ppm	parts per million
SJVAPCD	San Joaquin Valley Air Pollution Control District
UL	Underwriters Laboratories
U.S. EPA	United States Environmental Protection Agency
v	version

References

Joseph, S., P. Taylor, F. Rezende, K. Draper, and A. Cowie. n.d. "The Properties of Fresh and Aged Biochar." International Biochar Initiative. Available at https://biochar.international/guides/properties-fresh-aged-biochar/.

Mayhead, Gareth, and Peter Tittmann. 2012. "Outlook: Uncertain Future for California's Biomass Power Plants." *California Agriculture*, 66(1): 6-7. Available at https://ucanr.edu/repository/fileAccessPublic.cfm?fn=ca6601p6-91748.pdf.

PG&E (Pacific Gas and Electric Company). 2012. "Generator Interconnection Process: Wholesale Distribution Overview." September 18, 2012. Available at https://www.pge.com/assets/pge/docs/about/doing-business-with-pge/wholesale-distribution-process-overview.pdf.

Schmidt, Hans-Peter, and Kelpie Wilson. 2014. "The 55 Uses of Biochar." *The Biochar Journal,* Arbaz, Switzerland. ISSN: 2297-1114. Version 12, May 2014. Available at https://www.biochar-journal.org/en/ct/2.

Project Deliverables

Project deliverables, including interim project reports, are available upon request at pubs@energy.ca.gov, and include:

- TAC Meeting #1
- TAC Meeting #2
- TAC Meeting #3
- TAC Meeting #4
- TAC Meeting #5
- TAC Meeting #6
- CPR Meeting #1
- CBM Architecture in Field Audit Plan
- Measurement and Verification Plan
- UL Compliance Gap Analysis
- Biochar Testing Report
- Biochar Testing Plan
- Biochar Utilization Plan
- PP30 Gas-Making Module Engineering Validation Test Results
- PP30 Gas-Making Module Engineering Validation Test Plan
- PP30 Gas-Making Module Design Drawings Report
- PP30 Automation and Controls Module Design Drawings Report
- PP30 Automation and Controls Module Engineering Validation Test Results
- PP30 Automation and Controls Module Engineering Validation Test Plan
- PP30 Automation and Controls Module Design Drawings Report
- CBM Integration Engineering Validation Test Results
- CBM Prototype Manufacturing Report
- CBM Integration Engineering Validation Test Results
- CBM Integration Engineering Validation Test Plan
- CBM Integration Design Drawings Report
- UL Phase 1 Engineering Review Report
- CBM Manufacturing and Supply Chain Plan
- Bill of Material Report
- In-House CBM Commissioning and Bench Testing Plan
- Feedstock Qualification Plan
- Feedstock Supply Chain Report
- Interconnection Installation Plan
- Pilot Demonstration Site Preparation Plan
- Transportation and Installation Plan
- Pilot Demonstration Site Commissioning Plan
- Extended Operation Plan
- Measurement and Verification Report
- Technology Transfer Plan
- Technology Transfer Summary Report

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ENERGY RESEARCH AND DEVELOPMENT DIVISION

APPENDIX A: Measurement and Verification Report Calculations

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APPENDIX A: Measurement and Verification Report Calculations

Calculations for deriving available energy:

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

Comparing total system efficiencies, the following are found:

- CHP overall system efficiency according to 'Overall CHP System Boundary' in Figure 1. This is the efficiency of biomass energy content to net electricity generation and the output heat.

$$\eta_{ovl} = \frac{J_{net} + P_{th} + \dot{E}_{ch}}{\dot{E}_{FS}}$$

$$\eta_{ovl} = \frac{8.99 + 23.9 + 15.3}{85.93} = 56.1\%$$

- Study system efficiency according to the 'Study System Boundary' in Figure 1. This is the efficiency of producer gas energy content to net electricity and the output heat.

$$\eta_{sys} = \frac{J_{net} + P_{th}}{\dot{E}_{PG}}$$

$$\eta_{sys} = \frac{8.99 + 23.9}{48.4} = 67.9\%$$

- Thermal system efficiency of the CHP system is defined as the heat output from the system to the producer gas energy content.

$$\eta_{CHP,t} = \frac{P_{th}}{\dot{E}_{PG}}$$

$$\eta_{CHP,t} = \frac{23.9}{48.4} = 49.4\%$$

- Electricity efficiency of the generator. This is the efficiency of producer gas energy content to total electricity output.

$$\eta_{CHP,e} = \frac{J_{tot}}{\dot{E}_{PG}}$$

$$\eta_{CHP,e} = \frac{9.8}{48.4} = 20.2\%$$

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APPENDIX B: Tables

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APPENDIX B: Tables

Table B-1: Overview of Biochar Testing and Characteristics

Sample		1	2	3	4	5
Production Date		6/15/23	7/14/23	7/27/23	8/3/23	2/15/24
Test Results Date		8/3/23	8/3/23	8/16/23	8/16/23	3/15/24
Biomass Feedstock		Walnut Shells	Wood Chips	Wood Pellets	Pistachio Shells	Walnut Shells
Criteria		Test Results				
Organic Carbon (%)	**> 90%**	81.5%	94.4%	90.8%	92.90%	91.2%
H:C org Ratio	**< 0.7**	0.34	0.17	0.37	0.27	0.22
Surface Area (m^2/g)	**Declaration**	223	537	208	252	337
EPA 16 PAHs (mg/kg)	**IBI < 300 EBC <6**	FAIL (EBC) - 28	PASS - 1.5	PASS - 1.11	PASS -0	PASS - 2.5
EFSA 8 PAHs (mg/kg)	**EBC <1**	PASS – Non-detect	PASS - Non-detect	PASS - Non-detect	PASS - Non-detect	PASS - Non-detect
Heavy Metals (mg/kg)	**PASS (all metals below IBI thresholds)**	FAIL (Nickel 524 > 420)	PASS	PASS	PASS	PASS

EBC=European Biochar Certificate
Source: All Power Labs, 2024

Note that surface area correlation to butane activity as defined as reported by Soil Control Labs.