CALIFORNIA
ENERGY COMMISSION

Energy Research and Development Division

FINAL PROJECT REPORT

Cleaner Air, Cleaner Energy

Converting Forest Fire Management Waste to On Demand Renewable Energy

Gavin Newsom, Governor
May 2020 | CEC-500-2020-033

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Contract Number: EPC-14-051

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ACKNOWLEDGEMENTS

The authors would like to thank the project partners and all the folks at All Power Labs who contributed to this project. Our project partners included: the Green Waste Recycle Yard in Richmond (for hosting some of the infield pilot testing The Energy and Resources Group; Department of Environmental Science, Policy, and Management; Renewable and Appropriate Energy Laboratory; and the Goldman School of Public Policy from the University of California, Berkeley, for their in depth research into the large-scale regional tree die-off events in California as a resource distributed biomass energy solution. Lastly, over the course of this project, in addition to the authors of this report, many individuals from All Power Labs contributed to this project including; Alejandro Abalos, Joel Armin-Hoiland, Bill Bayer, Nick Bindbeutel, Nesdon Booth, Tyler Brown, Ike Cantrell, Jay Hasty, Ryan Hasty, Dylan Huber, Sam Kaufman-Martin, Abinashi Khalsa, Jaanisar Khan, Austin Liu, Adrienne Lemberger, Noah Levine, Juan Martinez, Johnny Mascolo, Nick Monahan, Andrew North, John Mortera, Steve Nelson, Hugh Patterson, Tom Price, Christine Salamante, Sarah Schubert, James Villalovos, Ferdinand Vinoya, Herman Vinoya, and Baylis Weaver.

Project Team

All Power Labs Engineering Development and Testing Team

This grant, the team evolved a bit from the team that originally started this project. Outlined are the initial research team and the final research team.

Initial Core Research Team

- Jim Mason: Project Manager and Principal Investigator
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- Green Waste Recycle Yard

See Appendix C for the technical paper elaborated by the University of California, Berkeley's team (Citation: Lara JD, Tubbesing CL, Battles JJ, Tittmann PW, Kammen DM. *Analysis of the Woody Biomass Feedstock Potential Resulting from California's Drought*. California Energy Commission. Publication Number: CEC-500-201X-XXX, Appendix C.)

Technical Advisory Council

This project used a technical advisory council of experts in the field, which included these individuals.

- Tom Miles, TR Miles Technical Consulting Inc: Principal and Expert in Biomass Energy, Fuel Handling, and Air Quality
- Rob Williams, University of California, Davis: Research Engineer, Biomass Energy and Fuels
- Brendan Keefe, Sovereign Energy Storage: Developer of Energy Storage and Renewable Energy Projects

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 CEC and the state's three largest investor-owned utilities — Pacific Gas and Electric Company, San Diego Gas & 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.

Cleaner Air, Cleaner Energy: Converting Forest Fire Management Waste to On Demand Renewable Energy is the final report for the research and development project (Contract Number EPC-14-051) 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 CEC at 916-327-1551.

ABSTRACT

Large-scale regional tree deaths can create disposal challenges but have the potential to produce substantial feedstock for renewable electricity production. Using this feedstock, this project offers a solution that addresses a range of California’s energy, climate, and air quality goals. The project team designed, tested, and demonstrated a 150-kilowatt modular biomass gasification electrical generator system called the Powertainer. This technology makes possible the generation of renewable electricity using fire-damaged material, while lowering air pollution emissions when compared to open burning.

The use of forest residues from high fire risk regions to fuel the Powertainer benefits California. Using biomass material from dead trees makes forest fires less prone and less extreme, and produces fewer harmful emissions, while reducing property damage. Harvesting forest products and generation of distributed renewable electricity supports the local economy and creates jobs. The biochar production adds to the benefits of using biomass gasification systems, since it can result in a carbon-negative outcome, contributing directly to the reversal of climate change.

Addressing the annual tree mortality crisis requires use of 9,589 Powertainers. In total, the Powertainers would consume 10 million bone dry tons of lumber per year running 60 percent of the time (or 5,256 hours per year). This scenario would produce 7,560 gigawatt hours of renewable electricity. When compared to open pile burning, it would reduce carbon dioxide emissions by 20.3 percent, methane by 51.7 percent, carbon monoxide by 99.9 percent, and particulate matter by 99.9 percent. Annually, this technology has the capacity to sequester 1.45 million metric tons of CO2, create 7,000 jobs, and manage 700,000 acres of forest.

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

Please use the following citation for this report:

Mason, Jim, Ariel Fisk-Vittori, Brendan Quinlan, and Justin Knapp. 2020. *Cleaner Air, Cleaner Energy: Converting Forest Fire Management Waste to On Demand Renewable Energy*. California Energy Commission. Publication Number: CEC-500-2020-033.

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EXECUTIVE SUMMARY

Introduction

Climate change is contributing to a forest health crisis in California, with a tree mortality emergency that resulted, according to the Mortality Task Force, in over 130 million dead trees in 2017. This fuel supply has contributed to catastrophic wildfires throughout California, releasing record amounts of greenhouse gases into the atmosphere. There is a pressing need for an economical and climate-sensitive strategy to thin the forests reducing the risk of wildfires, while also addressing the state's environmental and clean energy goals. The state's current forest fire management practice aims to protect human life and communities but focuses heavily toward prescribed burns. For example, felled trees have been hauled to localized log landing sites and burned. This practice is expensive, limited, and creates additional problems, such as air quality issues, the release of large amounts of black carbon and greenhouse gases into the atmosphere, and fails to harvest the energy stored in the timber.

Additionally, California's utility grid is vulnerable to catastrophic ecological and weather-related events such as the Camp Fire that ravaged the northern portion of the state in November 2018. It is crucial to provide alternative energy solutions that can feed into the grid (thereby reducing strain), and function in off-grid and emergency environments.

This project offers a solution that uniquely addresses a range of California's energy, climate, and air quality goals. The Powertainer is a 150-kilowatt modular biomass gasification electrical generator developed under this project. It represents one of the few on-demand electrical generation technologies that can meaningfully address this range of challenges. During the project period, the project team designed, tested, validated the performance of the Powertainer, and used the technology to generate renewable electricity from fire remediation material, demonstrating its ability to lower air emissions when compared to the open burning alternative, while meeting applicable Shasta County air quality standards.

Alternative energy solutions have the prospect of helping to reduce Californians' energy costs by reducing the use of centralized power plants and municipal-scale generation. Biomass energy is unique among other technologies by converting biomass waste streams into a renewable energy source. As the state's population and gross energy consumption rises, it is necessary to create a parallel power generation strategy that supplements the utility grid ensuring the state can produce sufficient power.

The effects of climate change have contributed to extreme drought and the tree mortality crisis. The research derived from this project helps address these challenges and advances California's clean energy policies.

The Powertainer also contributes to the following policy objectives:

- Senate Bill 100 (*California Renewables Portfolio Standard Program* [Chapter 312, Statutes of 2018])
- Senate Bill 350 (*Clean Energy and Pollution Reduction Act of 2015* [Chapter 547, Statutes of 2015])

- Renewables portfolio standard (Senate Bill X1-2, [Simitian, Chapter 1, Statutes of 2011); Senate Bill 107 [Simitian, Chapter 464, Statutes of 2006]; Senate Bill 1078 (Sher, Chapter 516, Statutes of 2002])
- Assembly Bill 32 (*The Global Warming Solutions Act of 2006* [Chapter 488, Statutes 2006])
- Senate Bill 1122 – Bioenergy feed-in tariff (Chapter 612, Statutes of 2012)
- Senate Bill 96 (*Committee on Budget and Fiscal Review*, Chapter 356, Statutes of 2013)
- Executive Order B-55-18 to Achieve Carbon Neutrality by 2045 (September 2018)
- Proclamation of a State of Emergency to protect communities against unprecedented tree die-off (October 30, 2015)
- Short-Lived Climate Pollutant Reduction Strategy (March 2017)

The Powertainer is a technology suitable to address this emergency by generating electricity and heat from dead trees and producing biochar for agricultural applications. Traditional large centralized biomass plants require fuel to be transported large distances, potentially offsetting the value of the fuel itself. The premise behind the Powertainer is that the technology fits within a standard shipping container that can be easily moved and set up close to fuel sources.

One of the largest obstacles experienced by this type of technology is the expensive regulatory challenges that delay project deployment. To have a viable portable energy solution, regulations are required that support small-scale, distributed energy projects. To facilitate the process of obtaining permits for biomass operations, permitting agencies (and legislators) must be informed about the benefits of unconventional renewable energy technologies, such as gasification. Permitting agencies have little familiarity with biomass energy technologies, especially at this small scale, resulting in small facilities having to comply with permitting requirements designed for large-scale projects. Further difficulty results from certification agencies such as Underwriters Laboratories not having a defined category for this type of technology. Another difficulty stems from the current readiness level of the technology, which has not reached commercialization. With the tree mortality emergency ongoing, and greater damage from forest fires each year directly affecting public safety, the development and implementation of real solutions should be accelerated as much as possible. Regulatory barriers affecting technology development should be addressed.

Project Purpose

This team designed, deployed, and tested a modular 150-kilowatt, mobile biomass gasification generator (the Powertainer) that converts forest slash into on-demand renewable energy, while meeting California air quality standards. The project team anticipated that the primary technical challenge would be to successfully scale the gasifier and the gas making system. However, the team experienced other unforeseen challenges, the most important having to do with regulation and interconnection. The regulatory challenges centered on costs, lead times, and permitting requirements not suited for an emerging technology. Regardless of these barriers, the project team was able to successfully operate and demonstrate the technology. However, before reaching commercial readiness, All Power Labs identified that further maturity of the system and new features were necessary to maximize the value of harvesting forestry biomass waste. Therefore, All Power Labs is working on the improvement and refinement of the Powertainer under a new California Energy Commission's (Energy Commission) project. The improved technology will be called the Powertainer plus.

The project team expected to complete a beta prototype of the Powertainer and demonstrate its ability to use forestry biomass waste to produce clean renewable power, and tie that electricity into the electrical grid. However, due to regulatory challenges, the team was not able to demonstrate the technology while connected to the grid. Therefore, the Powertainer demonstrated its operational status and capabilities in a standalone, off-grid demonstration.

The Powertainer is important for California because of the broad range of benefits it offers, especially when addressing the tree mortality crisis by using forestry biomass waste as fuel. The forestry waste can be converted to on-demand, clean, renewable energy, as well as a very high quality biochar byproduct. When biochar (which looks like a fine-grained charcoal) is made, the organic material is converted into a stable form of carbon that can't easily escape the atmosphere. Thus, the forest waste becomes largely carbon neutral. Using biochar as a soil amendment improves the soil's ability to attract and hold moisture and nutrients (like nitrogen and phosphorous).

This technology enables an integrated forestry management strategy that promotes thinning of the forest, which aids in reducing the risk of catastrophic forest fires, and contributes to increased water security with the reduction of water used to fight wildfires as well as increased soil water retention due to the use of biochar. In addition, the Powertainer reduces greenhouse gas emissions and some criteria pollutants such as carbon monoxide and small particulate matter. The reduction of air pollutants is substantial, especially when compared to forest fires or open burning of the dead trees. This solution monetizes the fire remediation harvests, highlighting their potential to help finance fire management programs.

The project results are two-fold. All Power Labs will use the results to continue maturing the Powertainer platform and marketing material to support the launch of future Powertainer projects — either as an equipment sale, or a waste-to-energy project. Secondly, it is also important that the regulatory challenges experienced in the project become visible to appropriate policy makers. In that way, regulatory barriers can be removed or reduced for projects using bioenergy solutions — such as the Powertainer — to address the tree mortality crisis.

Project Approach

To successfully design and build a 150-killowatt portable biomass generator, all system components had to fit inside a standard 20-foot-long (6 meters) shipping container. The primary integrated components include the hopper feed system, biomass gasifier and filter, flare, engine genset (self-contained and dedicated electrical generation system) and emissions control, and automation system. Once built, the project team performed a combination of on- and off-site remote testing of the Powertainer. The team developed and used engineering and design validation testing procedures to qualify individual components — as well as the fully integrated system — and enable a feedback loop for system improvements. For example, the gasification system uses instrumentation and data logs to understand system performance and dynamics. The team performed in-field testing to gain a deeper understanding of real-world operations and associated challenges. Final performance and emissions testing included 40 hours of full system operations.

All Power Labs addressed technical challenges through an iterative process of physical testing and refinement. This approach enabled the team to implement a distributed testing approach proving and maturing individual components, then integrating all systems together to better understand how all components work together. The development of the Powertainer flare represents a good example of this process. The flare uses an automated mixing system to control the stability of combustion inside the flare. The team designed and assembled the flare as a standalone system to isolate the testing of the automated mixing system. After understanding and confirming the flare's performance, the project team installed it on the Powertainer for further testing and refinement.

The non-technical challenges focused on regulatory, interconnection, and permitting requirements, which were complex and costly considering the scale of the project installation. Some of the complication relates to non-standardized air quality permitting requirements that make permitting simpler in some jurisdictions and more difficult in others. Others include flat rate permitting costs for systems regardless of the system's size. Unless regulatory requirements change, it will be difficult and expensive to prove the performance and viability of a gasification system when connected to the electric grid, especially for small, distributed-scale projects. Exacerbating the issue is the reality that small-scale, portable biomass generation equipment is new, compared to established technology; and that regulatory requirements are not suited for this specific architecture and portable project model.

Project Results

The project team completed and demonstrated the Powertainer prototype. The final product included changes from the original proposal. Site and regulatory challenges prevented the project from operating the Powertainer at its intended site in Placer County, with grid interconnection. Instead, the project team conducted the final performance testing at the All Power Labs facility in Berkeley, without an interconnection.

During the 40 hours of off-grid performance testing, the technology met the majority of the performance targets set in the testing plan. However, it is worth noting that the Powertainer was not able to reach the expected electrical output of 150-killowatt during this test period. The team expects that the lower electrical output is the result of a pressure drop caused by "bell packing" (which is where producer gas is choked off and does not flow consistently through the cross section of the gasifier restriction) in the gasifier's ash-removal system, preventing an adequate amount of gas to get to the engine. The team thinks this issue can be resolved by improving the grate basket design in the gasifier's ash removal system to enable the spent char to exit the system without inhibiting gas flow.

Despite some design issues, the Powertainer demonstrated its ability to use forestry biomass waste to create portable clean renewable energy. Through the project, the Powertainer demonstrated many competitive advantages, such as its small-scale design, portable architecture, capital cost, fuel flexibility, and production of electricity and biochar. This multi-model design maximizes the climate impact value of this technology, making it a unique carbon-negative emissions technology. The Powertainer is still in a prototype testing stage and requires additional testing and refinement before the technology will be ready for commercial deployment. Changes in regulatory and permitting requirements would facilitate the deployment of the Powertainer product.

Conclusion

The 150-killowatt Powertainer demonstrated how a containerized and portable gasification system could address the tree mortality crisis by converting forestry waste into clean, renewable energy, and sequestering carbon by producing biochar. Despite experiencing both technical and regulatory challenges, this project sets the groundwork for future studies and development using the Powertainer. This technology continues to represent an attractive option that supports California's goals related to clean energy, climate change, and air quality. Because this technology addresses many benefits to California, it is critical to continue developing the Powertainer until it becomes a viable technology and energy option that can be deployed across California, especially areas affected by the tree mortality crisis.

Recommendations

In the midst of the changing climate and the effects already experienced across the state, it is critical that policy makers recognize the importance and unique benefits of biomass energy and promote the biomass market. In particular, innovative use of thinned material and other biomass harvested to reduce the risk of wildfire, to support forest-dependent economies, and ongoing forest management activities. One strategy is to encourage the siting of wood products manufacturing facilities and small-scale biomass energy near each other, to create regional economic hubs. Such hubs would become ideal locations for the Powertainer to use biomass waste to create electricity and biochar.

To be successful, the state needs to address the regulatory challenges inherit in pilot testing. The team experienced obstacles in the process of getting permits and interconnection approval, especially for a pilot project using an innovative energy technology. This not only makes pilot projects difficult to validate, but also slows down commercialization. It also provides an example of the challenges the market will face until products become more commonly used. For a research and development project, with a technology at an early development level, the usual regulatory and permitting costs, schedules, and requirements are very challenging to overcome. Based on this, a special category of permits and/or exemptions could be sponsored at the state-level to support the development and pilot testing of new technologies. Such an approach would make it easier to test new products, accelerate the proving process, and therefore, reduce the time it takes to bring it to market.

Specifically, the team recommends further investment to bring this product to commercial production. Additional funding will enable improvements to the existing design, but also allow the development of additional features enhancing the benefits of this technology, especially for its application to the tree mortality crisis. Some of these new features includes increased use of waste, higher electrical output, added combined heat and power, enabling usable heat, and increased production of high-temperature biochar.

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

All Power Labs continues to share the development of this product with the public. It expects release of the Powertainer to the market starting in 2020. The team is applying all the lessons learned from this project in a new Energy Commission project, which develops higher-capacity power generation, increased biochar off-take capability, combined heat and power component, and other improvements. The team expects to complete and test the Powertainer plus in 2020.

All Power Labs is researching technology architectures that leverage regulatory interconnection maturity of other renewable generation technology, such as solar. For instance, the project team is identifying opportunities for integrating energy storage and inverter technology to overcome regulatory hurdles, since the grid-tie market understands those components very well. This work would greatly increase the viability of biomass as a renewable energy solution. In addition, All Power Labs is reviewing off-grid applications, which provide meaningful waste disposal capacity per unit, and produce biochar for agronomic and commercial use.

To help this new and important innovative technology reach the market, All Power Labs uses a handful of online and public-facing outreach opportunities. As an authority in small-scale gasification technologies, All Power Labs' website is a go-to destination. By highlighting the Powertainer as an upcoming technology, All Power Labs is able to bring international attention and interest to the Powertainer. As effective as All Power Labs' online presence is, it also prioritizes in-person outreach within California by using monthly open houses, and dedicated gatherings and demonstrations, focused on the Powertainer technology.

The initial target market for this technology is the biomass waste management industry — one that interfaces with forestry products, produces biomass waste, and has electricity and heat demands. In many ways this represents an optimal use for this type of technology, which provides important benefits to California. In addition, since the Powertainer produces a very high-quality biochar byproduct, this technology has the added advantage of being carbon negative.

Another major hurdle to market adoption relates to being able to point to a project that has been able to successfully work through regulatory challenges and operate in a target market. Once this occurs and there is a precedent, All Power Labs anticipates that the market will open up to more projects across the state.

All Power Labs has a business model combining direct retail equipment sales with the provision of waste-to-energy services to generate revenue from the deployment of Powertainers projects. In the waste-to-energy services model, All Power Labs develops projects, owning and operating the equipment itself, and the site host or off-taker pays for the energy, biochar, and waste processing services. This model eliminates up-front capital cost for the customer and provides All Power Labs with a recurring revenue stream. All Power Labs intends for the waste-to-energy services portion of its business to generate a larger share of revenue compared to retail sales, as it provides a more stable, and ultimately larger, revenue stream. Waste-to-energy service projects can also leverage structured financing, expanding All Power Labs' capacity to deploy revenue-generating assets.

In both models, All Power Labs' customers will be commercial or institutional customers with biomass waste streams and energy requirements. To reach these customers, All Power Labs' marketing strategy consists of making connections using paid consultants and networking with regional partners — such as trade groups and academics — followed by targeted periodical and online advertising in areas with high tree mortality.

Benefits to California

The Powertainer has the potential to create jobs across multiple sectors, including manufacturing, feedstock supply chain (harvesting, processing, and transport), equipment operation, construction, and project development. Some of the benefits that commercial-scale biomass power generation systems offer California ratepayers includes:

- Greater reliability, clean energy
- Improves energy security by supplementing the utility grid
- Lowers cost
- Increases safety by reducing wildfire risk
- Improves public health
- Promotes economic development
- Provides environmental benefits
- Advances state policy goals for climate change

CHAPTER 1: Introduction

Project Goals and Objectives

The project addressed California's tree mortality crisis and its stance on climate change, by developing and testing a new energy technology, the 150-kilowatt (kW) Powertainer. The Powertainer is a modular biomass gasification platform that converts woody biomass such as forest waste to renewable, on-demand, carbon-negative energy. In addition, All Power Labs partnered with two laboratories at the University of California, Berkeley. They conducted a comprehensive economic and regional analysis of large-scale regional tree die-off and inter-connection locations to determine the market opportunity for this novel technology, under this unique fire mitigation use case. Further, by monetizing forest refuse, the resulting increased thinning will aid in reducing the risk of catastrophic wildfire. Reduced forest load will also contribute to additional water and hydropower resources. With estimates based on historical data, gasification for energy instead of burning for disposal will substantially reduce greenhouse gas emissions.

Through this project, All Power Labs demonstrated the impact of the 150-kW, 20-inch containerized biomass gasification platform operating on fire-hazard load reduction, while at the same time producing electricity.

The goals and objectives of this project include:

- Proving the design intent and viability of modular 150-kW systems to convert forest waste to electricity, while meeting applicable emissions standards
- Analysis and summary of air quality improvements
- Quantifying the economics of small-scale biomass gasification to create renewable electricity, while improving air quality, and scope of potential market opportunity for biomass waste to scale as a renewable energy solution
- Quantifying the potential monetization of forest waste
- Analysis of the financial value to the electrical grid of creating on demand mobile renewable electricity

The research under this project fits directly within the larger narrative of California's energy policy, as well as other climate-change policies and laws. This is an unprecedented time where the effects of climate change are being experienced throughout the state. Several years of drought and insect attacks have killed over 150 million trees and the state expects those numbers to increase until precipitation returns to normal levels over the course of many years. Governor Brown issued an emergency proclamation in October 2015 to raise awareness and start directly addressing this catastrophic issue. More recently, Executive Order B-42-17 aims to strengthen the response. The Powertainer is an ideal fit for addressing this emergency because the dead trees are a potential fuel that can produce electricity, usable heat, and biochar, providing products with immediate value across a larger range of benefits to the state.

The following additional policies are compatible with the Powertainer technology.

- Senate Bill 100 (California Renewables Portfolio Standard Program [Statutes of 2018]). Senate Bill 100 specifies 60 percent renewable energy by 2030 and 100 percent clean energy by 2045.
- Senate Bill 350 (Clean Energy and Pollution Reduction Act of 2015 [Statutes of 2015]). Senate Bill 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 (Senate Bill X1-2, (Simitian, Ch.1, Statutes of 2011); Senate Bill 107 (Simitian, Ch. 464, Statutes of 2006); Senate Bill 1078 (Sher, Ch. 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 the Renewables Portfolio Standard.
- Assembly Bill 32 (The Global Warming Solutions Act of 2006). Assembly Bill 32 created a comprehensive program to reduce greenhouse gas emissions in California. Greenhouse gas reduction strategies include a reduction mandate of 1990 levels by 2020 and a cap-and-trade program. Assembly Bill 32 also required the California Air Resources Board to develop a scoping plan that describes the approach California will take to reduce greenhouse gases. They must update the plan every five years.
- SB 1122 – Bioenergy feed-in tariff (Rubio, Chapter 612, Statutes of 2012). Senate Bill 1122 requires the California Public Utilities Commission to direct the investor-owned electric utilities to procure collectively at least 250 megawatts (MW) of eligible renewable energy from small-scale bioenergy projects with capacities of three MW or less.
- Senate Bill 96 (Committee on Budget and Fiscal Review, Chapter 356, Statutes of 2013). Senate Bill 96 stipulates that in administering the EPIC program, the Energy Commission fund research, 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 important technological challenges
- Proclamation of a State of Emergency to protect communities against unprecedented tree die-off (October 30, 2015). 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* (March 2017). 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 CO2. The impacts of short-lived climate pollutants are especially strong over the short-term. Reducing these emissions can have an immediate beneficial impact on climate change.

Technology Background

All Power Labs has been at the forefront of small-scale gasification technologies for over 10 years, designing, engineering, building, and deploying compact biomass gasifiers, largely for off-grid power use in the developing world. In 2012, the University of Minnesota and the United States Department of Energy hired All Power Labs to build the first Powertainer — a containerized, fully functional ‘alpha’ prototype, designed to operate on the combination of corncobs and diesel. This project continued to leverage All Power Labs’ smaller units and scale it to a larger form factor to create a 150-kW power plant in a 20-foot-long container designed to operate on a variety of forest products.

The beta Powertainer uses an innovative Imbert-style downdraft gasifier paired with an internal combustion engine to produce up to 150 kW of electrical power from forest refuse biomass. The system converts a portion of the biomass into biochar, which provides agronomic and climate benefits when returned to the soil via co-composting. The 150-kW Powertainer is designed for distributed generation applications, ease of use, and deployment by integrating all the major assemblies and components into a standard 20-foot-long shipping container.

Market and Technology Challenges

The Powertainer continues to be a technology with immense potential to address and contribute towards California's clean energy goals. The premise behind the Powertainer and its design is that it fits in a shipping container 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 has to be transported large distances, potentially offsetting the value of the fuel itself. The largest obstacles experienced during this project had to do with regulatory challenges, which represent the largest hurdle related to market penetration. To develop a viable portable energy solution that can address a challenge such as the tree mortality crisis, it is essential that regulatory requirements be established that better support the development of project models and energy technology options. Regulations should provide an incentive for pilot testing in real world use cases. The permitting challenges experienced during the project make a new energy technology like the Powertainer take longer to prove and bring to market. Experts anticipate that any new energy technology will experience challenges in these areas. The permitting and interconnection process proved to be cost and time prohibitive, especially for a new emerging energy technology developed by small companies. In addition, Pacific Gas and Electric Company’s experience illustrates that a utility has little incentive or interest in enabling new distributed technologies to connect with the grid. Additionally, the team experienced that permitting agencies have little familiarity with biomass energy technologies at this small scale, which results in them having to meet extreme permitting requirements. This challenges the ability for projects to get off the ground — especially emerging energy technologies.

The market is currently unable to address these regulatory challenges because the technology development has not reached a state where it can be deployed. Therefore, the market is not yet fighting the same regulatory challenges as were experienced through this project and regulations have not been developed to address these situations. With the tree mortality emergency ongoing and greater damage from forest fires occurring each year, public safety is directly affected. The development and implementation of real solutions must be accelerated as much as possible with regulatory barriers impacting the acceleration of development and technology being reduced, relaxed, or removed.

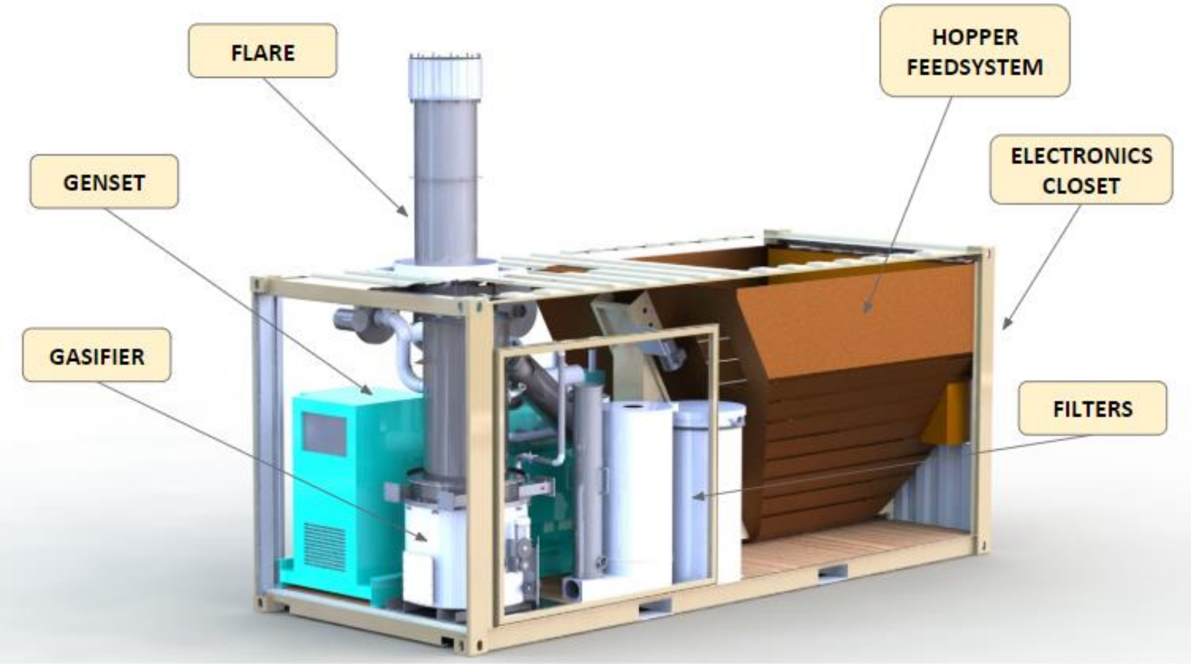
CHAPTER 2: Powertainer Design and Validation Testing Results

Powertainer Design Summary

Under the scope of the engineering development, the project team designed and tested a beta 1 Powertainer prototype, which consists of the following subsystems, as presented in Figure 1:

- Enclosure and Hopper Feed System
- Gasifier and Filter
- Flare
- Genset
- Exhaust Control System
- Automation Controls

Figure 1: Powertainer Design Drawing Rendering with Major Subsystems Call-Outs



Source: All Power Labs (2020)

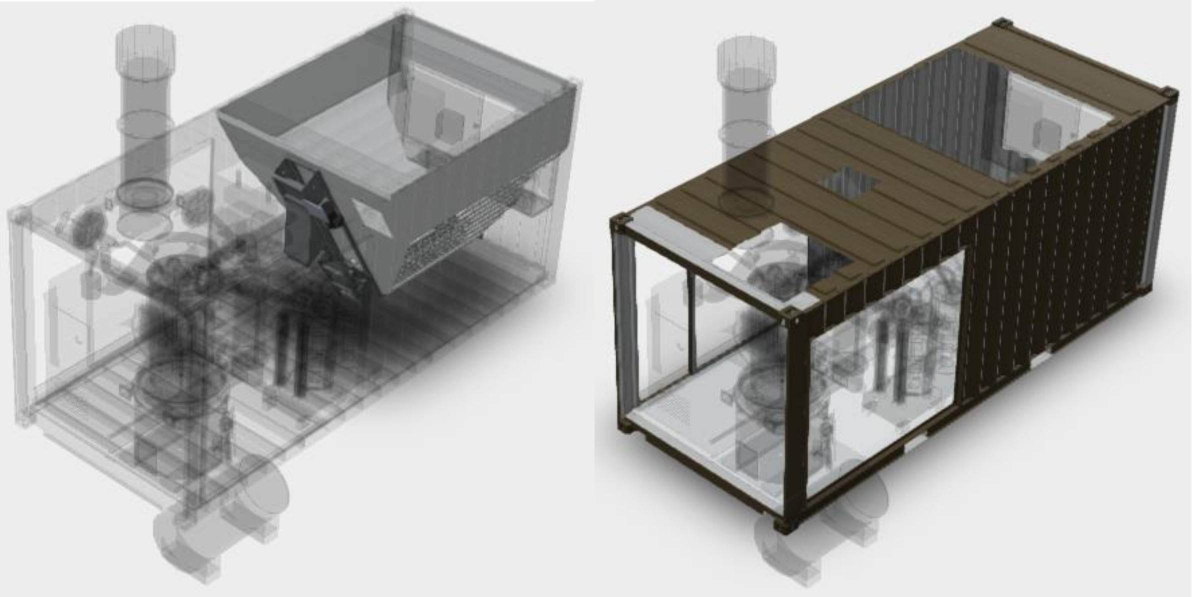
The following sections explain the design, engineering validation testing and design validation testing activities and the results of each subsystem.

Enclosure and Hopper Feed System, Engineering and Design Validation Testing

The Powertainer enclosure uses a 20-foot-long shipping container (Figure 2). The design added doors for additional access to strategic components; particularly the engine and gasifier, and included a pass-through into the roof for the flare stack and exhaust routing to feed through. The design also positioned an electrical panel enclosure in the rear of the enclosure to house the automation controls components.

The purpose of the hopper is to store the biomass used to operate the Powertainer. Its location is in the back half of the container and is open to the atmosphere from above, so operators are able to load easily the fuel from above. The hopper holds enough fuel for an eight-hour run during a high load (100– to 150-kW) application. The design of the hopper uses sheet metal in layers to allow hot air to flow into the fuel to enable final drying. The "spine" at the bottom of the hopper covering the drag chain components works as a fuel-metering device. Steel beams run across the top of the hopper to allow for a tarp or soft cover to protect fuel from weather events.

Figure 2: Enclosure Design Drawing Renderings



Source: All Power Labs (2020)

Engineering Validation Testing Criteria

- Internal feed rate. The internal feed system can sustain a fuel transfer rate to the gasifier of up to 4.28 kilograms/minute.
- External feed rate. The external feed system can sustain a fuel transfer rate to the gasifier of up to 4.28 kilograms/minute.

Engineering Validation Testing Results

Table 1 shows the results from the fuel feed system evaluation.

Table 1: Evaluation Results Powertainer Feed System, Engineering Validation Testing

Test	Criteria/ Threshold	Measured/ Calculated Values	Result	Description
Internal feed rate	4.28 kg/min	10 kg/min	Pass	The internal feed rate was greater than the threshold value in the criteria
External feed rate	4.28 kg/min	>10 kg/min	Pass	The external feed rate was greater than the threshold value in the criteria

kg/min = kilograms/minute

Source: All Power Labs (2020)

- Internal feed system. The system was successful at delivering the required feed rate to allow peak power and high uptime without overloading any of the motors or exceeding any of the allowable duty cycles. The internal fuel conveying system, comprising of the fuel drag chain, fuel valve, and fuel auger, was used at 15 percent duty cycle at 50 kW load. This implies the system can handle 333 kW of load at 100 percent fuel conveyor system duty cycle. All components are rated for continuous duty, so this number accurately represents the system maximum capacity.
- External feed system. A forklift emptied super sacks (bulk storage bags filled with fuel) into the hopper. This method was able to keep up with fuel consumption with a large margin of extra capacity. The system was able to deliver sufficient fuel using this technique as long as there was more than one operator present. The forest sector presents a variety of off-the-shelf systems that can deliver fuel to the hopper within the given specification.

Design Validation Testing Criteria

- Fuel dryness. Green-basis percent moisture content by mass is less than 30 percent.
- The airlock leak-down rate. This rate is the change in pressure divided by the change in time for the fuel feed subsystem while installed in the Powertainer system. It must not exceed the threshold value of 25 Pascal/second. The system leak rate will measure the gas tightness of the fuel feed subsystem as a part of the Powertainer system.
- Unscheduled maintenance. The feed systems encounter less than one instance of unscheduled maintenance per 200 kilowatt-hour (kWh) of electricity produced by the genset.

Design Validation Testing Results

Table 2 shows the results from the Powertainer feed system evaluation.

Table 2: Evaluation Results Powertainer Feed System, Design Validation Testing

Test	Criteria/ Threshold	Measured/ Calculated Values	Result	Description
Fuel dryness	<30% db	11.80% db	Pass	The moisture content of the fuel was below the threshold value in the criteria
Airlock leak-down rate	<25 Pa/s	30 Pa/s	Fail	The leak rate was calculated to be greater than the threshold value
Unscheduled maintenance	<1 Failure / 200 kWh	1 Failure / 200 kWh	Fail	Two failures of the feed system were recorded over 400 kWh of testing

db = dry basis Pa/s = Pascal/second

Source: All Power Labs (2020)

- Fuel dryness. Since walnut shells are a readily available waste byproduct in California and have optimal size, shape, and moisture characteristics, the project team selected this feedstock for the early testing. However, as the performance of subsystems are profiled and proven, other fuels such as wood chips will be qualified and tested. Poor weather conditions posed a challenge for maintaining optimal moisture content.
- Airlock leak-down rate. With the air intake on the gasifier sealed and vacuum pulled on the system using the gas blower, the project team can observe the amount of vacuum the gasifier is experiencing. Then, the gas blower valve is shut and the MangoES, a remote monitoring data collection system, measures the leak down rate over time. Since the feed system air lock ended up not being airtight, the gas making system was unable to meet the intended criteria.
- Unscheduled maintenance. The flex switch recalibration was likely required because the automation is set up to respond very quickly to changes in fuel level. This behavior pushes fuel against the flex switch frequently, likely leading to a circumstance where the switch was actuated with too much force from fuel packing.
- The input/output board failure resulted from being next to the exhaust catalyst. The first time was likely an internal safety disengaging the board before hardware damage occurred. The second failure resulted in permanent hardware failure of the component.
- Adding hysteresis to the fuel feed program so that the flex switch is not actuated as often will reduce wear and liability of failure of this component.
- The input/output converter board location should be far away from heat sources to prevent thermal failure modes.

Gasifier and Gas Filtration, Engineering and Design Validation Testing

The gasifier can be broken down according to three distinct assemblies, including the gas cowling, hearth, and pyrocoil.

The gasifier cowling assembly is the lower portion of the gasifier, where the final stage of gasification takes place — reduction — and where the ash removal system is located. The gas cowling assembly includes the cowling vessel wall, the grate basket that holds the charcoal for reduction, and ash removal scroll and auger.

The hearth is the component in the gasifier where the combustion takes place and is the only stage within the gasifier with the presence of atmospheric air — it is located between the pyrocoil and the gas cowling. The materials used to build the hearth included high-grade, high-temp alloy — 310 stainless steel — filled with a cast refractory insulation to address the high temperature conditions created inside the gasifier. The hearth also includes 18 air nozzles made from 310 stainless steel where the pre-heated atmospheric air enters the combustion zone.

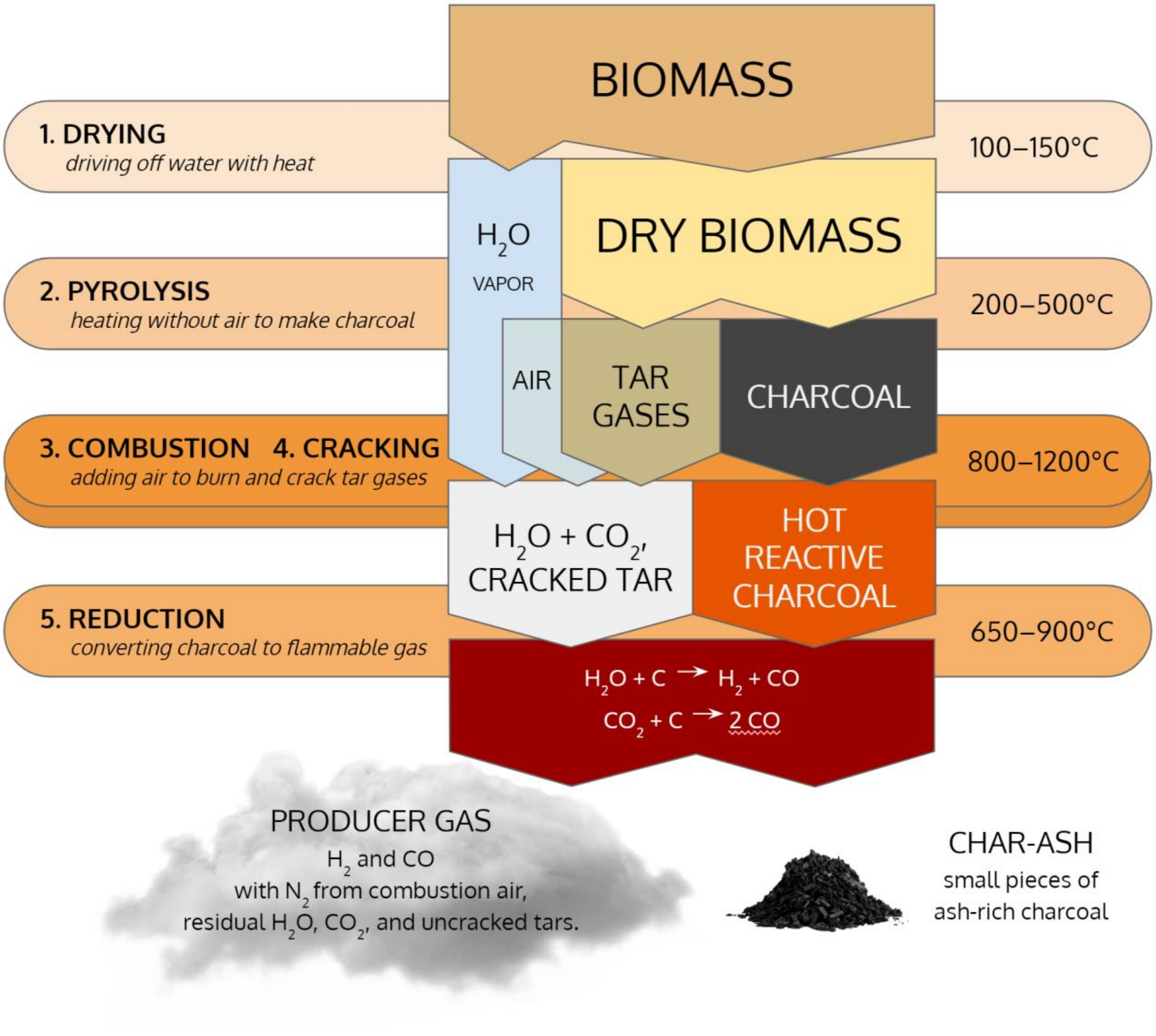
The pyrocoil is the component where pyrolysis process takes place, using the heat from the engine exhaust to convert dry biomass to charcoal. It is comprised of the double walled vessel that delivers preheated fuel into the combustion zone. It also includes a fuel level sensor used to control to fuel feed into the gasifier and a lighting port system on the sidewall to light the reactor at the beginning of operation.

Other relevant gasifier components include the ash collection system and the gas out manifold and air preheat heat exchanger.

Figure 3 shows a diagram of the gasification process and Figure 4 depicts the gasifier design drawing renderings.

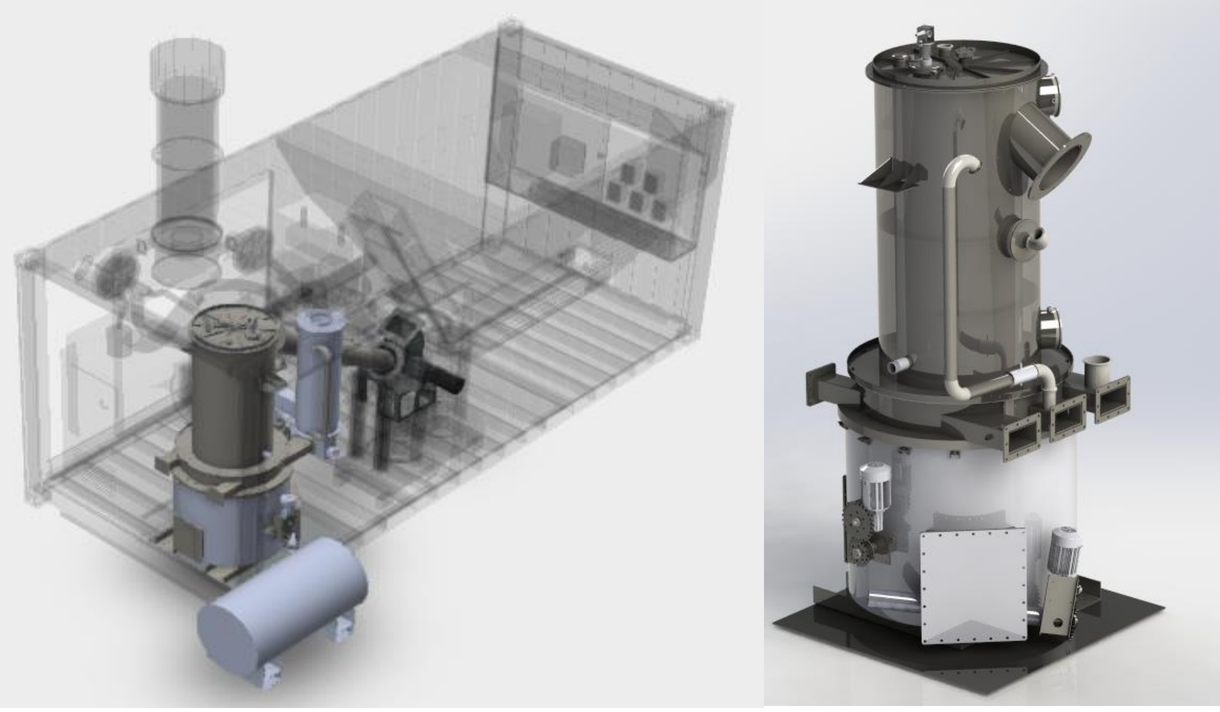
The filter system includes a “wet cyclone” that acts as a scrubber and a “char candle” for the filter media. The wet cyclone uses the condensate in a spray to drop out particulate and other items that condense, such as water vapor and tars. It also controls the temperature of the gas before going into the char candle filter. The char candle consists of four filter candles operating in parallel. Each char candle uses the charcoal waste byproduct from the gasifier, which has proven to have very high absorption capacity. The conditioned gas penetrates through the outer wall of each char candle and out a central volume where the gas can exit out of the assembly before it mixes with air again and enters the engine. This filter architecture maximizes the surface area in which the producer gas penetrates the charcoal filter media.

Figure 3: Diagram of Gasification Process



Source: All Power Labs (2020)

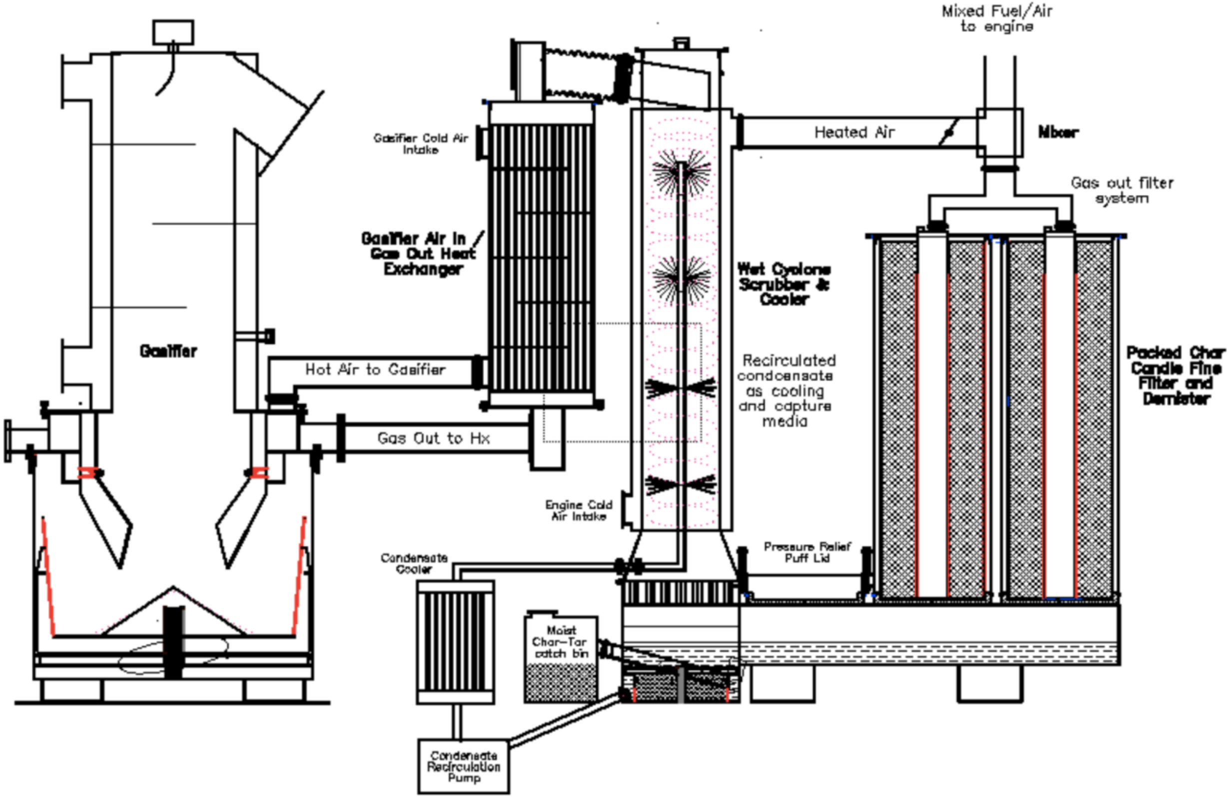
Figure 4: Gasifier Design Drawing Renderings



Source: All Power Labs (2020)

Figure 5 illustrates the configuration of key components between the gasifier and filtration system.

Figure 5: Gasifier and Gas Filtration Design Drawing



Source: All Power Labs (2020)

Engineering Validation Testing Criteria

- Gasifier leak rate. The gasifier leak rate is the amount of pressure drop over a specific period. The system passes the test if the gasifier leak rate is fewer than 10 Pascals per second.
- System vacuum leak check. This procedure measures the maximum amount of vacuum pressure that can be achieved inside the gasifier when installed in the Powertainer. The system passes the test if the measured vacuum pressure is able to exceed 2,500 Pascals.
- System leak rate. This rate is the change in pressure over a specific period while the gasifier is installed in the Powertainer. The system passes the test if the gasifier leak rate is fewer than 25 Pascals/second.

Table 3 describes the results of the gasifier engineering validation testing. The team tested the main areas: gasifier leak rate, system vacuum leak check, and system leak rate.

Table 3: Evaluation Results Gasifier, Engineering Validation Testing

Test	Criteria/ Threshold	Measured/ calculated values	Result	Description
Gasifier leak rate	<10 Pa/s	<1 Pa/s	Pass	The leak rate was calculated to be less than the threshold value and no bubbles were present during the pressure leak testing.
System vacuum leak check	>2500 Pa Vacuum	2600 Pa Vacuum	Pass	The maximum vacuum pressure was greater than the threshold value.
System leak rate	<25 Pa/s	30 Pa/s	Fail	The leak rate was calculated to be greater than the threshold value.

Pa/s = Pascal/second

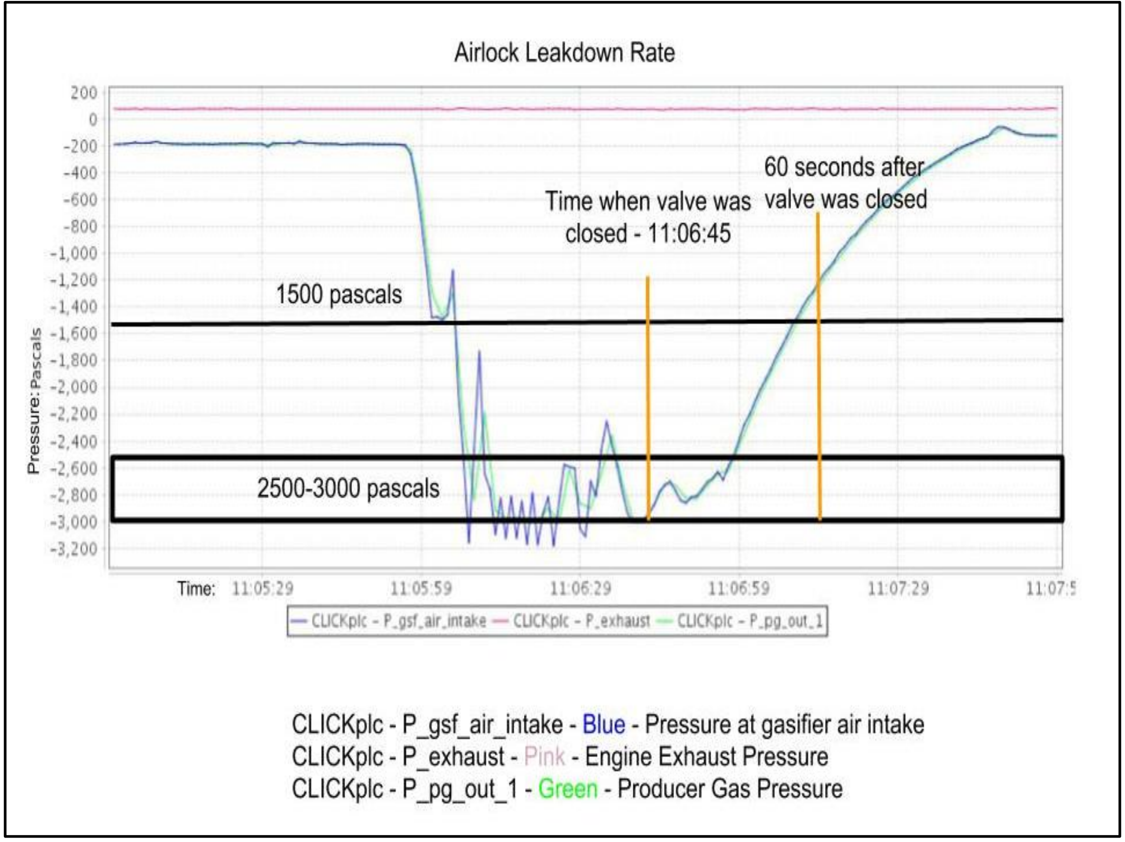
Source: All Power Labs (2020).

Engineering Validation Testing Results

- Gasifier leak rate. This test measured the leak rate of the standalone gasifier, before installation with the Powertainer. The results of the test measured below the threshold value and passed the evaluation. In addition, bubbles were not present during the final pressure leak test, further passing the evaluation.
- One of the main challenges experienced was spotting leaks at welded joints. The project team conducted numerous iterations to reduce the leak rate to an acceptable level.
- System vacuum leak check. The procedure intended to assess the gasifier readiness while installed in the Powertainer system.

Figure 6 shows the maximum vacuum pressure in the gasifier achieved with the flare blower system. This was a critical test to verify the starting/running conditions of the gasifier when integrated with the Powertainer. The maximum vacuum pressure measured during this test reached 2600 Pascals, exceeding the threshold of 2500, which passed the evaluation. This test determined that enough of a vacuum could be achieved to start and operate the Powertainer successfully.

Figure 6: System Leak Check and System Leak Rate Measurements



Source: All Power Labs (2020).

A challenging issue that arose was the sealing between ports and safety valves in and out of the gasifier. The design and methods used to seal these junctions was iterated upon until passing the test.

- System leak rate. This test intended to assess the gas tightness of the gasifier while installed in the Powertainer system. Large leaks could be a safety hazard and cause operational problems. The team conducted several iterations and found many leaks across the assembly, which were subsequently sealed. The system leak rate was improved but the star valve was the major source of leakage that could not be mitigated. The leak was found by pressurizing the system and observing a hissing sound coming from the star valve. Since the air tightness of the star valve was unable to be improved in this design, the leak rate was higher than the threshold value and, therefore, failed the evaluation.

  It was deemed safe to continue testing even with a large leak rate from the star valve due to the downdraft architecture of the reactor and the addition of pressure relief valves. The air leak into the reactor from the star valve allows the gasification process to continue but some control of air mixture and air temperature in the gasifier enabling combustion is lost. During normal operation without leaks, the air is preheated with the existing gases using a heat exchanger.

Design Validation Testing Criteria

- Start-up time. This test measures the amount of time until the gasifier has achieved temperatures suitable for engine operation, which must not exceed the less than a 15-minute threshold. The gasifier start-up time will provide planning and operational data for future testing and possible customers.
- Shutdown time. This test measures the amount of time until the gasifier has achieved temperatures and pressures suitable for engine shutdown with no operator supervision — which must not exceed the less than 15-minute threshold. The gasifier shutdown time will provide planning and operational data for future testing and possible customers.
- Maximum producer gas flow rate. This test measures the producer gas flow rate required to achieve an electrical power output of 150 kW, which must be equal to or greater than the threshold of 175 cubic meters of producer gas per hour. The maximum producer gas flow rate will help influence future testing and customer decision making.
- Continuous operational time. This test measures the amount of time the Powertainer is operating continuously while exporting 75 kW of electricity, which must be greater than the 8-hour threshold value.
- Producer gas tar concentration. This test measures the concentration of volatile organic compounds contained per normal cubic meter of producer gas, which must not be greater than the threshold of 1000 mg of tar per cubic meter.
- Fuel consumption. This test measures the amount of fuel consumed per kWh, which must be equal to or less than the 1.2 kg fuel/kWh threshold. The fuel consumption is a basic measure of gasifier efficiency and provides insight into the economics of the Powertainer.
- Failure frequency. This test measures the rate of mechanical failures that result in a machine shutdown per kilowatt-hour of electricity produced, which must be less than or equal to the threshold of 0.005 failures/kWh.

Table 4 shows the results from the gasifier design validation testing. The team tested six areas under the design validation testing: start-up time, shutdown time, maximum producer gas flow rate, continuous operational time, producer gas tar concentration, fuel consumption, and failure frequency.

Table 4: Evaluation Results Gasifier, Design Validation Testing

Test	Criteria/ Threshold	Measured/ Calculated Values	Result	Description
Start-up time	<15 minutes	70 minutes	Fail	The start-up time was greater than the threshold value
Shutdown time	<15 minutes	15 minutes	Pass	The shutdown time was equal to the threshold value
Maximum producer gas flow rate	>175 m^3 PG/hr	125 m^3 PG/hr	Fail	The maximum producer gas flow rate achieved was less than the threshold value
Continuous operational time	>8 hours	11.5 hours	Pass	The continuous operational time was equal to the threshold value
Producer gas tar concentration	<1000 mg Tar/Nm^3	581 mg Tar/Nm^3	Pass	The producer gas tar concentration was less than the threshold value
Fuel consumption	<1.2 kg fuel/kWh	2.25 kg fuel/kWh	Fail	The fuel consumption was greater than the threshold value
Failure frequency	<0.005 Failures/ kWh	0.01 Failures/kWh	Fail	The failure frequency was greater than the threshold value.

m3 PG/hr = cubic meters of producer gas per hour . tar/Nm3 = tar per normal cubic meter of gas

Source: All Power Labs (2020).

Design Validation Testing Results

- Gasifier start-up time. The results of the test measured 70 minutes, which is greater than the threshold. Therefore, the start-up time failed this evaluation. The root cause of this was due to a large fuel bed in the gasifier, which takes a long time for the heat to penetrate. For future work, the research team will add more ignition ports and test an accelerant to reduce the start-up time. The gasifier architecture may also be changed to an innovative new design that is believed to greatly reduce the start-up time.
- Gasifier shutdown time. The system achieved shutdown temperatures within approximately 15 minutes of engine shutdown, which is equal to the threshold. Hence, the shutdown time passed this evaluation.
- Maximum producer gas flow rate. The results of this test measured 125 cubic meters of producer gas per hour, which is below the threshold required to achieve 150kW of power. Therefore, the max producer gas flow rate failed this evaluation. The root cause was due to a pressure drop in the gasifier from a phenomenon known as bell packing,

which chokes the system, limiting the gas flow to the engine. This can be resolved with a change in geometry of the grate basket.

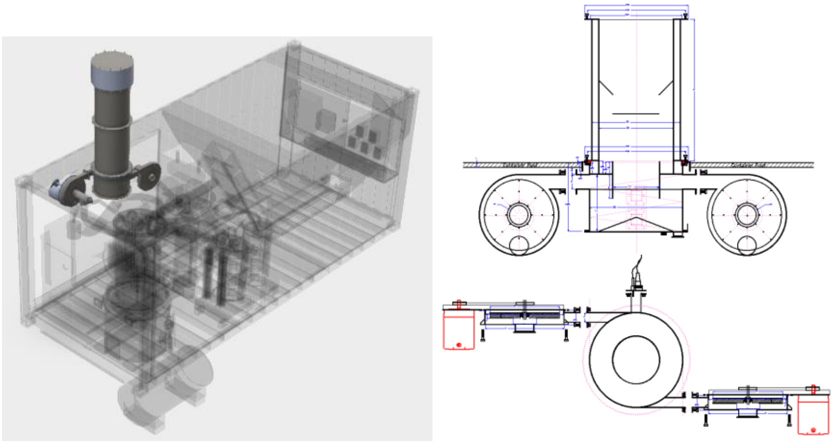
- Continuous operational time. The results of this test measured 11.5 hours, which is above the threshold; and therefore, passed this evaluation. The operation of this test run ended when the ash collection system was full and needed to be emptied.
- Producer gas tar concentration. The results of this test measured 581 mg tar per normal cubic meter in the producer gas, which is below the threshold and therefore passed this evaluation. Since achieving lower tar results is still an objective to improve O&M, for future work, the project team is developing a novel gasifier architecture to reduce tar amounts.
- Fuel consumption. The results for this test measured 2.25 kg fuel/kWh, which is higher than the threshold, and therefore, failed this evaluation. The test failed the evaluation primarily due to the fuel consumed during the longer than expected start-up time. To mitigate this issue for future testing, a new gasifier architecture will be installed that will greatly increase start-up time and improve gasifier efficiency and lower the fuel consumption. Note increasing the rates of biochar product will adversely affect fuel efficiency related to electricity production.
- Failure frequency. This test measured how often failures occurred during Powertainer operation. Multiple electrical and mechanical failures were recorded during the Powertainer testing period. For future work, better heat management, more robust mechanical design, and more pressure-relief valves will be implemented to mitigate failures.

Flare, Engineering Validation Testing and Design Validation Testing

The flare is used during the start-up and shutdown stages, before and after engine operation to cleanly burn the gas produced by the gasifier as it comes up to temperature or is being cooled down. The flare mixes the gas with air inside of the combustion chamber to enable combustion before being vented through the exhaust stack. The gas and air have separate blowers that allow the flare to be tuned in real time to match the composition of the gas for a clean exhaust and allow for automated mixture control when paired with an oxygen (O2) sensor signal. For safety, a Nomex cozy was made to insulate the combustion chamber within the enclosure and a flame arrestor was used within the stack to prevent any embers from exiting into the environment. The flare includes a propane assist and automatic lighting system to guarantee reliable operation.

Figure 7 illustrates the flare design and location of the flare in relation to the full Powertainer.

Figure 7: Flare Rendering and Design Drawing



Source: All Power Labs (2020).

Engineering Validation Testing Criteria

- Flare vacuum strength. This test measures the maximum negative pressure created by the flare blower system, which must be greater than the threshold value (>2500 Pascals vacuum). The vacuum strength is measured in Pascal of vacuum and must meet the threshold value to achieve starting conditions in the gasifier and maintain a combustible environment in the flare.
- Flare gas flow rate. This test measures the volumetric flow rate of the gas that is supplied to the flare, which must be greater than or equal to the threshold value 65 cubic meters per hour. The flare gas flow rate is a critical component for achieving complete combustion of the producer gas and volatile organic compounds.
- Flare temperature. This test measures the temperature of the flare, which must be greater or equal to 1202°F (650°C). Achieving this threshold is critical to ensuring the complete combustion of the producer gas and the complete destruction of volatile organic compounds.

Table 5 shows the engineering validation testing threshold criteria and measured results for the flare.

Table 5: Flare Evaluation Results, Engineering Validation Testing

Test	Criteria/ Threshold	Measured/ Calculated Value	Result	Description
Vacuum strength	>2500 Pa Vacuum	2600 Pa Vacuum	Pass	The vacuum pressure produced by the flare passed the evaluation
Flare gas flow rate	>65 m^3/hr	65 m^3/h	Pass	The gas flow rate that was calculated was equal to the threshold value
Flare temperature	>1202 °F (650 °C)	1562 °F (850 °C)	Pass	The flare temperature was greater than the threshold value

Pa = Pascals; m^3/hr = cubic meters per hour

Source: All Power Labs (2020).

Engineering Validation Testing Results

- Vacuum strength. The results of this test measured 2600 Pascals vacuum, which is greater than the threshold, and it therefore, passed the evaluation.
- Flare-gas flow rate. The results of this test measured 65 cubic meters per hour, which is equal to the threshold. Therefore, it passed the evaluation.
- Flare temperature. The results of this test measured 1562 °F (850 °C), which is greater than the threshold. Therefore, it passed the evaluation. The team observed the major fluctuations in the flare temperature, but during normal running conditions, the temperature did not drop below 1202 °F (650 °C).

Design Validation Testing Criteria

- Complete combustion. Carbon monoxide (CO) concentration must be measured three meters (horizontal distance) from the base of the flare stack. The threshold is less than 35 parts per million. Thirty-five parts per million represents the maximum allowable value for the time-weighted average concentration of carbon monoxide over the course of one hour of exposure, as set forth by the National Institute for Occupational Safety and Health. Hydrogen gas (H2) and Methane (CH4) are under the explosive limit. The verification is that there is no visible flame above the flare.
- Ignition of flare gases. Ignition must occur 100 percent of the time when combustible gas is flowing through the flare. There must be no occurrences of failure. The flare is turned on at least 10 times on propane and then switched to producer gas. The success rate (SR) must be 10/10. The team is responsible to control the flare manually for this test.
- Spark arresting. No sparks, bits of ash or carbon must be observed to leave the flare while the flare is running.
- Heat shielding. Outer surface of the heat shield surrounding the connection point at the base (on top of the container where the flare-mounting ring is welded to the container) should not exceed 200°C.

Table 6 outlines the design validation testing criteria thresholds and measured results.

Table 6: Evaluation Results Flare, Design Validation Testing

Test	Criteria/ Threshold	Measured/ Calculated Value	Result	Description
Complete combustion	<35 ppm and no visible flame	200 ppm and no flame	Fail	The emissions from the flare were higher than the threshold value. No flame was observed
Consistent ignition	=10 successes / 10 attempts	10 successes / 10 attempts	Pass	The flare was successfully ignited 10/10 times
Spark arresting	No visible particles leaving flare	No particles observed	Pass	No particles were observed to leave the flare during the testing period
Heat shielding	<392 °F (200 °C)	464 °F (240 °C)	Fail	The temperature on the outer shell of the flare was above the threshold value

ppm = parts per million

Source: All Power Labs (2020).

Design Validation Testing Results

- Consistent ignition. The flare automation of the ignition system failed and caused damage to the flare system. The automation system failed due to inadequate control logic. After switching the flare to manual control, the flare system achieved a success rate of 10/10.

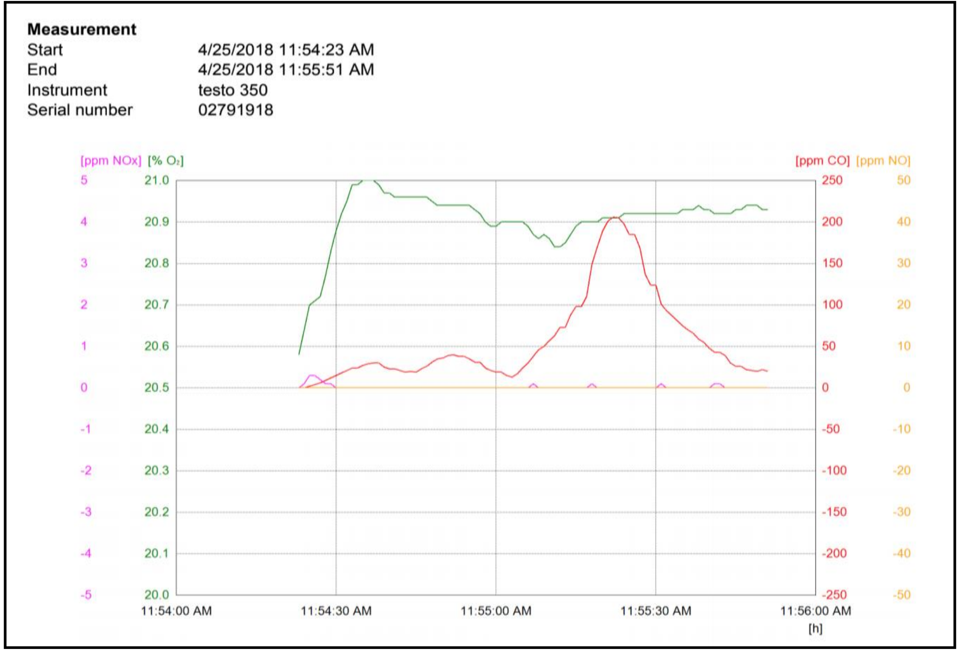
  Automation was required to have a flare system that will reliably combust producer gas without discharging a large amount of CO from the system.

- Spark arresting. No particles were observed to leave the flare during the testing period, and therefore it passes the evaluation. Having a simple stainless mesh flame arrestor is sufficient to prevent incandescent particles from ejecting from the flue. This architecture will likely be used in following generations of Powertainer flare systems.
- Heat shielding. The results of this test did not meet the test criteria and therefore failed the evaluation. While this system failed this test, major revisions had to be made and after adding insulation was added to the assembly walls, noticeable improvements were observed which the project team determined would be safe enough for continued testing and operations.

The team believes that the design will pass once retested. At the time of this test, the flare needed to be repaired and resealed. Temperatures above 1,823 °F (1,000 °C) had degraded the sealing surfaces where the stack joins the container causing gases to escape easily. In addition, the project team took a sample 0.6 meters from the flare stack not the three meters called out above.

Figure 8 shows the measured CO and nitrogen oxides (NOx) emissions from the flare stack.

Figure 8: Flare Emissions April 25, 2018



Measurement	
Start	4/25/2018 11:54:23 AM
End	4/25/2018 11:55:51 AM
Instrument	testo 350
Serial number	02791918

PPM NOx- Parts per million nitrogen oxides; % O2- Percent oxygen; PPM CO- Parts per million carbon monoxide; PPM NO- Parts per million nitric oxide.

Source: All Power Labs (2020).

Overall, the project team believes the flare can easily perform its objective of complete combustion while in use. All sizing of combustion chambers and stack height appear to be correct and this design will likely be used in the future in a variety of sizes.

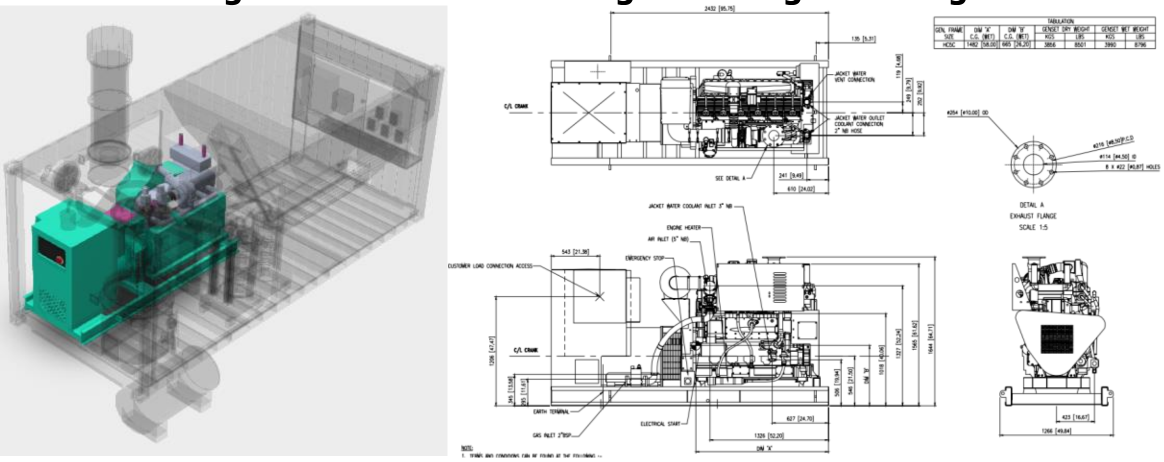
The project team will continue to automate the air/fuel mixing in the flare to achieve the threshold value shown in Table 6.

For future testing, the project team is considering refractory material to provide better heat shielding and durability.

Genset Engineering Validation Testing and Design Validation Testing

The QSK19G (genset model #) is a 336 kW natural gas engine generator set including a Stanford generator, an engine control unit (made up of sensors to monitor the condition of the engine/generator, wire harness and main board), and a cooling package that is designed to operate remotely from the genset. The Engine Control Unit (ECU) was replaced completely with MegaSquirt ECU to have better control of the engine dynamics required for operating with producer gas. Figure 9 illustrates the genset specs and location in relation to the rest of the container.

Figure 9: Genset Rendering and Design Drawing



Source: All Power Labs (2020).

Engineering Validation Testing Criteria

- Battery charging voltage. This test measures the voltage required to charge the internal battery. The threshold for this test must be in the range of the threshold value (24/28 volts). The battery charging voltage must meet the threshold value to prevent damage to internal systems and the batteries.
- Generator output voltage. This test measures the voltage from the generator supplied to the customer. The threshold for this test must maintain 280 Volts, plus or minus 24. The generator voltage must be within the acceptable range to prevent damage to equipment or grid tie with a utility.
- Maximum power output. This test measures the maximum power output of the Powertainer. The threshold must be greater than or equal to the 150 kilowatt-electric (kWe). The maximum power output will provide insight into the Powertainer capabilities. Table 7 outlines the genset criteria thresholds and measured results.

Table 7: Evaluation Results Genset, Engineering Validation Testing

Test	Criteria/ Threshold	Measured/Calculated Value	Result	Description
Battery charging voltage	24 - 28 Volts	26.75 Volts @ idle 26.75 Volts @ 50 kW	Pass	The battery charging voltage was within the threshold range
Generator output voltage	$480\,Volts \pm 24\,Volts$	477 Volts L1-L2 @ idle/50 kW 478 Volts L2-L3 @ idle/50 kW 480 Volts L3-L1 @ idle/50 kW	Pass	The generator output voltage was within the threshold range
Maximum power output	>150-kWe	100-kWe	Fail	The maximum power output was less than the threshold value

Source: All Power Labs (2020).

Engineering Validation Testing Results

- Battery charging voltage. The results of this test measured 26.75 volts at idle and at load which is within the range of the threshold. The test therefore passed the evaluation. The battery charging voltage was recorded using the grid tie control panel from deep sea electronics. A major improvement to the battery charging was switching from an alternator to a switching power supply. This battery charger was selected to replace the alternator so that the engine was not required to take on unnecessary parasitic load to keep the batteries charged. The generator and DC rectifier was used to generate the power used by the battery charger.
- Generator output voltage. The results of this test measured between 477 and 480 volts at idle and at load, which is within the range of the threshold. The test therefore passed the evaluation. The generator output voltage was recorded using the grid tie control panel from deep sea electronics. The voltage was automatically maintained by the grid tie control panel and would alert the user if the voltage was out of the threshold range.
- Maximum power output. The maximum power output achieved was 100 kWe. The maximum power output was below the threshold value and failed the evaluation. The Powertainer system did not achieve 150-kWe of power output. While the engine did achieve a maximum load of 100 kW, it could not maintain an electrical voltage of 480 volts for more than five minutes. The project team removed several gas filtration systems and increased power output to 100 kWe. Upon further inspection, the technical team found the char removal system to be ineffective at removing char and played a major role in reducing power output.
- For future testing, the filtration system and fuel mixing system will be adjusted. The char removal system in the gasifier will be fixed by adjusting the geometry of the grate basket. A new gasifier architecture will be investigated to eliminate the char removal problem.

Design Validation Testing Criteria

- Continuous run time at partial load. This test validates that the Powertainer is capable of operating at a threshold of at least 8 hours at 33 percent of maximum load (50 kW).
- Continuous run time at full load. This test validates that the Powertainer is capable of operating at a threshold of at least 1 hour at 150kW load.
- Sound testing. This test measures the maximum sound level at two distances from the Powertainer. The sound threshold for this test is less than or equal to 80 A-weighted decibels (dbA) at three feet and 72 dbA at 21 feet. Decibel levels 3 feet away should be kept to 80 dbA or under to avoid hearing damage for operators without hearing protection. Decibel levels at 21 feet away should be kept below 72 dbA for regulatory reasons.[1]

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[1] Aaberg, Dennis. "Generator Set Noise Solutions: Controlling Unwanted Noise from on-Site Power Systems." www.cumminspower.com, Cummins Power Generation , 2007.

Table 8 provides the results from the evaluation phase of the genset design validation testing section.

Table 8: Evaluation Results Genset, Design Validation Testing

Test	Criteria/ Threshold	Measured/ Calculated Value	Result	Description
Continuous run time at partial load	>8 hours @ 50 kW	11.5 hours	Pass	The continuous run time at partial was greater than the threshold value
Continuous run time at full load	>1 hour @ 150 kW	0 hours	Fail	The continuous run time at full load was less than the threshold value
Sound testing	<80 dbA (3’) <72 dbA (21’)	91.8 dbA (3’) 74.8 dbA (21’)	Fail	The decibel reading for the two distances were greater than the threshold values

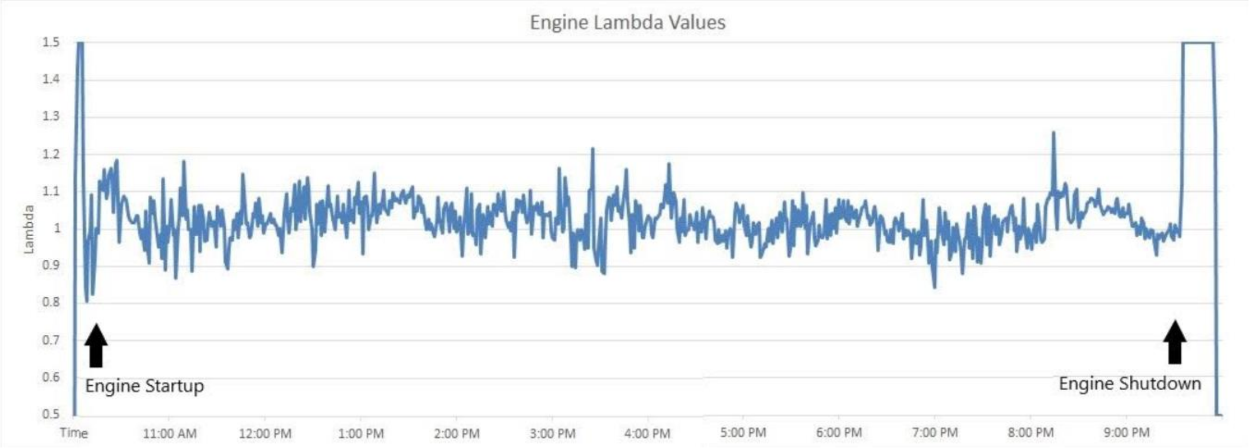
Source: All Power Labs (2020).

Engineering Validation Testing Results

- Continuous run time at partial load. The results of this test measured 11.5 hours of continuous run time, which was greater than the threshold value and therefore passed the evaluation. The team recorded manually the time and load and reported the data on a spreadsheet. A major improvement to the run time capability was the reduction of filtration devices before the engine. The filtration devices were causing a large pressure drop and restricting gas flow. Another improvement was the reduction of automated control. The automated controls on the engine, gasifier, and fuel feed system proved to be unreliable. Switching these systems to partial manual control or even full manual control enabled better compensation for bad gas quality or poor air/fuel mixing.

  Figure 10 shows the engine lambda values for the 11.5-hour run period at 50 kWe. Lambda represents the ratio between the amount of oxygen present during combustion in the engine versus the amount required to combust a unit of fuel which has a lambda value of one. When more oxygen is present, the value is greater than one and when less oxygen is present, the value is less than one. This can be a proxy for how well the engine is running. However, since a lambda value of one does not necessarily result is the best emissions; the amount of oxygen can be adjusted to meet emissions targets. For the Powertainer, a lambda of 1.05 was found to achieve the best emissions results. This will be discussed further in the emissions section of the report below.

Figure 10: Engine Lambda Values for 11.5-hour Run, December 10, 2018



Source: All Power Labs (2020).

- Continuous run time at full load. The test was not able to achieve the full 150kw and therefore failed the evaluation. The team observed a variety of potential root causes for not hitting the target load including air fuel mixture controls, fuel feed challenges, char removal system challenges, and gasifier dynamics.

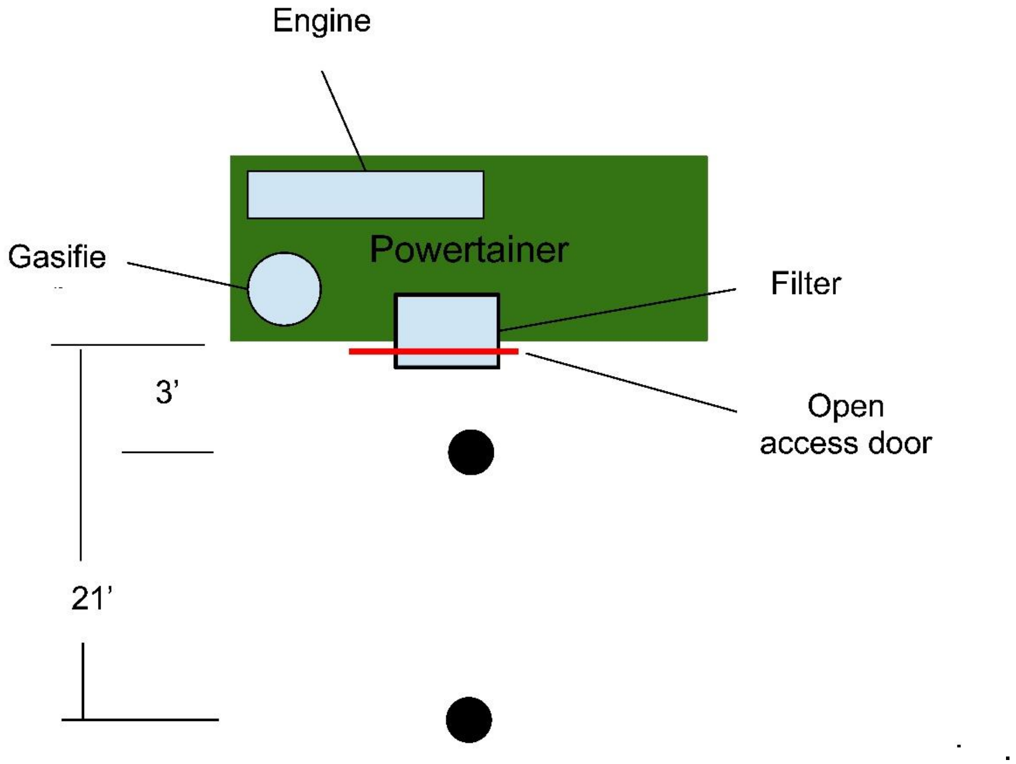
  The air servo on the air/fuel mixture controls was problematic. The issue stemmed from two main sources: air leaks and control loop tuning. Air leaks resulted in uncontrolled air fuel mixture going into the engine. The control loop tuning was slow and unable to keep up with a dynamic air/fuel mixture.

  For future testing, a better proportional integral derivative control (PID) loop must be implemented into the air servo to improve the response and keep up with the dynamic air/fuel mixture. All air leaks around the air servo need to be sealed and vibration resistant hardware needs to be used. The failure of the char removal system was a major hindrance to achieving the required load for one hour. The char removal system in the gasifier will be fixed by adjusting the geometry of the grate basket.

  When rating an engine for producer gas operation, generally one can expect 60 percent of the nameplate power. The engine is rated at 570 kW and the generator head is rated for 300 kW. Therefore, the project team expected 342 kW available from the engine. This is plenty of power headroom to yield the intended 150 kW of electrical power.

- Sound testing. The decibel reading for the sound testing were measured to be greater than the threshold values for distances of 3 feet and 21 feet away. Figure 11 illustrates the position of the measurements.

Figure 11: Sound Testing Locations



Source: All Power Labs (2020).

In the figure, the green box represents the Powertainer with the locations of the genset, gasifier, and filter assemblies. The two block circles blow the green box represent the location where measurements were made, at 3 feet and 21 feet from the container.

The decibel readings were above the threshold values due to removal of the access door for the Powertainer filter illustrated in Figure 11 and lack of sound dampening material.

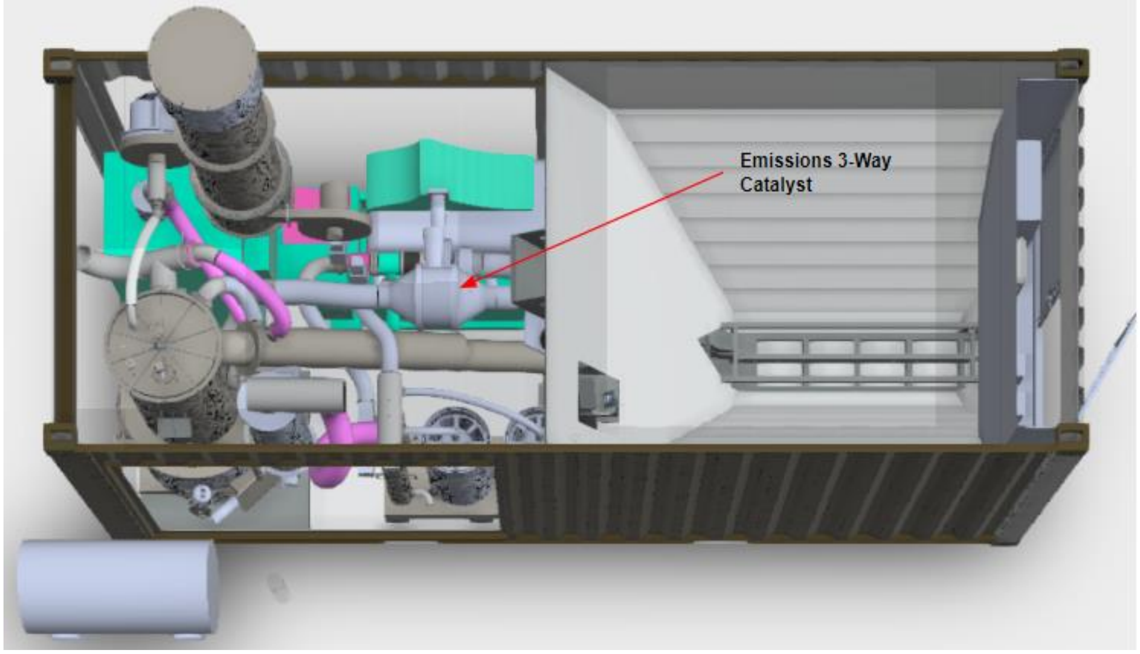
For future work, the technical team plans to install maintenance doors with sound dampening material on the interior, which will further improve sound levels.

Emissions Control System, Engineering and Design Validation Testing

The primary emission control technology used on the Powertainer is a 3-way catalyst developed by Diesel Controls Limited. The three-way catalyst requires a narrow mixture control and is more costly than some of the alternatives but is more effective at reducing both CO and NOx emissions and can result in a slight increase in power output. The exhaust catalyst is located between the engine and the pyrocoil and will provide additional heat that will be used in the pyrocoil and fuel auger. Their use is explained later in the Heat Mining and Recycling section.

Figure 12 illustrates the emission control design.

Figure 12: Emissions Control Rendering and Design Drawing



Source: All Power Labs (2020).

The engineering validation testing, design validation testing, and results that were used to qualify the gasifier are described in this section.

Engineering Validation Testing and Design Validation Testing Criteria

- Criteria Pollutants. This test validates that the Powertainer is capable of meeting CO and NOx Best Available Control Technology (BACT) guidelines provided by the Bay Area Air Quality Management District (BAAQMD). The derived BACT guideline for CO is 675 parts per million (ppm) and NOx is 56 ppm. In-house emissions testing was performed with a Testo 350 emissions analyzer. A typical emissions test requires a trained technician to turn on the analyzer and set the sampling setting to sample. Once the Powertainer reached standard operating conditions as stated in the engineering validation testing results report, the technician inserts the sampling probe into the exhaust stack and samples for 10 minutes. The Testo 350 automatically samples the exhaust gas and records the data in a graphical form shown in Figure 13.

Engineering Validation Testing and Design Validation Testing Results

The best emissions results were found to be at an air/fuel ratio of 1.05 lambda, as shown in Table 9 and Figure 13. The CO emissions were within the BACT guidelines provided by the BAAQMD.[2] However, the NOx emissions did not meet the guidelines.

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[2] "Bay Area Air Quality Management District Best Available Control Technology (BACT) Guideline." *Bay Area Air Quality Management District*, Bay Area Air Quality Management District, 22 May 2015, www.baaqmd.gov/permits/permitting-manuals/bact-tbact-workbook.

The criteria pollutants appeared to be reduced when the lambda set point was adjusted from 1.00 to 1.05. The air/fuel mixture control is a major factor when reducing emissions. During testing in March and December of 2018, the team observed that poor mixture stability increased criteria pollutant emissions. Figure 13 presents the results.

For future work, the project team plans to develop an improved mixture control to meet emissions guidelines. Fully automating the air intake and better control parameters for the governor control logic will improve mixture stability and lower emissions.

Table 9 provides the emissions results from the Powertainer, and BACT guidelines provided by the BAAQMD. The BACT is from an internal combustion engine fueled by biogas with a power rating greater than 50 horespower. CO and NOx were the two criteria pollutants measured in-house with a Testo 350 instrument.

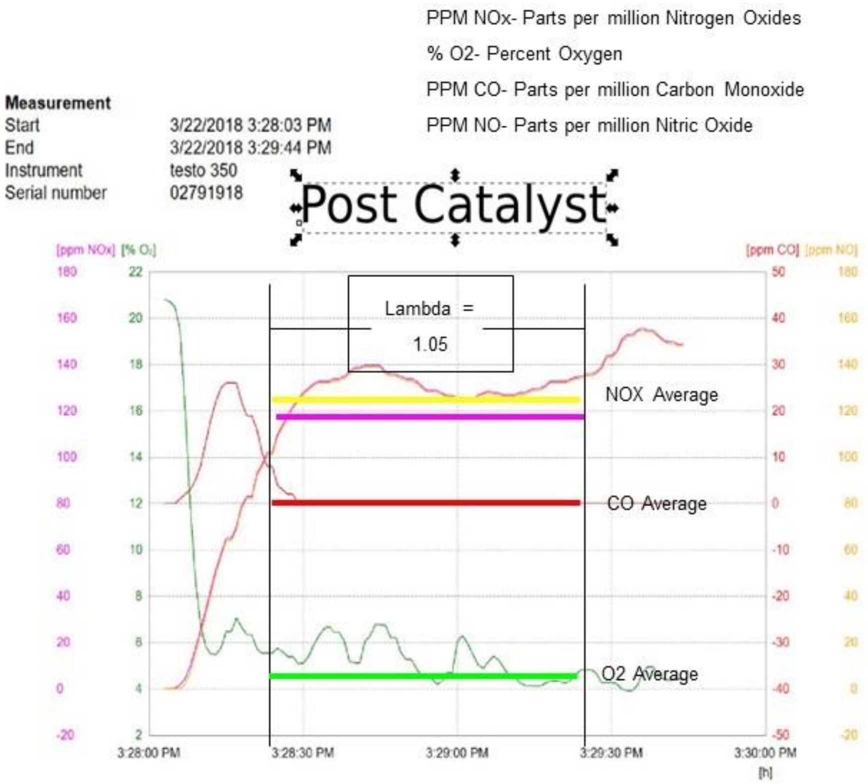
Table 9: Criteria Pollutant Results and Guideline from Bay Area Air Quality Management District

Lambda Value	Criteria Pollutants	Nomenclature	Results	Derived BACT Guideline
1.05	Carbon monoxide	CO	<2 ppmvd CO @ 15% O2	675 ppm (1.8 g/bhp-hr)
1.05	Nitrogen oxides	NO_x	<135 ppm NOx @ 15% O2	56 ppm (0.15 g/bhp-hr)

ppmvd = parts per million by volume, dry, ppm = parts per million, g/bhp-hr = grams per brake horsepower hour

Source: All Power Labs (2020).

Figure 13: Emissions Measurements, March 2018



Source: All Power Labs (2020).

Heat Mining and Recycling, Engineering and Design Validation Testing

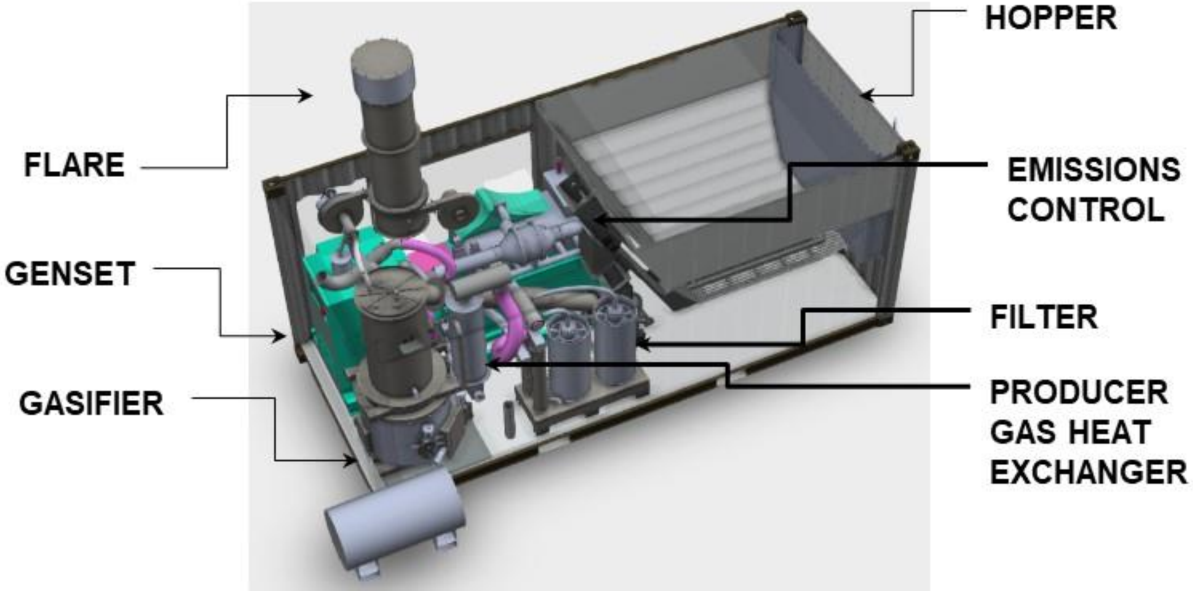
Plumbing on the Powertainer connects all the major subsystems together including the fuel feed system, gasifier, flare, filter, and genset and emissions control. Combined, they move the producer gas along with the air and engine exhaust, in and out of the gasifier, filter, genset, flare auger tube, and silencer. Most of this routing was done in four-, five-, and six-inch diameter stainless steel corrugated tubing with sanitary fittings welded on the ends. These fittings were selected because of their ability to be rapidly installed, disassembled, or rearranged so a variety of tests could be performed with many architecture options adding and subtracting smaller subsystems as needed. One of the areas that separates All Power Labs' architecture from alternatives is the capability to recycle the heat, resulting in higher efficiency and improved gas composition. Since gasification is a thermal conversion process, using heat that is available across the system architecture and used in strategic locations has enabled a more efficient gasification process as well as the production of cleaner producer gas. Outlined below are the key areas where waste heat is being used in the order of the flow of fuel.

- Fuel Feed Auger. The fuel feed auger exists between the fuel hopper and the gasifier. It includes an annular space around the augered fuel for the heat exchanger. The heat from the engine exhaust used in this annular space aims to dry the fuel and initiate the pyrolysis process converting the dried fuel into charcoal and pyrolysis gas. Drying is a critical process in gasification systems because gasifier temperatures are unable to exceed 212 °F (100 °C) until all moisture has been removed from the fuel.

- Pyrocoil. The pyrocoil exists at the top of the gasifier. It is where the fuel from the auger flows. It includes an annular space around the fuel for the heat exchanger. The annular space uses the heat from the engine exhaust to finish converting the dried biomass into charcoal and pyrolysis gas, both critical fuels for the combustion zone.
- Hearth and Exiting Gas Heat Exchanger. The hearth exists in the gasifier below the pyrocoil and is the location where combustion takes place requiring oxygen from the atmosphere. The temperature of the atmosphere used in the hearth needs to be as close to the combustion temperatures as possible to enable tar cracking in the combustion zone. The heat exchanger used to enable this heating of atmospheric air, is an external producer gas to air heat exchanger. The gas exiting the gasifier goes through a tube-in-shell heat exchanger passing the heat to the atmospheric air — preheating it before entering the hearth — where it is used to enable combustion and improve tar cracking.

Figure 14 depicts the location of all the major subsystems contributing to the heat mining and recycling.

Figure 14: Heat Mining and Recycling Design Rendering



Source: All Power Labs (2020).

Engineering Validation Testing and Design Validation Testing Criteria

- Engine Exhaust Temperature Incoming to Pyrocoil. This test measures the temperature of the engine exhaust before entering the pyrocoil. The threshold criteria for this test is greater than, or equal to, 650°C. This temperature will enable the pyrolysis process to occur in the gasifier.
- Engine Exhaust Temperature Exiting the Pyrocoil. This test measures the temperature of the engine exhaust after exiting the pyrocoil. The threshold criteria for this test is less than, or equal to, 752 °F (400 °C). The difference in exhaust temperature before and after the pyrocoil will identify whether sufficient heat is transferring into the pyrocoil to enable pyrolysis.

- Engine Exhaust Temperature Entering the Fuel Coil. This test measured the temperature of the engine exhaust before entering the fuel coil. The threshold criteria for the engine exhaust temperature at this location is between 392 °F (200 °C) and 752 °F (400 °C). At this temperature range, drying of the fuel in the auger will occur, but it will not be hot enough for pyrolysis. Pyrolysis needs to be avoided here to reduce material handling issues in the auger.

Table 10 shows the measured and calculated values of the parameters given in the criteria section.

Table 10: Measured and Calculated Values for Heat Mining and Recycling Subsystem Engineering Validation Testing

Test	Criteria/ Threshold	Measured/ Calculated Value	Result	Description
Engine exhaust temperature coming into the pyrocoil	≥ 1202 °F (650 °C)	768 °F (409 °C)	Fail	The exhaust gas incoming to the pyrocoil was less than the threshold value
Engine exhaust temperature exiting the pyrocoil	≤ 752 °F (400 °C)	612 °F (322 °C)	Pass	The exhaust gas exiting the pyrocoil was less than the threshold value
Engine exhaust temperature entering the fuel coil	Between 392 °F (200 °C) and 752 °F (400 °C)	617 °F (235 °C)	Pass	The exhaust gas entering the fuel coil was greater than the threshold value

Source: All Power Labs (2020).

Engineering Validation Testing and Design Validation Testing Results

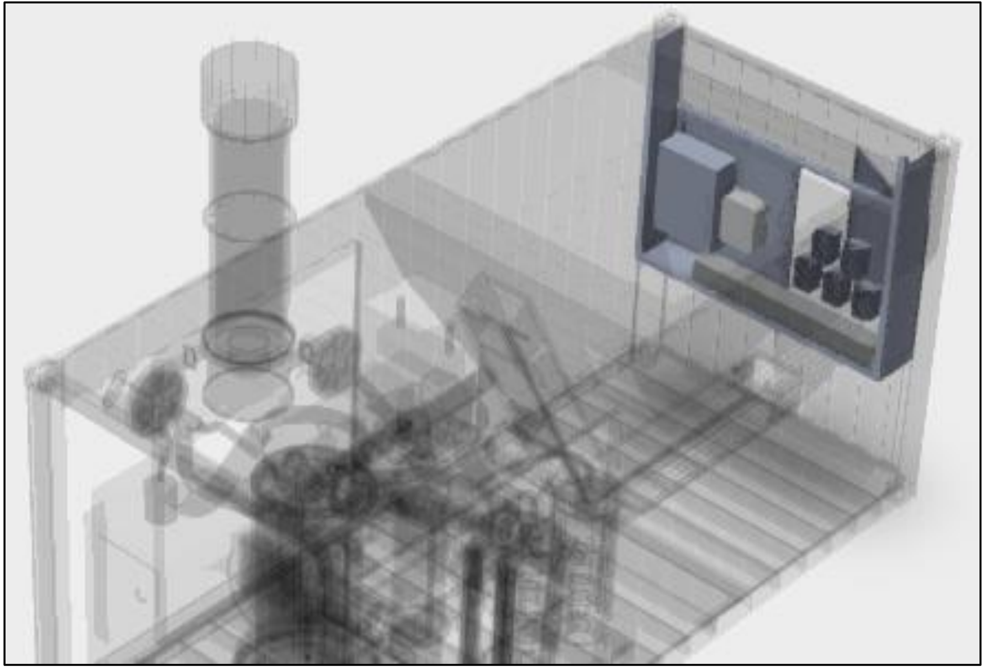
- Engine Exhaust Temperature Incoming to Pyrocoil. The results of this test measured 768 °F (409 °C), which is below the threshold temperature of 1202 °F (650 °C). Therefore, the test failed this evaluation. The project team believes that failure was due to not insulating the engine exhaust plumbing. For future work, the project team will insulate the exhaust plumbing.
- Engine Exhaust Temperature Exiting the Pyrocoil. The results of this test measured 612 °F (322 °C), which is below the 752 °F (400 °C) threshold. Therefore, the test passed this evaluation.
- Engine Exhaust Temperature Entering the Fuel Coil. The results of this test measured 617 °F (235 °C), which is within the threshold between 392 °F (200 °C) and 752 °F (400 °C). Therefore, the test passed the evaluation.

Automated Controls

Every major and minor subsystem within the Powertainer had some level of automation, and all were connected via the plumbing and automation. The majority of components were located within the large sub panel in the back of the Powertainer container and the smaller sub panel located above the generator. The controls for the variable frequency drives, breakers, process control unit controlling the feed system, and the flare, were in the larger subpanel; while the engine- and generator-related controls were located in the smaller panel. Electrical conduit was distributed throughout the Powertainer so that electricity and data could be delivered to all systems.

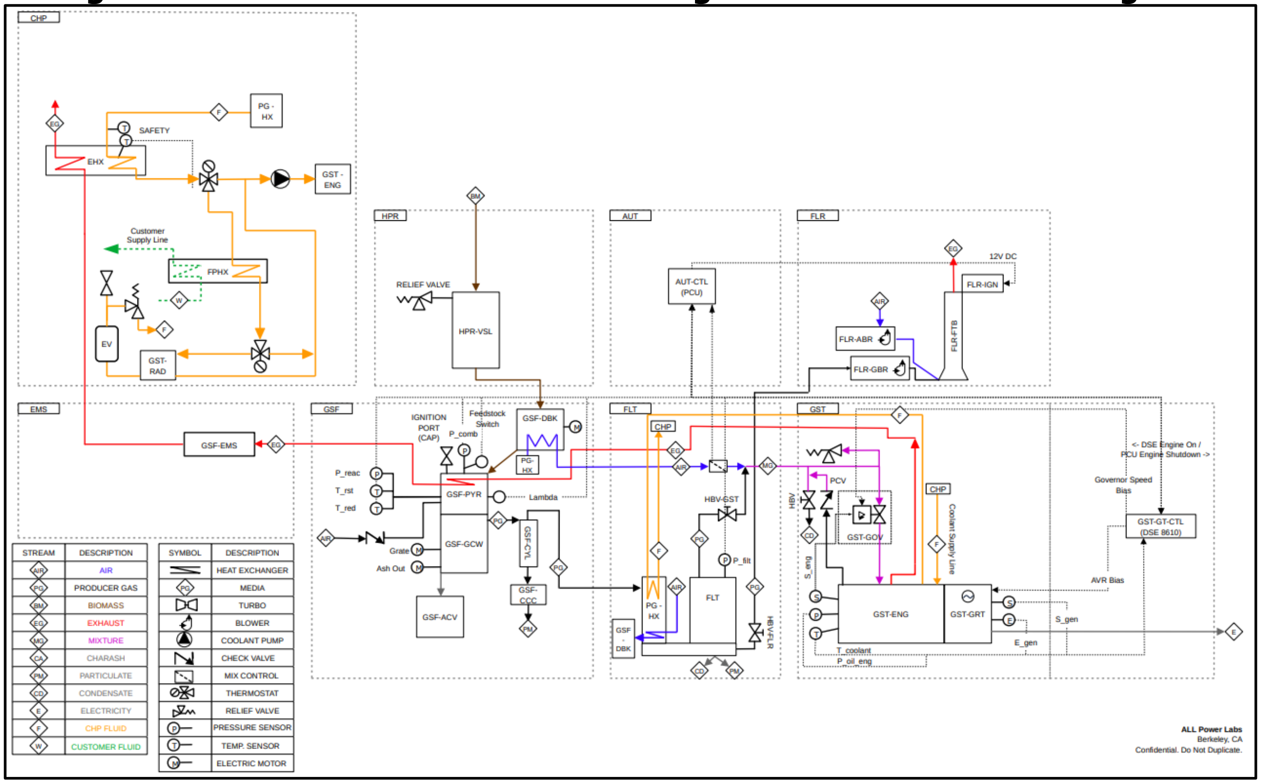
Figures 15 and 16 illustrate the location of the primary automation components in the Powertainer layout and the plumbing and instrumentation diagram of the Powertainer.

Figure 15: Automated Controls Design Rendering



Source: All Power Labs (2020).

Figure 16: Automated Controls Plumbing and Instrumentation Diagram



Source: All Power Labs (2020).

CHAPTER 3:
Performance and Emissions Testing Results

Powertainer Performance Testing Results

A 40-hour engine test on the fully assembled Powertainer was accomplished in December 2018. A consistent 50 kWe was exported for the duration of the test minus start-up and shutdown. Table 11 shows the operating schedule and performance from December 6–13, 2018.

Table 11: Operating Schedule and Performance

Date	Start Time	End Time	Hours	kWe Export	Comments	Operator
12/6/2018	16:30	21:00	4.5	50		Eli
12/7/2018	19:00	3:00	8	50		Baylis
12/8/2018	12:00	18:30	6.5	50		Julie
12/9/2018	17:30	22:00	4.5	50		Jacob
12/10/2018	10:00	21:30	11.5	50	Longest Run	Baylis
12/11/2018	19:30	1:30	6	50		Eli
12/14/2018	16:30	17:30	1	50	Emissions Test	Andrew
Total Hours			42			

Source: All Power Labs (2020).

The total hours of operation achieved during the testing period was 42. This test demonstrates that the Powertainer is capable of the minimum uptime required for testing and evaluation purposes. Some issues were encountered during the 40-hour performance testing such as power output. Figure 17 shows a picture of the Powertainer in operation.

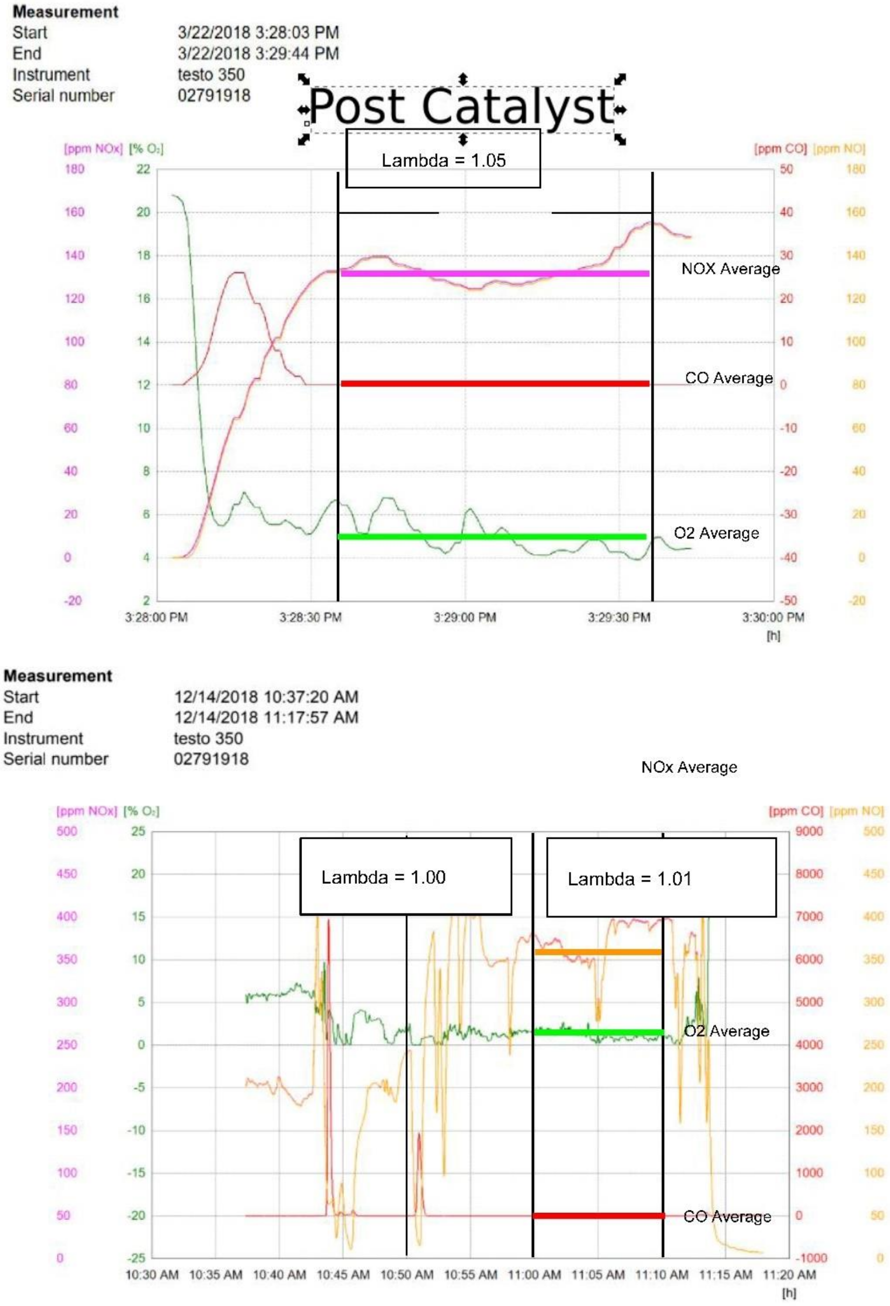
Figure 17: Operating the Powertainer

Photo Credit: All Power Labs.

Internal Emissions Testing

- Emissions monitoring and testing. The team monitored CO and NOx emissions during the 40-hour performance testing. Figure 18 shows the measured values from periods of testing in March and December 2018.

Figure 18: Measured CO and NOx, March 22, 2018 (Top) and December 14, 2018 (Bottom)



Source: All Power Labs (2020).

The technical team adjusted the air/fuel mixture (lambda value) and collected the subsequent emissions data during the test.

Table 12 shows lambda values and the resulting criteria pollutant levels. (Note that CO is measured in parts per million, volumetric dry [ppmvd] and NO_2 is parts per million [ppm].)

Table 12: Criteria Pollutant Results (Engine Exhaust)

Lambda Value	Criteria Pollutants	Results
1.01	Carbon Monoxide (CO)	<50 ppmvd CO @ 15% O_2
1.01	Nitrogen Dioxide (NO_x)	360 ppm NO_x @ 15% O_2
1.05	Carbon Monoxide (CO)	<2 ppmvd CO @ 15% O_2
1.05	Nitrogen Dioxide (NO_x)	135 ppm NO_x @ 15% O_2

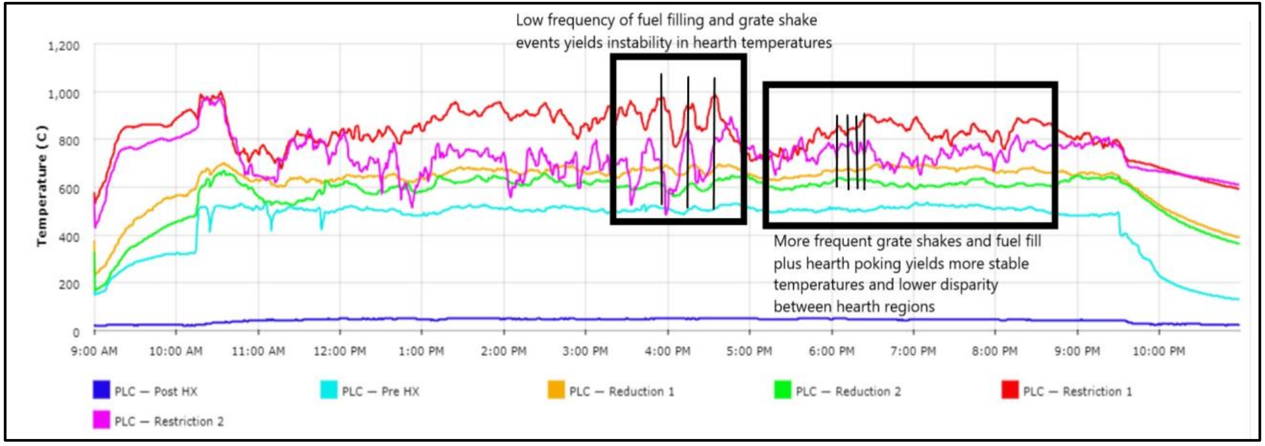
Source: All Power Labs (2020).

A lambda value of 1.05 was found to provide the lowest emission levels. The emission levels were below the Shasta County thresholds but higher than the BAAQMD guidelines as shown in Chapter 2. Emission levels can be further reduced by refining the PID values of the control logic for the lambda value. Reducing the variance in lambda will provide more complete combustion and less criteria pollutants.

Biomass Loading and Feed System

The biomass loading and feeding was performed throughout the 40-hour performance testing. The biomass loading was done with the forklift and supersack method as described in Chapter 2. The biomass feeding was performed by the integrated feed subsystem in the Powertainer, as described in Chapter 2. The feed system influenced gasifier temperatures as shown in Figure 19. It shows the influence that feeding and shaking the grate has on the gasifier dynamics. Each color in the graph represents different locations in the gasifier where temperature was recorded. Feeding fuel and shaking the grate at low frequencies leads to unstable hearth temperatures resulting in large temperature swings. Higher grate shaking and fuel feeding results in a more stable hearth temperature.

Figure 19: Gasifier Temperature vs Time at Different Grate Shake Frequencies, December 10, 2018



Low frequency of fuel filling and grate shake events yields instability in hearth temperatures

More frequent grate shakes and fuel fill plus hearth poking yields more stable temperatures and lower disparity between hearth regions

Note: PLC stands for programmable logic controller and is the generic name for the automation system that was used for data collection during this test.

Source: All Power Labs (2020).

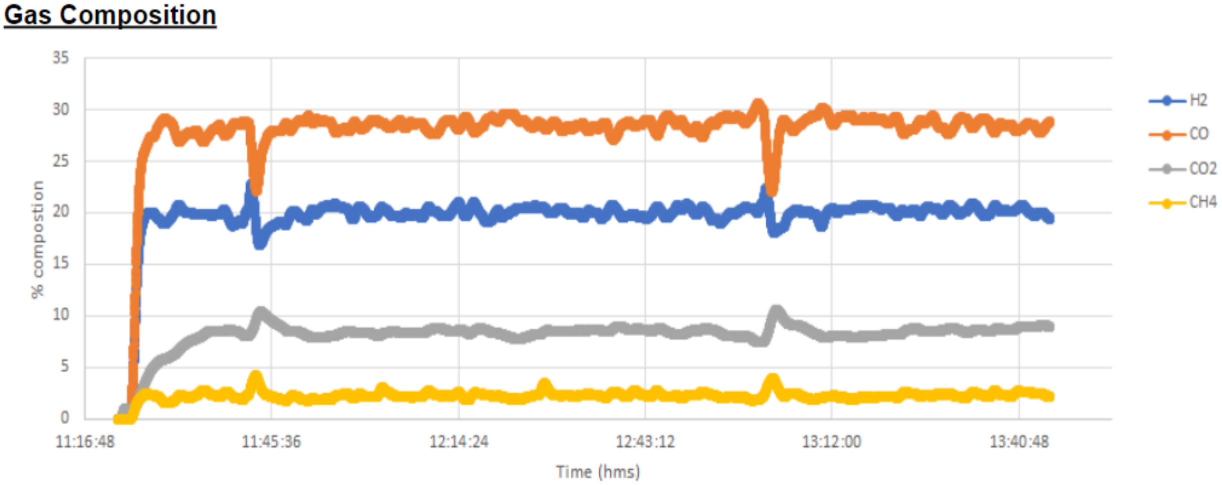
The team observed several feed-system issues during the 40-hour performance test.

- Hearth poking method due to bridging/ratholing. The fuel touching the wall of the pyrocoil adheres to the wall and subsequently creates ratholing conditions. Due to the ratholing conditions, fuel flow is restricted and insulated from preheating from the pyrocoil resulting in fresh fuel flow directly into the combustion zone without sufficient pre hearth pyrolysis. For future work, the team expects to identify several solutions to mitigate or eliminate these issues.
- The newer swirl hearth reactor architecture. The horizontal retort solves this by using a mechanical conveyor to move material through the pre hearth pyrolysis zone and delivering it directly to the hearth without any opportunities for bridging on restrictions or need for hearth poking to maintain consistent fuel flow through the hearth.
- Refinement of automation. To remove the requirement for human monitoring of the feed system, an automation capable of responding to mechanical binding is needed. For example, on All Power Labs' smaller scale biomass generator, when the fuel auger binds and the motor current spikes, the auger is reversed and then the auger resumes its normal operation. If the auger does not successfully solve the bind with reversing, then the machine will throw an error message. With a strictly Programmable Logic Controller (PLC) FDFx-based automation architecture, tuning features like this will be much easier and accessible than using the All Power Labs native process control unit automation board.

Gasifier

Gas composition is a key metric to evaluate gasifier performance. Figure 20 shows the measured gas composition from the Powertainer gasifier during a sample run.

Figure 20: Gasifier Gas Composition, August 2, 2017



Source: All Power Labs (2020).

Measured producer gas composition when flaring, showing a relatively high CO concentration. Gas composition was very stable and within the expected range for producer gas.

Average measured composition: H_2: 20%, CO: 28%, CO_2: 8%, CH_4: 2.3%, MJ/Nm3: 7.0 MJ/m3

The gas composition values are compared to literature values in Table 13 for a standard Imbert gasifier.[3]

Table 13: Gas Composition Comparison

Gas	Powertainer Gasifier	Standard Imbert Gasifier
H_2	20%	17%
CO	28%	19%
CO_2	8%	14%
CH_4	2.3%	2%
HHV	7.0 MJ/m^3	5.03 MJ/m^3 (136 BTU/scf)

HHV = Higher Heating Value, scf = standard cubic foot. Note: The standard Imbert gasifier was tested with corn cobs as fuel, the HHV was converted from BTU/scf to MJ/m^3

Source: All Power Labs (2020).

The comparison of the gas composition suggests that the Powertainer gasifier was performing above industry average. This is evident by the increased hydrogen and carbon monoxide levels, which can be explained by the successful use of heat mining from the exhaust gasses to aid the gasification process. The heat mining aided the gasification process by reducing the amount of air required for gasification and thus reducing the nitrogen dilution.

Another key metric when evaluating a gasifier is the bulk tar. Tar is a broad term used to define many species of Volatile Organic Compounds (VOC), Semi-VOC, and various hydrocarbons.[4]

Figure 21 shows the measured bulk tar using the All Power Labs developed online tar tester which is able to measure tar in the gas stream in real time.

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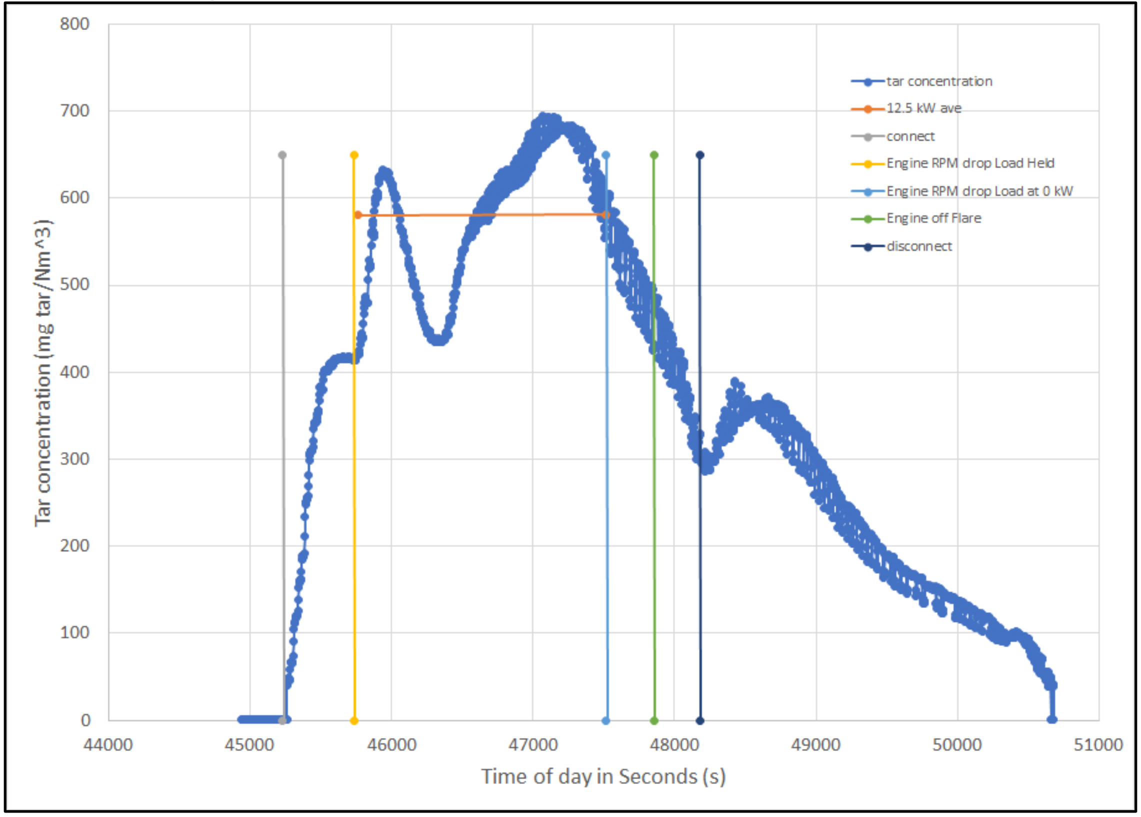
[3] Reed, Thomas B., and Agua Das. "Handbook of Biomass Downdraft Gasifier Engine Systems." *Handbook of Biomass Downdraft Gasifier Engine Systems*, Solar Technical Information Program, Solar Energy Research Institute, 1988.

[4] Prabir Basu. Biomass Gasification and Pyrolysis: Practical Design and Theory. Academic Press, Elsevier, 2010.

Figure 21: Tar Test Post Filter, February 28, 2018



Source: All Power Labs (2020).

The average tar concentration was 581 mg tar per normal cubic meter of gas at the post filter location after standard operating conditions were achieved as described in the engineering validation testing results report. Typical tar concentrations for a standard Imbert gasifier are expected to be between 1000 and 5000 mg of tar per normal cubic meter of gas. Assuming the tar concentration of the gasifier is approximately double the post filter location, which is seen with All Power Labs' smaller-scale biomass generator, the tar concentration measured for the Powertainer gasifier should be in an expected range.

For future work, a new gasifier architecture using the "swirl hearth" promises to reduce the tar numbers substantially. This is achieved by better separating the tar cracking, combustion, and reduction zones, and enabling better heat use, preventing competition between the two reaction pathways. This ensures thorough tar cracking prior to reduction. Because reduction zone real estate is only dedicated to reduction reactions, there is more residence time for the cracked tar and combustion products through reduction.

The batch type char removal system limited run-time duration to about six hours at 50 kW before collection vessels reached capacity. The risk of overfilling could cause auger motor damage. The next iteration will have an isolation valve so that vessels can be swapped during operations while the system is hot and in the final version will feature an airlock and continuous automatic conveying/quenching of the charcoal. Figure 22 illustrates the challenge with the char removal system.

Figure 22 illustrates measured pressures across the gasifier system during a performance test. Each color in the graph represents different locations pressure was measured across the

Powertainer. Spikes in the post filter pressure indicate events where bell packing in the gasifier broke allowing expected gas flows and pressures to occur.

Figure 22: Gasifier Pressure vs Time as Grate Shake Occurs

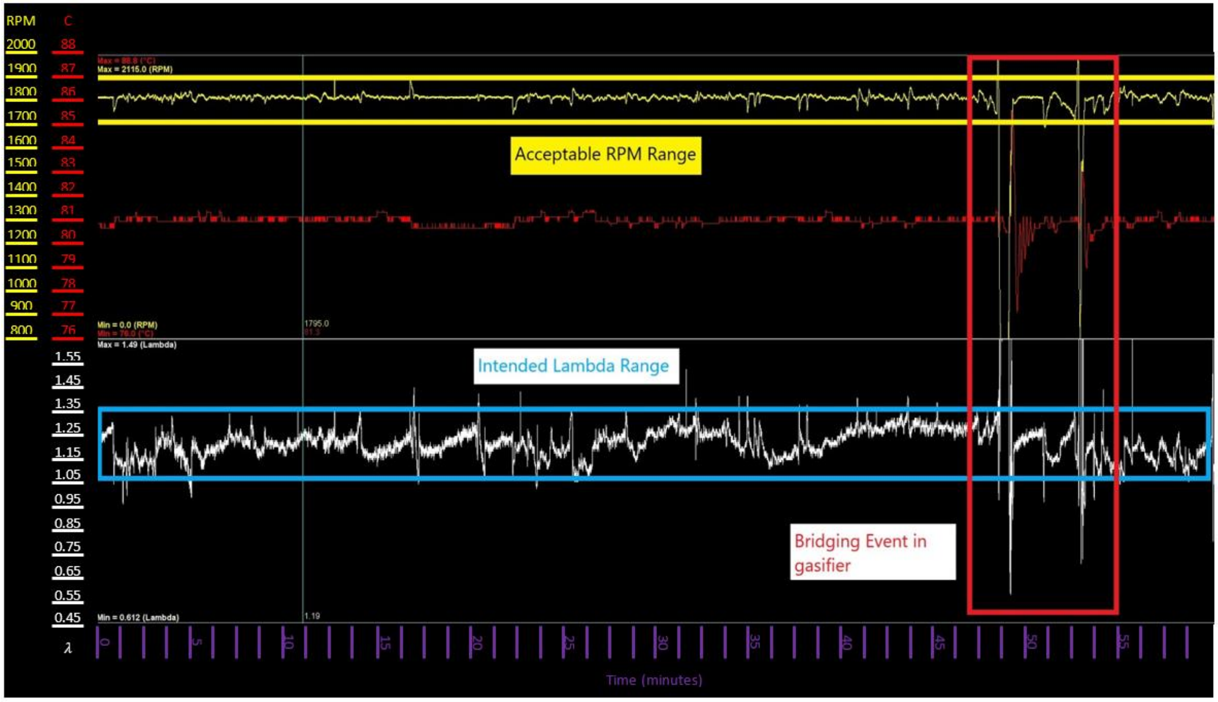
Source: All Power Labs (2020).

The team observed several issues in the gasifier during the 40-hour performance testing.

The grate shake interval needs to be driven off of temperature and pressure such that fuel flow issues in the reactor can be mitigated by agitation. Often reactor conditions and pressure drop issues could be stabilized by activating more aggressive and more frequent grate shaking.

- Char removal system discussion and the observed bell packing. Gasifier performance was hindered by bell packing, which is where producer gas is choked off and does not flow consistently through the cross section of the gasifier restriction. This occurs when the ash removal system does not adequately remove the spent char, and fine particles fill the void spaces that the gas needs to flow through the gasifier. The power output of the gasifier is directly related to flow area and reaction opportunity on the fuel surface. Upon inspection of the fuel within the ash removal system, considerable packing was observed. The flow of char and ash through the restriction is determined by the grate basket geometries of basket height, diameter, and cone angle. The culprit here is the cone, which is supposed to keep fuel from forming a stationary column in the center by pushing it to the outside of the basket. This issue was anticipated on the Powertainer, but the angle was not sufficiently adjusted to account for the scale up. Further work on the gasifier will include iterations on grate basket cone angle.
- Pressure drop is a means to measure gasifier performance and the amount of gas that can be produced. The higher the difference in pressure pre-filter and pressure air intake observed, the higher the power output should be. Figure 23 shows the engine at maximum effort; however, the power output was only 50 kW throughout. In some instances, the pressure drops were much less during bell packing breakup events, the 50-kW load was accomplished without full effort from the engine. This illustrates that the gasifier should be expected to deliver sufficient gas for much higher loads if the bell is not packed.

Figure 23: Engine Dynamics, Engine RPM (yellow), Lambda (white), Engine Coolant Temperature (red), December 10, 2018



Source: All Power Labs (2020).

Automation Controls

The developed Powertainer automation system consists of a patch work of a custom All Power Labs native process control unit and an economy PLC system. Due to challenges experienced with this system, the project team has started to transition to a robust industry standard Siemens PLC suite that will enable collaboration with a larger pool of expertise than was available over this automation architecture.

The automation was developed and implemented as the last step of integration and this created problems with proper wire routing and did not allow sufficient time for automation development before it was necessary to run the machine for engineering validation testing / design validation testing. The subsequent design for the next Powertainer is organized to run automation development in parallel to hardware. The project team expects to have logic for all subsystems tested before final integration begins. This development strategy will yield a much better automation platform.

Table 14 illustrates the automation development narrative of the automation system. The beta 1 was developed under this grant. The beta 2 represents the next version of the Powertainer. While an integrated automated system on beta 1 was achieved, some edge cases and basic wiring challenges made it more difficult to repair because the exotic architecture forced the project team to run many of the systems in a semiautomatic state to successfully complete the run times required to perform testing. Each subsystem under the new architecture will be re-automated and the intended cut in for the automation is separated by development milestones as illustrated.

Table 14: Component Automation List

Component Name	Automated for Beta 1	Automated for Beta 2 EVT/DVT	Automated for Beta 2 Commissioning	Automated for Beta 2 Field Operation
Grate Shaker	yes*	yes	yes	yes
Ash Auger	yes*	no	yes	yes
Fuel Auger	yes*	yes	yes	yes
Rotary Valve	yes*	yes	yes	yes
Fuel Drag Chain	yes*	yes	yes	yes
Flare	yes*	yes	yes	yes
Engine Mixer	yes	yes	yes	yes
Engine Fuel Handoff	no	no	no	yes
Turbo bypass	NA	no	yes	yes

Note: * represents reliability challenges experienced during performance testing where manual intervention was required to maintain operations. EVT = Engineering validation testing, DVT = Design validation testing.

Source: All Power Labs (2020).

Engine Genset

The genset was tuned and optimized to hold engine revolutions per minute (RPM) steady and keep lambda values within a reasonable range. Several improvements were implemented to the genset to achieve engine RPM and lambda control.

- Dedicated power supply. The ignition and control system had a dedicated power supply so that engine cranking would not rob power from ignition and controls. This proved to be a crucial upgrade from testing in March for engine reliability and starting.
- Added automated air mixing valve. The automated air mixing valve allowed for stable engine operation across varying gas quality and more predictable emissions results.
- Electronic Control Unit settings. Optimal ignition settings were achieved with the ECU. Coil dwell time was tuned to four milliseconds (ms) and ignition advance was ideal at the angle, 42 degrees.
- Figure 23 shows the engine RPM and lambda values vs time. The lambda values presented are controlled with an automated air mixer valve with some iterations of tuning. The time required to tune the air mixer valve to achieve consistent air/fuel mixture was not available. However, stable engine RPMs was achieved over normal gasifier operating conditions. The engine shutdown events toward the end of the run resulted from gasifier bridging that was particularly difficult to resolve. While not a frequent failure mode, with the expected gasifier upgrades, it is expected that the air

mixer valve will be able to secure engine operation stability through normal gasifier fluctuations

- For future work. The air mixer valve will be tuned to achieve a stable lambda value. The generator will be fully controlled by the Deep Sea Electronics module. Better communication between the gasifier and genset will be implemented to reduce shutdown events such as the event shown in Figure 22.

Power Production

The Powertainer achieved 100 kW as maximum power with stable power production at 50 kW. The throttle position as a percent, with 100 percent being full open and zero percent full closed, was used to determine if the engine had power headroom to increase load. While observing the throttle position, the team noted that at 50 kW the throttle position varied from 15 percent to approximately 85 percent at 50 kW. A lower throttle position percent was seen shortly after grate shakes hinting that fuel flow in the gasifier was a key driving factor in power output capability. The throttle position increased between grate shake intervals and spiked during bridging events and related fuel flow issues.

The primary issue hindering higher power production over 100 kW is not the genset due to the observation of the throttle position. The issue was determined to be the char removal system in the gasifier. As the gasifier reduction zone packs full of small char particles, a large pressure drop is observed and shown in Figure 21.

For future work, the char removal system in the gasifier will be redesigned as discussed in Chapters 2 and 3 to solve the bell packing which will result in high gas flow enabling higher power production.

Powertainer Emissions Testing Results

Third party emissions analysis was done on the Powertainer by Atmospheric Analysis & Consulting, Inc. to verify that the Powertainer emissions meet the Shasta County BACT thresholds.[5] A Tedlar bag sample was taken at the post catalyst location and then transported via courier service to Atmospheric Analysis & Consulting, Inc. for analysis. Two analysis methods were used on the bag sample: Unites States Environmental Protection Agency (USEPA) 3C for fixed gases (including carbon monoxide, carbon dioxide, and methane) and USEPA TO-15 for VOCs. The team did not measure nitrogen oxides, sulfur oxides (SOx), and particulate matter (PM) during the 40-hour performance testing since analysis was not available from the Tedlar bag sample. Third party testing that would have been able to provide these additional tests were both cost and time prohibitive for this project. Nitrogen oxides were however able to be measured in-house by All Power Labs in previous testing phases. The results are shown in Chapter 2 and meet the derived BACT thresholds for Shasta County.

To allow comparison, Shasta County pound per day BACT thresholds were converted to concentrations (ppmv) by assuming an exhaust mass flow rate of 7.16 kg/kWh (based on previous producer gas generator flow rate data) and 16 operating hours per day (Table 15)

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[5] California Air Resources Board. "R2-1.HTM." *Shasta County AQMD List of Current Rules*, 28 Dec. 2018, www.arb.ca.gov/drdb/sha/cur.htm.

Table 15: Shasta County Pollutant Thresholds and Third Party Emissions Results

Pollutant	Derived BACT Threshold (ppm_v)	3rd party results (ppm_v)	Interpretation
Reactive organic compounds	145	0.08552 (USEPA TO-15)	Below BACT Threshold
Nitrogen oxides	145	Not measured	Not measured by 3rd party, measured in house and shown in Chapter 2
Sulfur oxides	1,025	Not measured	Not measured
Particulate matter (PM10)	3,000 mg/m^3	Not measured	Not measured
Carbon monoxide	4,700	<1,000 (USEPA 3C)	Below BACT Threshold
Carbon dioxide	None	170,000 (17%, USEPA 3C)	No BACT requirement
Methane	None	<1,000 (USEPA 3C)	No BACT requirement

For the purposes of this report Volatile Organic Compounds (VOC) and Reactive Organic Compounds (ROC) are treated as the same, which is conservative since ROC are a subset of VOC. A molecular weight of propane (44 g/mol) was assumed for organic compound threshold conversion, a bulk ROC/VOC number was determined by summing all detected organic compounds.

Source: All Power Labs (2020).

Seventy VOCs are evaluated by USEPA TO-15 of which four are detected, all others are non-detect in the sample. This combined concentration was below 1 ppm, well below the derived Shasta BACT threshold for Reactive Organic Compounds (ROCs). Of the four compounds, benzene is regulated as a California Toxic Air Contaminant (CTAC) and USEPA Hazardous Air Pollutant (HAP), chloromethane is regulated as a HAP, and the others are not regulated as TAC or HAP compounds. All measured pollutants were below the derived Shasta County BACT thresholds. Table 16 shows all detected VOCs.

Table 16: Detected Volatile Organic Compounds

VOC	3rd party Measurement (ppb v/v) by USEPA TO-15
Chloromethane	11.0
Acetone	57.9
Ethyl Acetate	10.8
Benzene	5.82

Source: All Power Labs (2020).

Shasta County thresholds were met for ROCs / VOCs and CO. NOx, SOx and PM were not measured by the third party. These emissions were not measured due to the high cost and time constraints. For future work, All Power Labs will continue to adjust the air/fuel mixing system to further reduce emissions and find resources for third party emissions testing to measure the pollutants that were not measured.

CHAPTER 4:
Feedstock Locations and Siting

Large-scale regional tree die-off events, which have occurred recently in the Western U. S., can create woody biomass disposal challenges and the potential to produce substantial energy feedstock. Electricity generation has been proposed to mitigate the biomass disposal needs following the tree die-off resulting from California's 2012–2017 drought. University of California, Berkeley evaluated biomass feedstock availability and feasibility at fine spatial resolution by combining US Forest Service Aerial Detection Survey data with forest structure maps generated from pre-drought imagery and data. The project team developed a method, and then built a database used to calculate tree size, biomass volume, and terrain information across California. The resulting database can properly estimate harvesting and transportation costs and realistically assess the economic potential of the dead tree biomass feedstock. This information is critical for evaluating policy alternatives and public investments intended to reduce human risks associated with the recent tree die-off.[6]

Resource Analysis Results

Using a novel method to estimate the standing dead (SD) biomass available for electricity generation in California from the 2012–2017 tree mortality crisis, University of California, Berkeley's analysis show that there are 18.7–69.4 million Bone Dry Tons (BDT) of feasibly harvestable SD biomass feedstock, with the true value likely closer to the upper bound of that range. The amount of SD biomass considered "cost-effective" for electricity generation is 7.6–27.9 million BDT. This cost-effective estimate represents only about 30 percent of the total SD biomass in the state resulting from the die off. Thus, harvesting standing dead trees for energy feedstock is not a comprehensive solution for removing the bulk of recently dead trees in California, especially given that other factors, such as transport costs, are not included in the present feasibility assessments. However, the University of California, Berkeley team estimated that approximately 30 percent (23.60 million BDT) meets minimum operational criteria for potential cost-effective harvest for bioenergy. To put the figure in context, this is equivalent to 4 to 14 percent of California's annual in-state electrical energy generation showing that biomass energy could be used for both SD tree hazard reduction and renewable energy production.

Moreover, this analysis provides the first estimate of live tree carbon loss resulting from the drought. The estimates of total SD biomass are equivalent to 11.2 to 40.6 teragrams carbon (Tg C) across all areas surveyed by, or roughly 1.1 to 3.8 percent of total aboveground forest carbon in California. [28]As these standing dead trees decay, their carbon will transition to the atmospheric pool. These estimates of the carbon contained in standing dead trees will aid in the statewide carbon accounting needed for California to reach its climate change mitigation goals. The method introduced here can also be used to improve calculations of aboveground live carbon losses due to tree die-off elsewhere, as previous attempts to estimate biomass and

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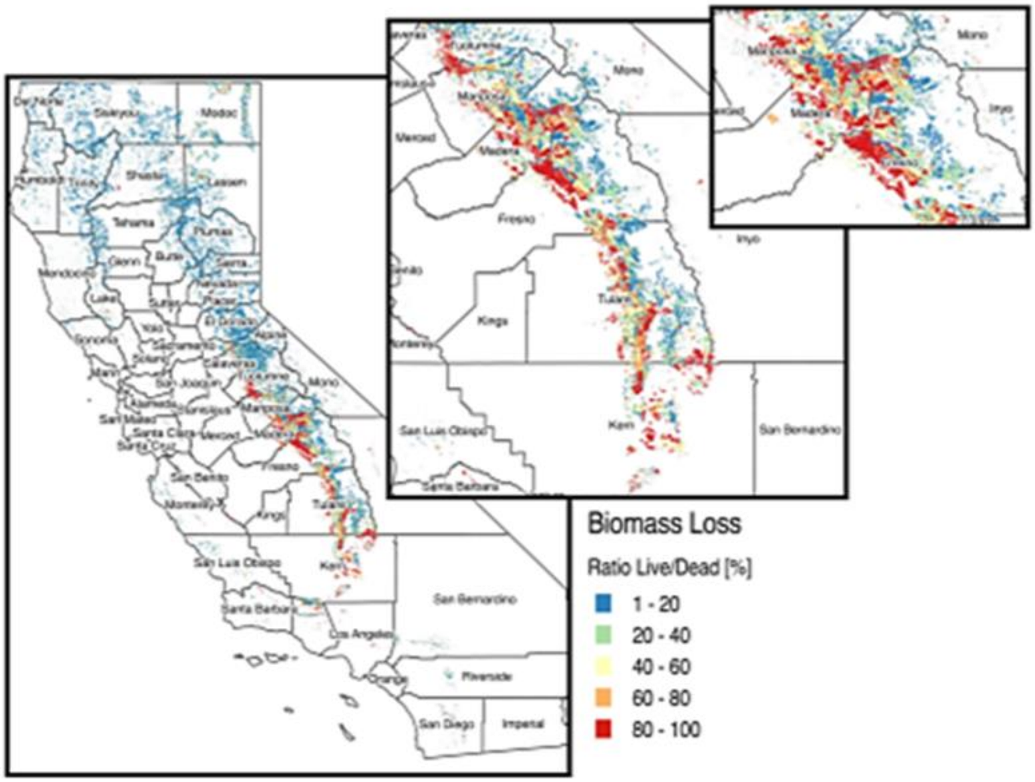
[6] The data that support the findings of this study and the resulting SQL file to restore the database are available in figshare with the identifier data DOI(s) https://doi.org/10.6084/m9.figshare.c.4117328.v2.

carbon loss from tree mortality events applied simple conversion factors for all trees of a given species, ignoring fine-scale variation in tree sizes.[29,30]

The largest quantities of SD biomass in California are found in the southern Sierra Nevada, which is largely concentrated in only 11 counties. Together, these 11 most-affected counties contain 85 percent of the total SD biomass resulting from recent tree die-off. In some of these counties, the "cost-effective" feedstock is as low as 15 percent of the total (e.g. Tulare County), indicating that state policies to address risk in high-mortality counties may need a comprehensive approach including other approaches in addition to electricity generation.

Figure 24 shows the yearly biomass resulting from 2012 to 2017 tree mortality in California, using component ratio method (CRM) (blue) and Jenkins (red) biomass estimators. The upper bars represent biomass estimates using the assumption that aerial detection survey (ADS) detects all dead trees ≥25 cm diameter at breast height (DBH) with equal likelihood, while the lower bar represent the lower bound estimate made using the assumption that ADS detects all trees ≥2.5 cm DBH with equal likelihood.

Figure 24: Ratio of Dead/Live Biomass



Source: University of California, Berkeley and All Power Labs (2019).

Policy Recommendations

Estimates of the carbon contained in standing dead trees will aid in the statewide carbon accounting needed for California to reach its climate change mitigation goals. The method introduced here can improve calculations of aboveground live carbon losses due to tree die-off elsewhere, due to the previously mentioned shortcomings of past estimates.

This research has resulted in the following policy recommendations:

1. Subsidizing tree removal in hazard zones through electricity production is not a successful strategy since a large portion of the trees that need to be removed are in areas with geophysical conditions that make electricity production uneconomical.
2. Electricity infrastructure in rural locations severely limits the economic feasibility of the Bioenergy Market Adjusting Tariff (BioMAT) program since interconnection costs can be very large, thus making the economic case for electricity production less attractive. Additionally, Investor Owned Utilities (IOUs) may require the installation of new infrastructure, which is entirely infeasible for temporary projects like land restoration, wildfire mitigation, or disaster cleanup.
3. Consequently, the state should invest directly in tree removal and distribution grid upgrades, instead of creating subsidies through uneconomical Feed in Tariff rates.
4. Better coordination between project developers, PG&E, and The California Department of Forestry and Fire Protection (CAL FIRE) is necessary to develop "clusters" of projects over areas close to the high hazard zones. This will be more effective than the current strategy of letting the developers find the parcels to develop by themselves. In many occasions, this results in high interconnection costs, uneconomical biomass stock supply and long-term unsuitability of the projects. Additionally, knowledge transfer between industries and government entities will be more effective with a targeted approach to biomass processing.

CHAPTER 5: Manufacturing and Production Readiness

Powertainer Beta 1 Manufacturing Summary

Powertainer assembly occurred between March 2016 and April 2018. Motivated system layout and assembly order of operations of the major subsystems was critical when designing and manufacturing components in such a constrained space, which was explored using an iterative in-situ design build process. Thorough review of all operator access points as well as maintenance strategy was identified while determining the system architecture and layout.

During this iterative process, a handful of refinements, improvements and optimizations were determined. The following summarizes the details the sequence of assembly and refinements of each subsystem that occurred during the assembly process. Figure 25 depicts a picture of the Powertainer.

Figure 25: Powertainer with Gasifier, Flare, and Genset

Photo Credit: All Power Labs.

Enclosure, Hopper, and Feed System

The enclosure and feed system where the first items were built and did not experience any noteworthy challenges. Figure 26 shows a picture of the enclosure.

The Powertainer enclosure is comprised of a custom 20 ft (six meters) shipping container. Added doors gave additional access to strategic components — particularly the engine and gasifier. Pass through panels built into the roof allowed for the flare stack and exhaust routing to feed through. An electrical panel enclosure installed in the rear of the enclosure houses the automation controls components.

Figure 26: Enclosure/Container

Photo Credit: All Power Labs.

The hopper and feed system consists of custom metal fabricated components along with electric motors and sensors. Fabrication and integration of these components occurred in situ of the container. After customizing the container, the hopper and feed system represent the first subsystem added to the enclosure.

The main components of the feed system include the drag chain used to move fuel from the hopper to the airlock and the heated auger. Within those main components, motors, variable frequency drives, level sensors, and other mechanical assemblies exist to support the operation of these devices.

Figure 27 shows the picture of the hopper feed system.

Figure 27: Hopper Feed System

Photo Credit: All Power Labs.

Engine Genset

Engineers added the engine genset to the container after installing the hopper feed system. The genset (Figure 28) ended up being a much tighter fit than anticipated between the fuel hopper and the container doors. Some items, such as the alternator, were removed to fit within the available space inside the container. The next version of the technology will place the genset in a dedicated engine/combined heat and power (CHP) container, separating it from the gas making components.

Figure 28: Engine Genset

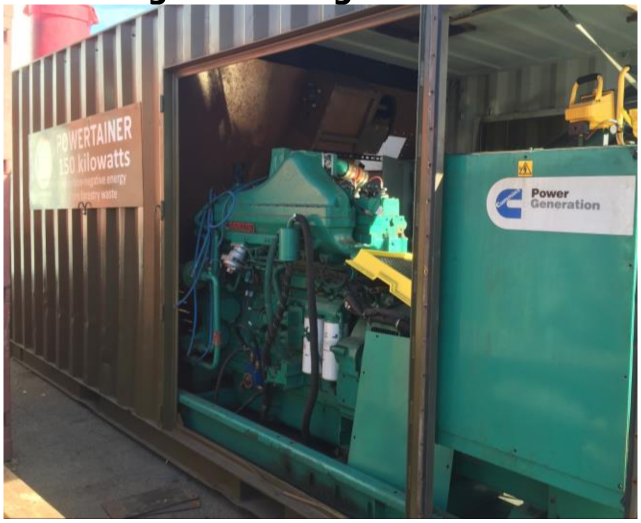


Photo Credit: All Power Labs.

Gasifier and Filter

After the engine, the team assembled the fuel auger and the gasifier in the container. Alignment of the first auger ended up being off, which made it unable to connect to the gasifier. The design of the auger boot was updated, remade and reinstalled to enable better alignment and fit up. The filter assembly was the last major assembly installed. Due to some performance challenges of the filter, multiple iterations of the design were made and installed. The gasifier and filter assemblies were mostly assembled outside of the container and then placed in the shipping container via a forklift. The team expects to use a similar process for subsequent builds of the Powertainer. The height constraints inside the container make assembly of these subsystems difficult unless done outside the container. Figure 29 shows the gasifier and filter integrated into the Powertainer.

Figure 29: Gasifier and Filter

Photo Credit: All Power Labs.

Flare

The team installed the flare assembly after the gasifier. The close proximity of the flare blowers to the flare body made assembly difficult. In addition, the gas blower motor was very heavy for the assembly and required additional support. The team expects to use the same assembly process for subsequent builds.

Figure 30 shows the Powertainer flare.

Figure 30: Flare

Photo Credit: All Power Labs.

Plumbing, Emissions Control, and Automation

Emissions control (Figure 31), plumbing (Figure 32), and automation controls (Figure 33) were integrated throughout the time the other subsystems were being installed but were the last categories of components to complete. The tight space made integration of both plumbing and electrical difficult to install and access during troubleshooting. The team will redesign these components in the next version of the Powertainer.

Figure 31: Emissions Control

Photo Credit: All Power Labs.

Figure 32: Perspective of the Plumbing System

Photo Credit: All Power Labs.

Figure 33: Automation Control System

Photo Credit: All Power Labs.

Product Transport

After building the Powertainer, it was relocated to Green Waste Recycle Yard in Richmond, California to test for transportation and simulate remote operations. To transport the Powertainer, there were some components that were disassembled, including the flare, the gasifier ash collection vessel, some external filtration components, and the cooling package. Once broken down with parts and doors secured, it was easy to forklift the Powertainer onto a flatbed truck for transport. Figure 34 shows some pictures of the movable capacity of the Powertainer.

Figure 34: Powertainer in Transport

Photo Credit: All Power Labs.

Technology Readiness and Forward-looking Considerations

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."[7] During this grant, the Powertainer has progressed from a TRL level 4 to a TRL 6, which can be summarized as "Engineering/pilot-scale similar (prototypical) system validation in relevant environment". Based on this, the beta 1 Powertainer has not yet reached technology maturity suitable for production readiness. The beta 2 Powertainer currently being developed will be much closer to production readiness, but since new features are being added and developed under this grant, an additional round of refinement and proving before able to truly reach production readiness will likely be required. Descriptions of each relevant TRL are outlined in Appendix A.

In addition, after building the beta 1 Powertainer, the team decided that the available volume inside a 20-foot-long shipping container was insufficient for fitting all subsystems in a clean form factor that could be reasonably productized and outsourced. The value in using a shipping container is that the world knows how to move them around and if the form factor is compromised, so is the transportation and logistics of moving the product. Based on this, starting with the beta 2 Powertainer, it was decided to split the Powertainer up into two 20' shipping containers: one housing the "gas and char making" subsystems and the other, the "power generation" (electricity and heat) subsystems. This is also done in part to house similar components that can all be outsourced together. The gas making subsystems are almost all sheet metal vessels which can easily be outsourced together and the power generation subsystems almost all related to engines and generators which can easily be outsourced together. This new restructuring of the product for the Beta 2 Powertainer (Figure 35) under the new EPIC grant will be divided as follows:

Gas Making Module

- Container
- Hopper Feed System
- Gasifier
- Flare
- Gas Making Automation and Controls

Power Generation Module

- Gas Filter and Producer Gas Heat Exchanger
- Engine / Genset
- Emissions Control and Exhaust Heat Exchanger
- Cooling Package and CHP Circuit

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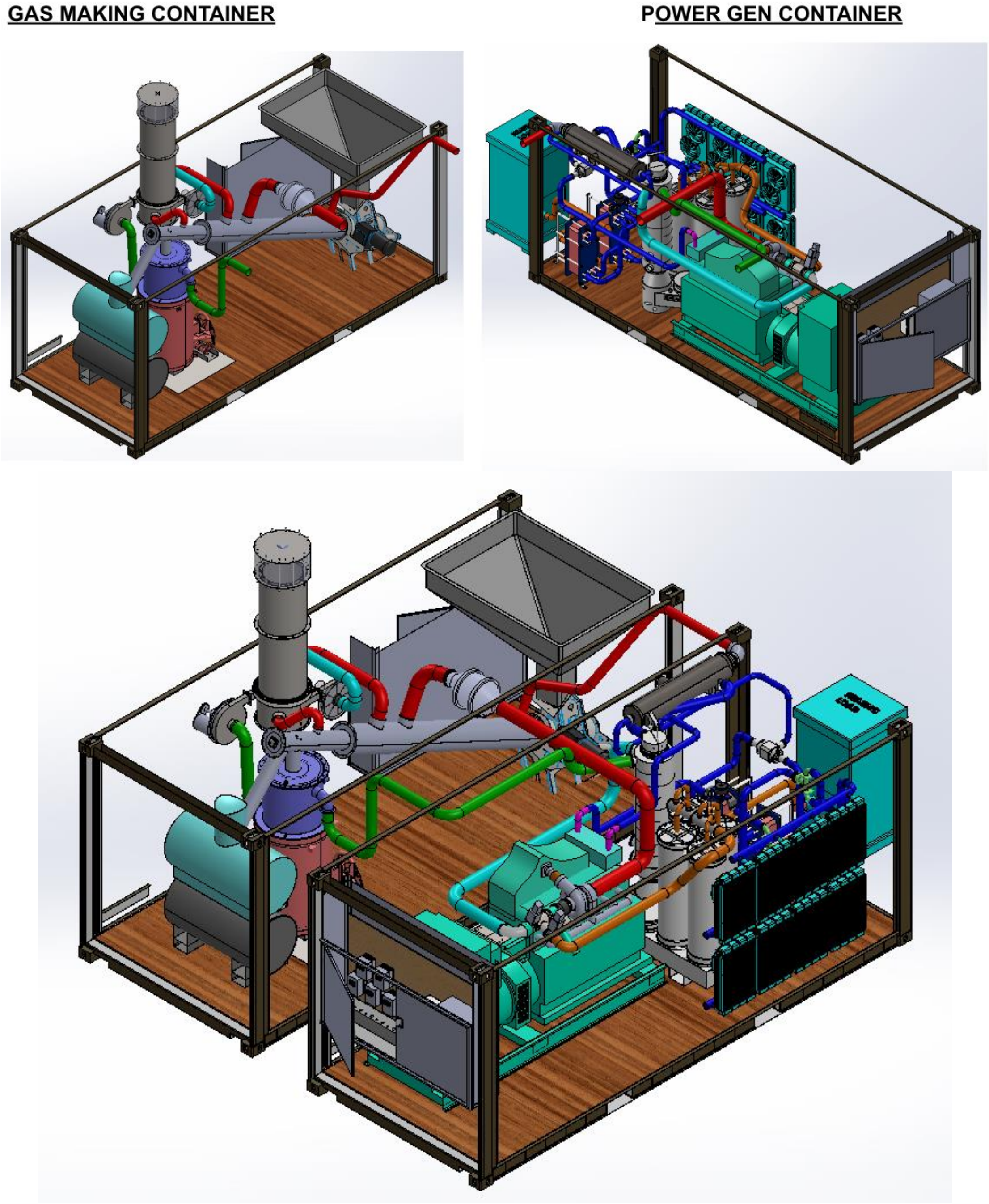
[7] "Definition Of Technology Readiness Levels" from NASA, accessed at https://esto.nasa.gov/files/trl_definitions.pdf

Figure 35: Renderings of Beta 2 Powertainer



GAS MAKING CONTAINER

POWER GEN CONTAINER

Source: All Power Labs (2020).

Powertainer Platform Production Readiness

The Beta 1 Powertainer was largely built as a one-off at the All Power Labs facility in Berkeley, California. As a product early in its development roadmap, there was a need under this grant to build one Powertainer using in-house capabilities to get first-hand experience with the build, as well as implement design improvements immediately. As the Powertainer is proven as a product, it needs to be fabricated and assembled using a broader supply chain, as previously discussed in this report. Based on lessons learned and making methods used for the outsourcing of the smaller-scale Power Pallet, the Powertainer has adopted many of these lessons learned with the goal to be ready for a larger production release and deployment of a fleet of Powertainers. While some suppliers used to build Power Pallet components that were also used for Powertainer components, the difference in size and scale needs to be taken into consideration and a suitable supply chain built accordingly.

Supply Chain Readiness

Table 17 shows the production and manufacturing strategy with the prototype and Beta units primarily sourced in the U.S. with final assembly and testing in California. This comprehends the target market, which prioritizes initial deployment in California. The beta 1 Powertainer represents what was built under this agreement.

Table 17: Supply Chain Strategy
(With All United States-based Manufacturing Done in California)

System	Component	Beta 1 (1×)	Beta 2 (1×)	Beta 3 (5–10×)
Gas Making	Gas-Making Container	All Power Labs (USA)	Matthews Mechanical (USA)	New Ocean (China/Philippines)
	Fuel Feed System	All Power Labs (USA)	All Power Labs (USA)	New Ocean (China/Philippines)
	Gasifier	All Power Labs (USA)	All Power Labs (USA)	New Ocean (China/Philippines)
	Flare	All Power Labs (USA)	All Power Labs (USA)	New Ocean (China/Philippines)
	Automation/Controls	All Power Labs (USA)	All Power Labs (USA)	New Ocean (China/Philippines)
Power Gen	Power Gen Container	N/A	Matthews Mechanical (USA)	Haiti Power (China)
	Filter	All Power Labs (USA)	All Power Labs (USA)	Haiti Power (China)
	Engine Genset	All Power Labs (USA)	All Power Labs (USA)	Haiti Power (China)
	CHP Circuit	N/A	All Power Labs (USA)	Haiti Power (China)
	Emissions Control	All Power Labs (USA)	All Power Labs (USA)	Haiti Power (China)
	Automation/Controls	All Power Labs (USA)	All Power Labs (USA)	Haiti Power (China)
	Grid Tie	N/A	All Power Labs (USA)	Haiti Power (China)

Source: All Power Labs (2020).

While different in many respects in design, a similar supply chain is anticipated to be used in both the Beta 1 and Beta 2 Powertainers, primarily, due to the low volume required under each grant. The project team has identified several specific suppliers anticipated to be used for the key components that make up the gas making and power generation modules of the Beta 2 Powertainer.

The longer term, higher volume strategy is contingent on the Beta 2 design, which involves full turnkey assembly, testing, and fulfillment with a strategic partner. While supplier and strategic partner qualification have already begun, the primary search will be more proactively engaged when the product has matured and market signals confirmed. For purposes of this report, short and mid-term strategies are presented as it is more useful and relevant.

Table 18 shows the cost breakdown for Beta 1 and Beta 2 and commercial cost.

Table 18: Powertainer Cost Model for Beta 1, Beta 2, and Commercial Release

Super System	Subsystem	Beta 1 Cost	Beta 2 Cost	Commercial Cost
Gas-making Module	Feed System	$53,301.00	$53,301.00	$37,310.70
	Flare	$10,350.00	$10,350.00	$7,245.00
	Gas-Making Automation	—	$4,057.74	$3,246.19
	Gas-Making Container	—	$8,500.00	$5,950.00
	Gas-Making Integration	—	$12,000.00	$4,800.00
	Gasifier	$16,700.00	$16,700.00	$13,360.00
	Total:	**$80,351.00**	**$104,908.74**	**$71,911.89**
Power Generation Module	CHP	—	$20,650.00	$14,455.00
	Emissions Control	$6,400.00	$6,400.00	$5,760.00
	Filter	$7,060.00	$7,060.00	$4,942.00
	Genset	$69,650.00	$69,650.00	$66,167.50
	Power Gen Automation	$7,174.62	$7,174.62	$5,739.70
	Power Gen Container	$12,000.00	$12,000.00	$4,800.00
	Power Gen Integration	$8,500.00	$8,500.00	$5,950.00
	Total:	**$110,780.42**	**$131,462.62**	**$107,814.20**
Grand Total		**191,135.62**	**236,343.36**	**179,726.09**
Watts		**150,000**	**200,000**	**200,000**
$/Watt		**$1.27**	**$1.18**	**$0.90**

Source: All Power Labs (2020).

The investment required to initiate a production level of five to 10, with early-release Powertainers, would be minimal because they will likely be built in a low-volume manufacturing environment. The project team expected cost of goods sold to be higher due to the few being produced. Getting to higher volumes will require investment in tooling capex for certain parts and assemblies and is estimated to be around $250,000. Investing in these should result in reduced manufacturing costs.

The Powertainer Beta 1 unit requires additional development of new features and maturity of existing features before it is ready for commercial deployment. Most of these improvements address market requirements such as cost and features, which enable flexibility and maximization of product outputs to address specific project needs. The Beta 2 Powertainer has additional features including higher power output, higher system efficiency with the addition of integration CHP, increased biochar production, remote monitoring, and improved emissions control. As part of this grant, the new Beta 2 Powertainer will undergo in field-testing. Funding of $2.25 million to support this project was provided by the Energy Commission and matching funds. One additional prototype will be required to fine tune final details before having a commercial product. Funds required to support a Beta 3 prototype including intensive reliability testing and proving is estimated to be equal to the Beta 2 funds. The total investment required to reach a commercial product would therefore be $4.4 million and would be financed through either a new grant or commercial source.

CHAPTER 6: Technology/Knowledge/Market Transfer Activities

Technology/Knowledge Transfer Summary

To introduce this important innovative technology in the market, All Power Labs used a handful of both online and public-facing outreach opportunities. As an authority in small-scale gasification technologies, the All Power Labs website is a go-to destination, and by highlighting the Powertainer as an upcoming technology, the team was able to get international attention and interest for the Powertainer. As effective as All Power Labs' online presence, the project team also prioritized in-person outreach within California with monthly open houses and dedicated gatherings and demonstrations focusing on the Powertainer technology.

The initial target market for this technology was the biomass waste management industry, one that interfaces with forestry products, produces biomass waste and ideally has larger electricity and heat demands. This, in many ways, is an optimal use case for this type of technology, which maximizes the benefits to California. In addition, since the Powertainer produces a very high-quality biochar, this byproduct enables an additional market. Figure 36 illustrates the placement of the Powertainer in a waste facility.

Figure 36: Powertainer Demonstration at the Green Waste Recycle Yard

Photo Credit: All Power Labs.

To initiate market penetration, the team investigated and identified market hurdles. One major hurdle to enter this market is to convince early adopters to be the first to undertake commercial deployment of this relatively unknown and untested technology, whether in the retail or waste to energy services model. This will require All Power Labs to develop and successfully work through regulatory challenges, and successfully operate the first pilot Powertainer projects.

All Power Labs has set up a business model combining direct retail equipment sales and provision of waste-to-energy services to generate revenue from the deployment of Powertainer projects. In the waste-to-energy services model, All Power Labs develops projects and owns and operates the equipment itself. The site host or offtaker pays for the energy, biochar, and waste processing services. This model eliminates up-front capital cost for the customer and provides All Power Labs with a recurring revenue stream. All Power Labs intends for the waste-to-energy services portion of its business to generate a larger share of revenue compared to retail sales, as it provides a more stable, and ultimately larger, revenue stream. Waste-to-energy service projects can also leverage structured financing, substantially expanding All Power Labs' capacity to deploy revenue-generating assets.

In both models, All Power Labs' customers will be commercial or institutional customers with biomass waste streams and energy needs. To reach these customers, All Power Labs' marketing strategy consists of making connections using paid consultants and networking with regional partners, such as trade groups and academics, followed by targeted periodical and online advertising in areas with high tree mortality.

As shown in Table 19, All Power Labs initially announced the Powertainer in early 2011, around the time the team developed the alpha Powertainer under a DOE grant agreement. However, it was not until the announcement of a Beta 1 Powertainer developed under this project that the technology received substantially more interest. The vast majority of inquiries came from the U.S., and the majority of those came from California and the Pacific Northwest. This is likely due to All Power Labs headquarters being located in California. The outreach has occurred within the state, where there is a market need for such a technology to address energy, forestry and agricultural challenges.

Table 19: Powertainer Sales Leads 2011–2018

Year	Leads (1,382 total)	Country	Leads
2011	4	USA	860 (WA: 498, CA: 290, OR: 48, TX: 3)
2012	2	Canada	40
2013	46	Nigeria	24
2014	8	Australia	21
2015	132	South Africa	14
2016	983	Italy	14
2017	95	India	12
2018	112	Philippines	10

Source: All Power Labs (2020).

While there are applications for All Power Labs’ technology worldwide, the company’s broad waste-to-energy market is in the forestry sector in the western U.S. and Canada, where beetle- and drought-related tree mortality is widespread. However, because of technology fit and geographical proximity, All Power Labs is targeting its initial deployment in California’s market for tree mortality waste fire remediation.[8]

The ideal size of an initial Powertainer project is anticipated to be approximately 200kW electrical, 300–400kW thermal, and a biomass throughput of approximately 300kW/kWh. This represents the size of a single Powertainer being developed under a current Energy Commission project and is expected to be the maximum power generation possible within one or two shipping containers. As projects using the Powertainer are tested and proven, these projects will be able to scale to multiple Powertainers, depending on the availability of reliable fuel supply. With the small portable container, projects are anticipated to be limited to 1MW. When fuel supplies slow down, under the waste-to-energy service model, the Powertainers can be moved to a new location having a stable fuel supply. This is a major differentiator from the large centralized plant model.

Additional barriers and challenges for commercialization deal with regulatory challenges and technology readiness. While the Powertainer made major improvements under this grant, additional features and refinement are required before it is commercially ready. In addition, regulatory challenges should be addressed to ease the process for enabling pilot projects necessary for real-world proving, as well as for longer-term projects to maximize the benefits this technology offers the state when deployed at scale. The high costs and time required for bringing up projects will certainly be a deterrent for a larger-scale deployment of this technology unless relevant financial incentives are available.

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[8] USDA Office of Communications, *supra* note 1.

CHAPTER 7: Conclusions/Recommendations

The entire American West — California in particular — faces difficult and conflicting priorities over the management of public and private forestlands. Increasingly dry weather conditions, high fuel loading, due to decades of natural fire exclusion, and unprecedented tree mortality — due primarily to drought stress and an invasive bark beetle infestation — have resulted in a series of record-breaking wildfires and fire risk to forests and communities throughout California. Given dry conditions and overgrown forests, in most areas with high tree mortality rates, targeted thinning is the only safe and effective fire remediation method for landowners and resource managers. Thinning by use of centralized biomass power plants is not sustainable because transportation of the waste wood is generally expensive and tree mortality waste has little value for commercial lumber. Therefore, the only economical disposal option for the thinning waste is usually onsite open pile burning.[9] Yet, the fire danger in many areas is now too high for even this method, which also has air quality and public health concerns. Given the lack of safe, effective, and economical waste disposal options, forest biomass is left where it died, stored in overflowing lumberyards, or stacked on the side of rural roads — all causing a severe fire hazard. This threatens public safety and health, as well as the economies of rural communities, many of which are already struggling.

Officials in impacted counties expect millions more trees to die as beetle-related tree mortality continues to increase.[10] Although the tree mortality waste has been growing rapidly (806 percent in 2014, 113 percent in 2015, and 64 percent in 2016), the rate of growth is gradually slowing.[11] Assuming these trends continue, the serviceable available market will be approximately $172 million in 2022.[12] However, longer-term tree mortality trends beyond 2022, show additional waves of tree mortality, with peaks that will generate over twice as much waste as the current crisis. The problem requires a solution that is cross generational, addresses wildfires, and also accounts for problems of rotting wood that release greenhouse gases in vast quantities. The project team has developed a responsible way to process this waste that results in carbon sequestered as biochar — that will not only be retained in soil for centuries but will improve the soil at the same time.

Despite a clear need for the Powertainer technology, deployment of these systems in California has been challenging due to interconnection and permitting requirements that have proven to

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[9] Springsteen et al., Emission Reductions from Woody Biomass Waste for Energy as an Alternative to Open Air Burning, Journal of the Air and Waste Management Association, 61:63-68 (2011).

[10] University California, Davis Dept. of Plant Sciences, "How much drought can a forest take? Aerial tree mortality surveys show patterns of tree death during extreme drought", 20 Jan. 2017, https://news.plantsciences.ucdavis.edu/2017/01/20/how-much-drought-can-a-forest-take-aerial-tree-mortality-surveys-show-patterns-of-tree-death-during-extreme-drought/.

[11] Tree Mortality Task Force, *supra*.

[12] *Id.*

be complicated and costly, considering the small scale of the project. Some of the complication relates to non-standardized air quality permitting requirements. Others include flat rate permitting costs for systems regardless of system size. Unless regulations are revised, requiring an interconnection agreement with a utility that will pay for the electricity in order to realize value is a high bar to make these small, distributed-scale projects viable. Exacerbating the issue, this small-scale, portable biomass generation equipment is relatively new and current regulatory requirements are not suited for this specific architecture and portable project model.

Wood waste processing is a major driver to addressing the tree mortality crisis. In addition, market interest in a biochar generator of this scale and quality is very strong. All Power Labs has an existing micro-scale biomass gasifier known as the Power Pallet. However, this 25-kW system is not suitable to address the scale of this waste processing need. Therefore, All Power Labs has received substantial interest from multiple sectors for a larger product, like the Powertainer. In addition, the economics of power generation with renewable sources has changed substantially since the start of the project, with the cost of electricity steadily decreasing to a point where the return on investment for an energy-optimized, small-scale unit, is harder to financially justify. To create economic incentives that address the tree mortality crisis, the market needs to realize the value of other product outputs such as biomass waste processing and biochar production. Existing market signals recognize this forestry application, as well as other customers in wood products, agriculture, and urban green waste markets.

Development of a standardized, distributed-scale biomass generator, such as the Powertainer, is well on its way to becoming a product that can convert biomass forestry waste streams into value-add products such as electricity, heat, and biochar. The current technology architecture and data show substantial improvements with the lessons learned from this project. The project team has revised the product roadmap incorporating new features based on this knowledge and are using these insights for the Beta 2 unit funded under a separate Energy Commission funding opportunity.

Next Steps

All Power Labs continues to market the development of this product to its customer base and is signaling limited availability of the Powertainer in 2020. This creates market interest for the product, while continued development of new features and maturing existing features is occurring.

Lessons learned from this project will be applied in the updated version of the technology, where All Power Labs is seeking to develop higher electrical generation, biochar off-take capability, and other improvements.

The project team is researching technology architectures that leverage interconnection of other renewable generation technologies, such as solar. System designs that do not require interconnection are also being researched. For example, systems that integrate electricity storage and inverter technology are being developed to possibly overcome regulatory hurdles for interconnection to the grid. Additionally, off-grid applications are being researched where power generation is used to fill on-site demand, wood waste disposal is needed, and biochar can be sold for agronomic and commercial use.

Recommendations

In the midst of the changing climate and the negative effects already being experienced across the state, it is critical that policy makers recognize the importance and unique benefits of biomass energy. All Power Labs recommends the development of policies to promote the wood products market — particularly innovative use of thinned material and other biomass — to support forest-dependent economies and ongoing forest management activities. One suggestion is to encourage the siting of complementary wood products manufacturing facilities and small-scale biomass electrical generation plants to create regional economic hubs.

For this to be successful, regulatory challenges must be addressed. The obstacles that were experienced attempting to get permits and interconnection approval was far more challenging than expected. This regulatory hurdle not only makes pilot projects difficult to get off the ground (which slows down market readiness), but it also provides an example of the challenges the market will face with larger deployments. Because this is a research and development grant, the technology is not ready to satisfy the usual regulatory and permitting requirements. A special category of permits or exemptions — sponsored at the state level to support the development and pilot testing of new technologies — would substantially reduce the barriers to entry, accelerate the proving process, and therefore, reduce the time to market.

Regarding the technology, the team recommends that further investment is made to bring this product to commercialization. Additional funding will enable greater maturity of the existing design as well as additional features such as increased waste processing, higher electrical output, added combined heat and power enabling usable heat, and increased production of high temperature biochar. Further funding will also enable additional testing, which is critical for identifying failure modes to address and improve ease of operation.

CHAPTER 8: Benefits to Ratepayers

Biomass gasification power generation provides ratepayers with another 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 a myriad of issues associated with climate change, including drought, tree mortality, forest fires, and the need for more renewable energy. This project addresses the viability of mobile gasification systems based on harvesting fire-damaged forests. It highlights an option to help finance fire management programs. Furthermore, it demonstrates how this technology also provides the potential for a major reduction of harmful air emissions when compared to open burning of forest wastes.

The Powertainer's projected levelized cost of energy of $117.34 per MWh once commercialized, will increase the potential for mass commercial deployment of distributed biomass gasification technology, helping California reach its goal of developing bioenergy markets (Bioenergy Action Plan 2012) and meeting its ambitious renewable portfolio standard.

In addition, the carbon sequestration potential of the biochar is particularly groundbreaking. Very few technologies exist that can essentially sequester atmospheric carbon — which is what the Powertainer can do when paired with the natural forest ecosystem. The Powertainer is an innovative and groundbreaking bio-energy with carbon capture and storage technology. When introduced back into California's soils the biochar results in a carbon-negative energy solution, something that separates this technology from almost any other energy option. The biochar produced from this technology enables the sequestration of carbon that would otherwise have been released into the atmosphere.

When deployed at scale, the Powertainer will result in job creation across multiple sectors, including manufacturing, feedstock supply chain (harvesting, processing, transportation), equipment operation, construction, and project development. Some of the benefits commercial-scale biomass electrical 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.
- Improves energy security. The Powertainer develops a native Californian renewable resource and reduces any potential need for electricity imports from other states that generate power using coal.
- Lowers cost. The Powertainer'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).[13]

- Increases safety. By creating a market demand for forestry biomass waste, the Powertainer will increase safety by creating an economic driver to support forest thinning; thus, reducing the risk of catastrophic wildfire and damage/destruction of California's investor-owned transmission lines.
- Improves public health. The Powertainer substantially lowers criteria pollutant emissions and reduces wildfire danger, with its associated adverse public health impacts.
- Promotes economic development. The Powertainer's creation of demand for forest biomass waste, derived from California's unprecedented tree die-off, economically supports thinning operations and secondary markets such as mills. In addition, the Powertainer project creates manufacturing jobs.
- Provides environmental benefits. The broader societal impacts extend beyond pure business concern into ecological preservation and innovation as well. The thinning operations supported by the Powertainer 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 as biochar encourages plant growth that strengthens life along banks.
- Advances state policy goals for climate change. The Powertainer is not only an electrical generation technology but has a by-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 overcropped land can provide a huge benefit to 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 Powertainer are very intertwined. Activities such as forest thinning and removal of high fire risk forest biomass directly impact the health and safety of California residents, and the reliability of utilities. Salvage of biomass materials make forest fires less common and less extreme, producing fewer harmful emissions, as well as reducing potential future damage to property and utilities. By using this biomass for feedstock combined with the production of distributed renewable energy, economic benefits are created to support these activities and produce jobs. Which, with the added benefit of biochar production, can result in a carbon-negative outcome, contributing directly to reversing climate change impacts. Some of these benefits are illustrated in Figure 37, developed by the Placer County Air Quality District.[14]

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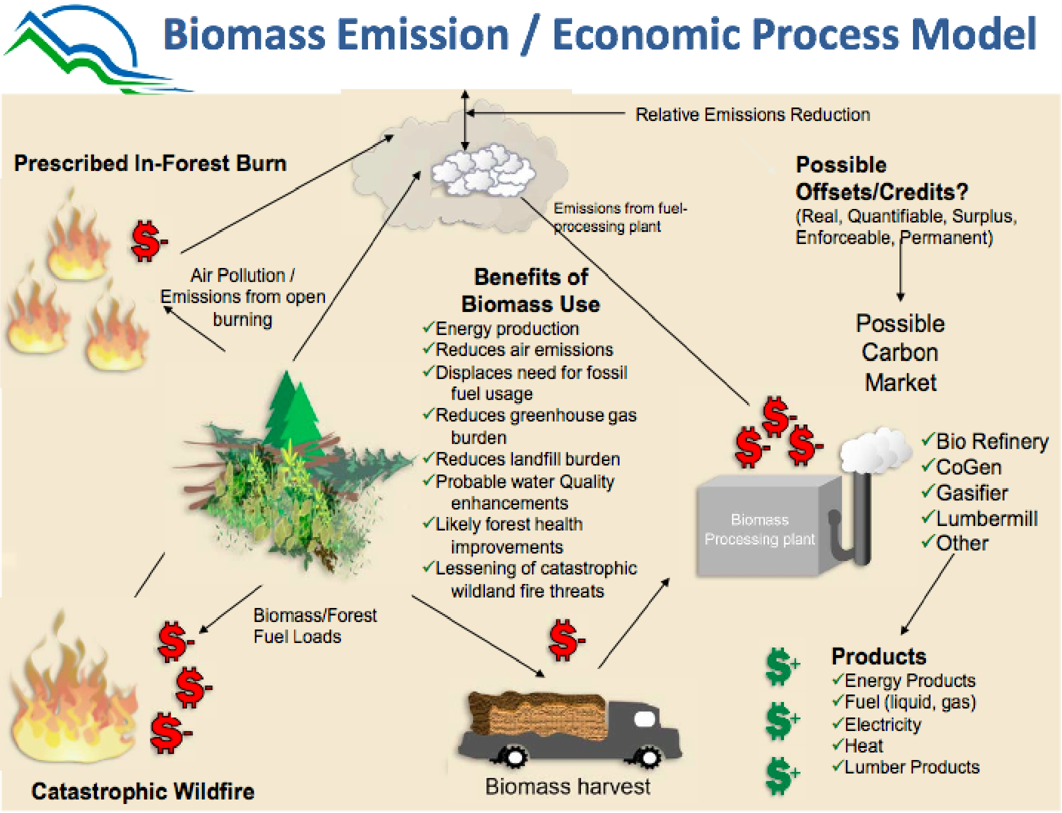
[13] "Electric Power Monthly" from the U. S. Energy Information Administration https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_5_6_a, accessed January 3, 2019

[14] 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 37: Biomass Emissions / Economic Process Model



Source: Placer County Air Quality District.

There are different use cases to which the Powertainer can be applied. To maximize the benefits of the Powertainer, the best use case intersects with the agriculture, forestry, and the urban green waste management sectors using waste streams rather than virgin material. Extending on this, by partnering with a company that already has a biomass supply chain — from which they are able to produce useful products, and as a result, produces a biomass waste stream suitable for the Powertainer — the benefits are compounded. The facilities of these companies often already have much of the biomass processing equipment that would be required for a Powertainer project. This, in return, minimizes the capital investment to bring a Powertainer project online. Such facilities often have the electric loads and the interconnection that are well suited for the Powertainer. These factors substantially reduce the barrier of entry to initiate a Powertainer project. Such a setup is the most cost optimized for bringing a project online with the primary expense being the Powertainer itself (at an estimated price of $250,000 to $300,000), plus the cost of permitting, interconnection, and integration, which are variable depending on the project location and regulatory jurisdiction.

Since this project, in the end, was not deployed to a site where it produced measurable value in the field, the calculated benefits are modeled and normalized in a way that can scale for multiple scenarios. To do this, the potential value of one bone dry ton of biomass, when used to fuel the Powertainer, was compared to an open burn use case (Table 20). This way, the benefits can easily be scaled to various deployment scenarios. Here, as seen in Table 21, the Powertainer was scaled to a number that would need to operate to address the amount of standing dead trees caused by the tree mortality crisis. For a single Powertainer operating at a green waste yard or mill, one bone dry ton would result in the following benefits compared to an open burn pile:

Table 20: Modeled Impacts from Processing One Bone Dry Ton Using the Powertainer

	Open Pile Burn	Powertainer 150	Impact
Electricity			
Electricity produced / grid electricity offset	0 kWh/ton	756.0 kWh/ton	+756.0 kWh/ton
Levelized cost of energy per ton	-	\$88.71/ton	+\$88.71/ton
Greenhouse Gases			
CO2 (direct biogenic emissions)	3,666 lb/ton [1]	2,922 lb/ton [2]	-744 lb/ton (20.3% reduction)
CH4	6.0 lb/ton [1]	2.9 lb/ton [2,3]	-3.1 lb/ton (51.7% reduction)
Carbon sequestered	0 lb/ton	79 lb/ton C [4] 290 lb/ton as CO2 [4]	100 lb carbon sequestration 290 lb/ton as CO2
Criteria Pollutants			
CO	126 lb/ton [1]	0.07 lb/ton [2]	-*125.9* lbs/ton (99.9% reduction)
NOx	6.0 lb/ton [1]	7.6 lb/ton [2]	+1.6 lb/ton (26.7% increase)
PM	13.0 lb/ton [1]	0.02 lb/ton	-1*2.98* lbs (99.9% reduction)
Other			
Jobs - O&M	No data	0.22 operator hour/ton	+0.22 operator hour/ton
Area of managed forest land	0.07 acre/ton	0.07 acre/ton	0% change

Note 1: Based on data from Springsteen.

Note 2: Based on testing for previous CEC agreement, assuming 7.16 kg/kWh wet exhaust flow rate. CO 2 ppm, NOx 135 ppm @ 15% O2.

Note 3: Using ½ of detection limit of 0.1% (1,000 ppm) the USEPA 3C method used - 500 ppm CH4.

Note 4: Assuming 5% biochar yield (biochar out/biomass in), 79% biochar carbon content. 1 lb, C = 3.67 CO2.

Note 5: Assuming 2 mg/m3 PM in exhaust

Source: All Power Labs (2020).

With the scale of the problem substantially more than one bone dry ton of biomass, the results were scaled for the total range of economically accessible standing dead trees based the University of California, Berkeley study conducted through this project. The amount of standing dead biomass that can be considered cost-effective for electricity generation is 7.6 to 27.9 million bone dry tons.[15] Tree mortality generated up to 60 million bone dry tons of material in 2016 and up to 15 million bone dry tons in 2017. Material expected at this scale of processing should aim to handle hazardous materials generation on the order of years. Processing 10 million bone dry tons per year would require 6 years to mitigate tree mortality from 2016. The results outlined in Table 21 illustrate a major contribution and benefit to California when compared to open burning, or even a case that does not use forest refuse, leaving the biomass to the risk of catastrophic wildfires.

Table 21: Modeled Impacts from Processing 10 Million Bone Dry Tons Per Year Using the Powertainer

	Open Pile Burn	Powertainer 150	Impact
Electricity			
Electricity produced / grid electricity offset	0 MWh	7,560,000.00 MWh/year	**7,560,000.00 MWh/year generation**
Levelized cost of energy			$887.1 million revenue at **$117.34/MWh sales price**
Greenhouse Gases			
CO2 (direct biogenic emissions)	18.3 million tons/year	14.6 million tons/year	3.7 million ton/year reduction **(20.3% reduction)**
CH4	30.0 thousand tons/year	14.5 thousand tons/year	15.5 thousand ton/year reduction **(51.7% reduction)**
Carbon sequestered	0.0 thousand tons/year	1,450.00 thousand tons/year as CO2	1,450.00 thousand tons/year as CO2 sequestered
Criteria Pollutants			
CO	630.0 thousand tons/year	0.4 thousand tons/year	629.7 thousand ton/year reduction **(99.9% reduction)**
NOx	30.0 thousand tons/year	38.0 thousand tons/year	8 thousand tons/year increase (26.7% increase)

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[15] From the CEC report *Analysis of the Woody Biomass Feedstock Potential Resulting from California's Drought*. Lara, Jose Daniel; Tubbesing, Carmen L.; Battles, John J., Tittmmann, Peter W.; and Kammen, Daniel M. 2018. California Energy Commission. Data set can be found at https://doi.org/10.6084/m9.figshare.c.4117328.v3

	Open Pile Burn	Powertainer 150	Impact
PM	65.0 thousand tons/year	0.1 thousand tons/year	64.9 thousand tons/year reduction **(99.9% reduction)**
Other			
Jobs	No data	7,192 jobs in O&M and material handling [1]	
Area of managed forest land	0.7 million acres//year	0.7 million acres/year	0.7 million acres/year (0% change) [2]

Note 1: Assuming jobs per MW slightly above typical ranges16 due to reduced economies of scale, this equals 0.75 jobs per unit. At a capacity factor of 60 percent (meaning it runs 60 percent of the time), a Powertainer 150 would consume 1,043 bone dry tons of wood per year, requiring 9,589 units or 1,438 MW of installed capacity to convert 10 million bone dry tons of wood per year. Note 2: No change under same quantity of material processed. Amount of material processed will depend on the economics of either method.

Source: All Power Labs (2020)

When deployed at scale, the model indicates major benefits across the state, including production of renewable energy, emissions reduction, job creation, carbon sequestration, and managed forest land, all at a levelized cost of energy 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 of renewable energy production, greenhouse gas 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 tree mortality emergency into a climate mitigation solution. Based on conversions using the California Air Resource Board, 10 million bone dry tons per year scenario from Table 22 would result in saving 7.89 million metric tons of CO2e, which is equivalent to 248 million therms natural gas.

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[16] https://www.eesi.org/papers/view/fact-sheet-jobs-in-renewable-energy-and-energy-efficiency-2015

Table 22: Powertainer Modeled Impacts Equivalences

	Powertainer 150	CO2e Equivalent (mission tons/year)	Equivalence (Therms natural Gas)
Electricity			
Electricity Produced / Grid Electricity Offset	7,560,000.00 MWh/year generation	2.445[17]	509 million therms NG
Greenhouse Gases			
CO2 (direct biogenic emissions)	3.7 million ton/year reduction	3.7	634 million therms NG
CH4	15.5 thousand ton/year reduction	0.388	66 million therms NG
Carbon Sequestered	1,450.00 thousand tons/year as CO2 sequestered	1.450	248 million therms NG
Total		7.98 million tons of CO2e	948 million therms NG

Source: All Power Labs (2020).

While this project experienced technical and regulatory challenges, it sets the groundwork for future studies and projects using the Powertainer biomass energy technology. This technology continues to represent a value proposition that benefits California's triple bottom line (energy, climate change, and air quality). Since the value proposition for this technology addresses so many benefits to California, it is critical to continue developing the Powertainer so that it becomes a viable technology and energy option that can be used across California in areas already seen hardest hit by the results of climate change.

The funding provided by this grant has provided the groundwork for future development of the Powertainer platform. The previous grant-funded innovations have been leveraged and combined with existing expertise at this new large scale; which is advantageous for improving market entry at the commercial/industrial scale. The next stage of development and proving has already begun with the new EPIC grant agreement where additional features and performance improvements will be added, along with in-region performance testing and proving. Key improvements include higher power output, higher efficiency, integration of thermal output, and increased biochar production, all strengthening the benefits this technology offers California. As illustrated in the Figure 38,[18] biomass energy, in comparison to

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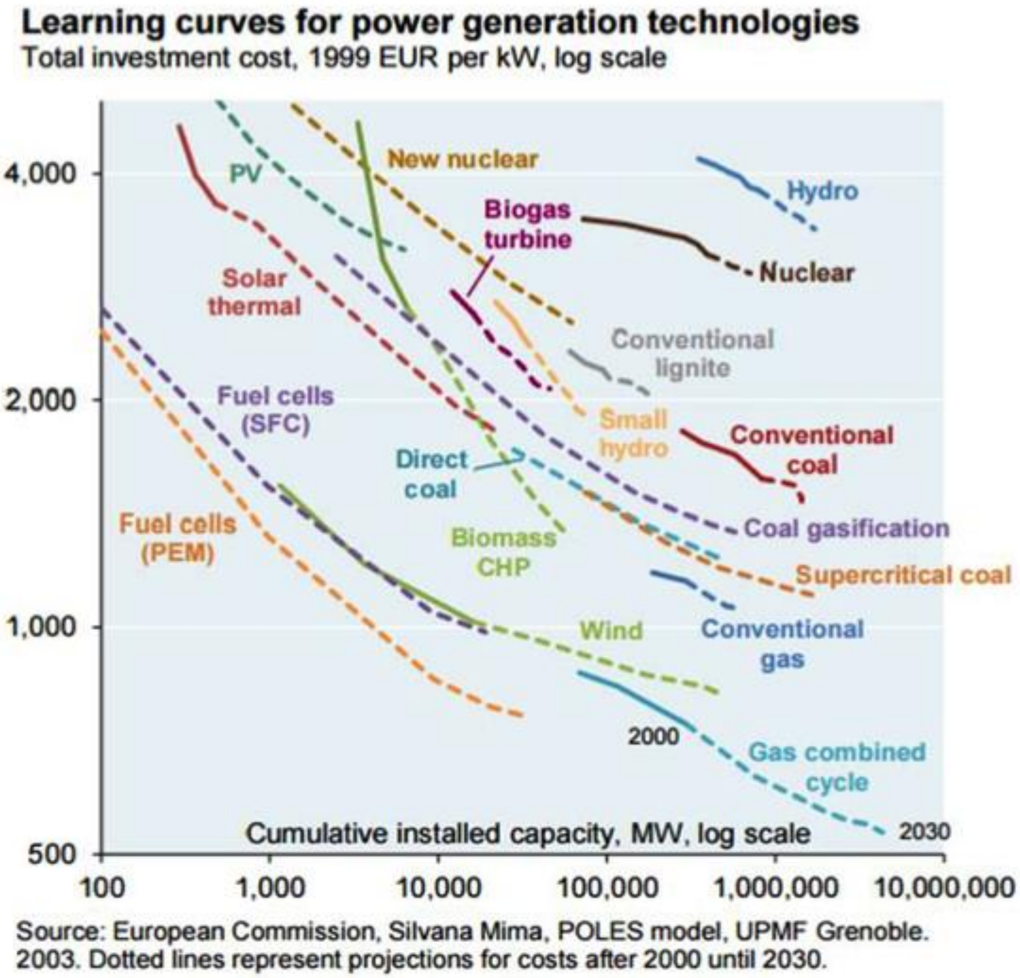
[17] 81.49 gCO2e/MJ = 293.4 gCO2e/kWh.
https://ww3.arb.ca.gov/fuels/lcfs/fuelpathways/comments/tier2/elec_update.pdf

[18] "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/.Accessed on February 2, 2019.

other power generation technologies has experienced a relatively rapid learning curve. Although biomass energy is considered a new technology when compared to other power generation technologies, minimal investment should be required to finish maturing this technology, deploy it at scale, and reap the multitude of benefits it can contribute to California.

Figure 38: Learning Curve for Power Generation Technologies



Learning curves for power generation technologies

Total investment cost, 1999 EUR per kW, log scale

Source: European Commission, Silvana Mima, POLES model, UPMF Grenoble. 2003. Dotted lines represent projections for costs after 2000 until 2030.

Source: European Commission, Silvana Mirna, POLES model, UPMF Grenoble. 2003.

To enable the adoption of this technology, it is recommended that California implement legislation that continues to fund research and reduces the permitting and interconnection barriers of entry for research projects.

LIST OF ACRONYMS

Term	Definition
AB	Assembly Bill: legislation from the California legislature
ADS	Aerial Detection Survey
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
CRM	Component Ratio Method
db	Dry Basis
DBH	Diameter at Breast Height
DFx	Design for x
DOE	Department of Energy: federal agency for energy policy and funding priorities
ECU	Engine Control Unit
EPIC	Electric Program Investment Charge
GWRY	Green Waste Recycle Yard
HAP	Hazardous Air Pollutant
IOU	Investor Owned Utilities
MW	megawatts
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
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
ROC	Reactive Organic Compounds: term of art for a subset of volatile organic compounds
ROI	Return on Investment: ratio between the net profit and cost of investment
SD	Standing Dead (trees): trees which are no longer living but have yet to be felled, a class of dead forestry mass
TAC	Toxic Air Contaminant: industry term for pollutants released from engines

Term	Definition
TAC	Technical Advisory Committee
Triple bottom line	Accounting framework that considers environmental, financial, and social goals.
TRL	Technology Readiness Level: a measure of maturity for a new technology
VOC	Volatile Organic Compound: a large class of organic materials, some of which are toxic

FURTHER READING

1 "Tree Mortality: Facts and Figures" (April 2017), published by the Tree Mortality Task Force of CAL FIRE, available at http://www.fire.ca.gov/treetaskforce/downloads/TMTFMaterials/Facts_and_Figures.pdf

2 Safeguarding California Plan: 2018 Update California's Climate Adaptation Strategy | January 2018. Accessed at https://www.cakex.org/sites/default/files/documents/safeguarding-california-plan-2018-update_0.pdf

3 Aaberg, Dennis. "Generator Set Noise Solutions: Controlling Unwanted Noise from on-Site Power Systems." *Www.cumminspower.com*, Cummins Power Generation , 2007.

4 "Bay Area Air Quality Management District Best Available Control Technology (BACT) Guideline." *Bay Area Air Quality Management District*, Bay Area Air Quality Management District, 22 May 2015, www.baaqmd.gov/permits/permitting-manuals/bact-tbact-workbook.

5 Reed, Thomas B., and Agua Das. "Handbook of Biomass Downdraft Gasifier Engine Systems." *Handbook of Biomass Downdraft Gasifier Engine Systems*, Solar Technical Information Program, Solar Energy Research Institute, 1988.

6 Prabir Basu. Biomass Gasification and Pyrolysis: Practical Design and Theory. Academic Press, Elsevier, 2010.

7 Quinlan, Brendan, et al. "The Use of on-Line Colorimetry for Tar Content Evaluation in Gasification Systems." *International Journal of Heat and Technology*, vol. 35, no. Special Issue 1, 20 Sept. 2017, doi:10.18280/ijht.35sp0120.

8 California Air Resources Board. "R2-1.HTM." *Shasta County AQMD List of Current Rules*, 28 Dec. 2018, www.arb.ca.gov/drdb/sha/cur.htm.

9 The data that support the findings of this study and the resulting SQL file to restore the database are available in figshare with the identifier data DOI(s) https://doi.org/10.6084/m9.figshare.c.4117328.v2.

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

APPENDIX A:
Technology Readiness Assessment Guide

Table A-1: Relevant Technology Readiness Level from the Department of Energy:[19]

Relative Level of Technology Development	TRL	TRL Definition	Description
Technology Development	TRL 4	Component and/or system validation in laboratory environment	The basic technological components are integrated to establish that the pieces will work together. This is relatively "low fidelity" compared with the eventual system. Examples include integration of ad hoc hardware in a laboratory and testing with a range of simulants and small scale tests on actual waste. Supporting information includes the results of the integrated experiments and estimates of how the experimental components and experimental test results differ from the expected system performance goals. TRL 4–6 represent the bridge from scientific research to engineering. TRL 4 is the first step in determining whether the individual components will work together as a system. The laboratory system will probably be a mix of on hand equipment and a few special purpose components that may require special handling, calibration, or alignment to get them to function.

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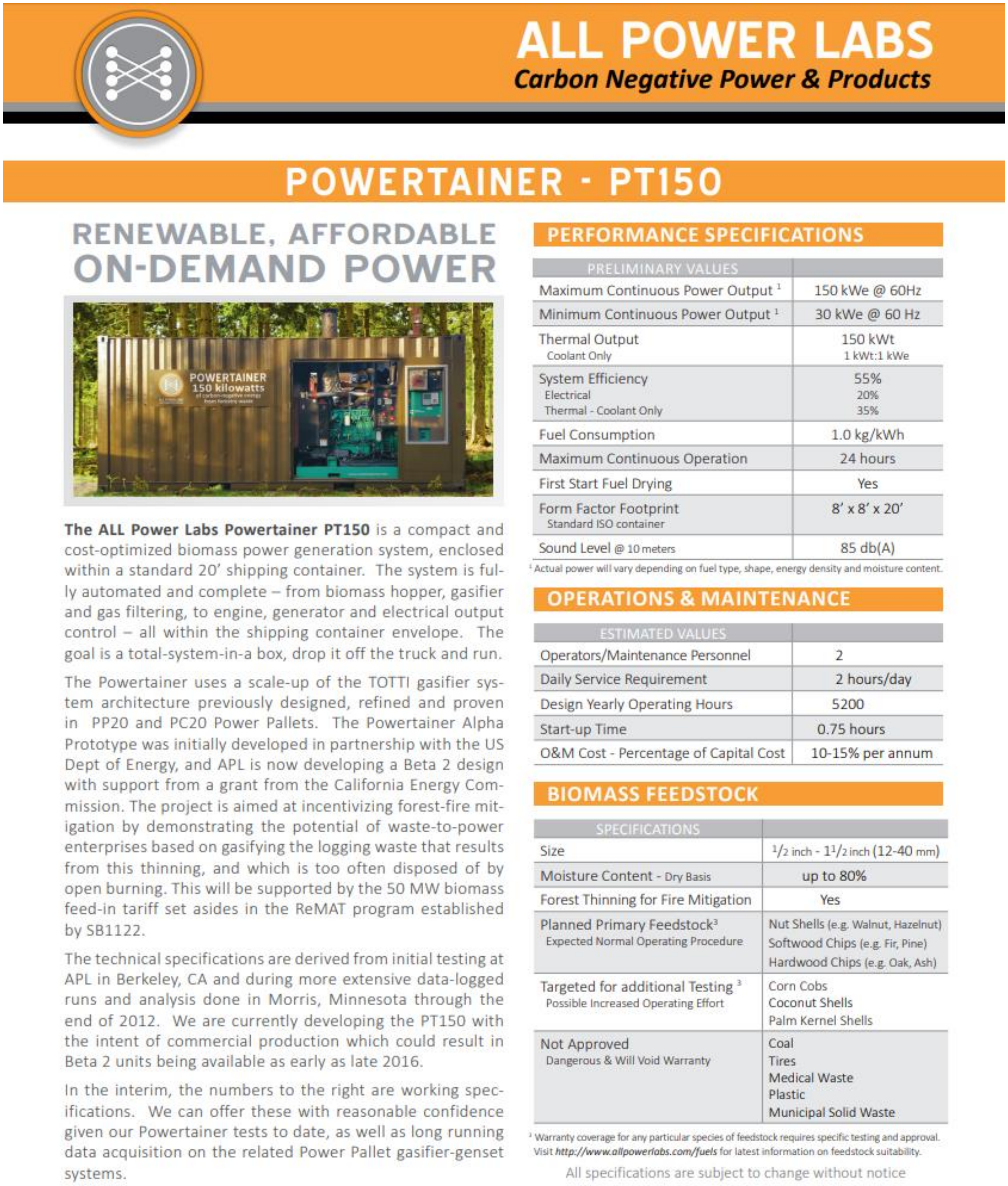
[19] Department of Energy's "Technology Readiness Assessment Guide", publication DOE G 413.3-4A 9-15-2011. Accessible at https://www.directives.doe.gov/directives-documents/400-series/0413.3-EGuide-04-admchg1

Relative Level of Technology Development	**TRL**	**TRL Definition**	**Description**
	TRL 5	Laboratory scale, similar system validation in relevant environment	The basic technological components are integrated so that the system configuration is similar to (matches) the final application in almost all respects. Examples include testing a high-fidelity, laboratory scale system in a simulated environment with a range of simulants and actual waste. Supporting information includes results from the laboratory scale testing, analysis of the differences between the laboratory and eventual operating system/environment, and analysis of what the experimental results mean for the eventual operating system/environment. The major difference between TRL 4 and 5 is the increase in the fidelity of the system and environment to the actual application. The system tested is almost prototypical.
Technology Demonstration	TRL 6	Engineering/ pilot-scale, similar (prototypical) system validation in relevant environment	Engineering-scale models or prototypes are tested in a relevant environment. This represents a major step up in a technology's demonstrated readiness. Examples include testing an engineering scale prototypical system with a range of simulants. Supporting information includes results from the engineering scale testing and analysis of the differences between the engineering scale, prototypical system/environment, and analysis of what the experimental results mean for the eventual operating system/environment. TRL 6 begins true engineering development of the technology as an operational system. The major difference between TRL 5 and 6 is the step up from laboratory scale to engineering scale and the determination of scaling factors that will enable design of the operating system. The prototype should be capable of performing all the functions that will be required of the operational system. The operating environment for the testing should closely represent the actual operating environment.

Relative Level of Technology Development	TRL	TRL Definition	Description
System Commissioning	TRL 7	Full-scale, similar (prototypical) system demonstrated in relevant environment	This represents a major step up from TRL 6, requiring demonstration of an actual system prototype in a relevant environment. Examples include testing full-scale prototype in the field with a range of simulants in cold commissioning. Supporting information includes results from the full-scale testing and analysis of the differences between the test environment, and analysis of what the experimental results mean for the eventual operating system/environment. Final design is virtually complete.
	TRL 8	Actual system completed and qualified through test and demonstration	The technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental testing and evaluation of the system with actual waste in hot commissioning. Supporting information includes operational procedures that are virtually complete. An Operational Readiness Review (ORR) has been successfully completed prior to the start of hot testing.

APPENDIX B:
Powertainer Product Fact Sheet



ALL POWER LABS
Carbon Negative Power & Products

POWERTAINER - PT150

RENEWABLE, AFFORDABLE ON-DEMAND POWER

The ALL Power Labs Powertainer PT150 is a compact and cost-optimized biomass power generation system, enclosed within a standard 20' shipping container. The system is fully automated and complete – from biomass hopper, gasifier and gas filtering, to engine, generator and electrical output control – all within the shipping container envelope. The goal is a total-system-in-a box, drop it off the truck and run.

The Powertainer uses a scale-up of the TOTTI gasifier system architecture previously designed, refined and proven in PP20 and PC20 Power Pallets. The Powertainer Alpha Prototype was initially developed in partnership with the US Dept of Energy, and APL is now developing a Beta 2 design with support from a grant from the California Energy Commission. The project is aimed at incentivizing forest-fire mitigation by demonstrating the potential of waste-to-power enterprises based on gasifying the logging waste that results from this thinning, and which is too often disposed of by open burning. This will be supported by the 50 MW biomass feed-in tariff set asides in the ReMAT program established by SB1122.

The technical specifications are derived from initial testing at APL in Berkeley, CA and during more extensive data-logged runs and analysis done in Morris, Minnesota through the end of 2012. We are currently developing the PT150 with the intent of commercial production which could result in Beta 2 units being available as early as late 2016.

In the interim, the numbers to the right are working specifications. We can offer these with reasonable confidence given our Powertainer tests to date, as well as long running data acquisition on the related Power Pallet gasifier-genset systems.

PERFORMANCE SPECIFICATIONS

PRELIMINARY VALUES	
Maximum Continuous Power Output[1]	150 kWe @ 60Hz
Minimum Continuous Power Output[1]	30 kWe @ 60 Hz
Thermal Output Coolant Only	150 kWt 1 kWt:1 kWe
System Efficiency Electrical Thermal - Coolant Only	55% 20% 35%
Fuel Consumption	1.0 kg/kWh
Maximum Continuous Operation	24 hours
First Start Fuel Drying	Yes
Form Factor Footprint Standard ISO container	8' x 8' x 20'
Sound Level @ 10 meters	85 db(A)

[1] Actual power will vary depending on fuel type, shape, energy density and moisture content.

OPERATIONS & MAINTENANCE

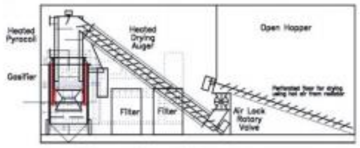
ESTIMATED VALUES	
Operators/Maintenance Personnel	2
Daily Service Requirement	2 hours/day
Design Yearly Operating Hours	5200
Start-up Time	0.75 hours
O&M Cost - Percentage of Capital Cost	10-15% per annum

BIOMASS FEEDSTOCK

SPECIFICATIONS	
Size	½ inch - 1½ inch (12-40 mm)
Moisture Content - Dry Basis	up to 80%
Forest Thinning for Fire Mitigation	Yes
Planned Primary Feedstock[3] Expected Normal Operating Procedure	Nut Shells (e.g. Walnut, Hazelnut) Softwood Chips (e.g. Fir, Pine) Hardwood Chips (e.g. Oak, Ash)
Targeted for additional Testing[3] Possible Increased Operating Effort	Corn Cobs Coconut Shells Palm Kernel Shells
Not Approved Dangerous & Will Void Warranty	Coal Tires Medical Waste Plastic Municipal Solid Waste

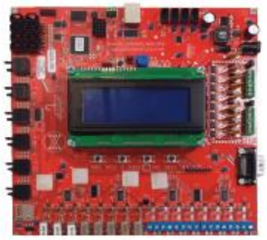
[3] Warranty coverage for any particular species of feedstock requires specific testing and approval. Visit *http://www.allpowerlabs.com/fuels* for latest information on feedstock suitability.

All specifications are subject to change without notice



Powertainer Alpha - Side View

3D CAD Powertainer Alpha



APL Custom Process Control

Deep Sea Grid Tie Control for Synchronous Generator

GASIFIER SYSTEM

FEATURES	
GEK TOTTI Gasifier - Multi-stage, Zone-separated Heat-regenerating, High-efficiency Architecture	✔
Fuel Moisture Tolerance	up to 80%
Biomass to Power Conversion[4] - Dry Basis	1.0 kg = 1 kWh
High Performance Neutral-Vane Multi-Cyclone	✔
Multi-stage Solid Particulate Filters	✔
Active Mist and Tar Filtration	✔
Continuous Char/ash Removal from Gasifier[5] 12-24 hr. service period	✔
Continuous Cyclone Particulate Removal[5] 12-24 hr. service period	✔
Continuous Fuel Feed via Airlock Including hopper, air lock, level sensing & ECU	✔

[4] Energy density of any given feedstock varies depending on various factors such as fixed carbon content.

[5] Char/ash & particulate byproducts vary depending on fuel type, shape, energy density & moisture content.

ENGINE & GENERATOR

FEATURES	
Spark Ignition IC Engine - 12-20 liter displacement	TBD
Electronic Governor	✔
Automated Syngas/Air Mixture Control	✔
Exhaust Cleanup - Catalytic Converter	CA Compliant
Synchronous or Induction Alternator	UL/NEMA Compliant
Field Configurable - All common phase & Voltage	✔
Grid Tie System - including controls & contactor	✔
Paralleling Capable	✔

AUTOMATION SYSTEM

FEATURES	
Full Temperature & Pressure Instrumentation	✔
Smart Grate, Fuel & Charash Auger Control	✔
Diagnostic Messages for Error Recovery	✔
User-Configurable Setpoints For all critical systems	✔
Datalogging for Gasifier	✔
Datalogging for Power Generation	✔
Remote Monitoring	✔

All specifications are subject to change without notice

APPENDIX C: Analysis of the Woody Biomass Feedstock Potential Resulting from California's Drought

The following document is a CEC Energy Research and Development Division interim project report "Analysis of the Woody Biomass Feedstock Potential Resulting from California's Drought" conducted by University of California, Berkeley.

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Abstract

Large-scale regional tree die-off events, which have occurred recently in the Western US, generate large quantities of standing dead wood and can spark concern over risks to local communities. In California, unprecedented tree die-off occurred following a 4-year drought and widespread pest outbreaks. State officials and agencies responded with policies to encourage removal of standing dead trees, focusing in particular on woody biomass energy as a disposal solution. We evaluate the feasibility of California's woody biomass disposal goals by quantifying the availability and accessibility of dead woody biomass feedstocks. We combine US Forest Service Aerial Detection Survey data with forest structure maps based on pre-drought imagery to generate a map of available woody biomass at fine spatial resolution. We then classify biomass feedstock estimates into feasibility categories based on operational forest management constraints including slope, mean tree size, and wilderness status. We find that 26.2-95.1 million BDT (million bone-dry tons) of dead biomass resulted from 2012-2017 tree mortality, with accumulations peaking in 2016. In other words, of the aboveground live tree biomass in 2012, 1.3% to 4.8% was dead by 2017. We find that 29% (7.6-27.9 million BDT) of total standing dead biomass meets minimum operational criteria for potential cost-effective harvest in terms of tree density, size and terrain slope. This proportion drops to as low as 16% in the most affected and therefore highest priority counties for tree mortality mitigation, highlighting the need for a comprehensive mitigation approaches that includes other biomass disposal strategies in addition to biomass energy.

Tree Mortality in California

In forests adapted to frequent fires, climate change and twentieth-century management practices such as fire suppression and timber harvesting have increased the likelihood of severe impacts from fire and insects [1, 2, 3]. The 2012-2015 drought in California, along with high tree densities in forests from which fire has been excluded, resulted in unprecedented tree die-off [3], drastically increasing the urgency of the fuel accumulation issue. Standing dead (SD) trees may increase fire hazard, increase carbon emissions, and place nearby communities at risk [4]. In 2015, California declared a state of emergency due to tree mortality [5] that directed state agencies to take steps toward facilitating SD tree removal immediately. However, the response has been slow, with only about 1.2 percent of SD trees removed as of December 2018 [6].

The present tree mortality crisis raises a number of critical questions, beginning with how to address risks associated with rapid tree die-off. Such die-off events are likely to occur more frequently in California given that severe droughts are projected to become more common [7]. Furthermore, with accelerating climate change, forests globally are susceptible to similar heat and drought induced tree mortality [8]. A major challenge to SD tree removal is that their commercial value is low. Even for trees that could otherwise be economically logged as timber, the rapid degradation of wood quality with time since death limits the window for effective harvest. Consequently, many SD trees of merchantable size remain in the forests or are disposed of using controlled open burns, which release CO2, particulate matter, and other criteria pollutants with adverse effects on human and environmental health [9]. One option for managing woody biomass is to use it for electricity generation, which results in lower emissions than controlled open burns and is less sensitive to wood decay than timber harvest. However, many biomass electricity generation facilities are no longer operational in the state [10] and the value of SD biomass feedstock is low. To address the tree mortality crisis, Gov. Jerry Brown, in his 2015 State of Emergency proclamation, ordered that the California Public Utilities Commission and California Energy Commission (CEC) help make woody biomass energy more economically feasible by providing incentives for bioenergy using trees from High Hazard Zones (HHZs) and by funding technology development. Using woody biomass including beetle-infested dead trees and residues from forest management operations for energy purposes has been explored in North America [11, 12]. However, siting new biomass energy facilities and evaluating biomass energy's potential in California requires detailed information on SD biomass feedstock availability – information that is currently lacking. The USFS monitors tree mortality across the state using Aerial Detection Surveys (ADS), but these surveys record only dead tree counts, leaving out other variables critical for estimating potential feedstock quantities and costs, such as biomass, mean volume per tree (VPT), tree density (TPA), and slope of the terrain (percent).

Research Objectives

The goal of this analysis is to produce a database of the woody biomass that has resulted from California's recent tree die-off, in particular those resources that could potentially be used as feedstock for energy production. The specific objectives of this analysis were to:

1) Produce a reliable, detailed, and geographically explicit database of the woody biomass that has resulted from California's recent tree die-off, and

2) Determine how much of this SD biomass meets minimum operational criteria (such as biophysical and ownership constraints) that enable harvest.

Methods

Three main steps were used to estimate the SD biomass that is potentially available for use as biomass energy feedstock. First, raw SD biomass densities were estimated at fine spatial resolution by combining ADS data with the Landscape Ecology, Modeling, Mapping, and Analysis (LEMMA) team's Gradient Nearest Neighbor (GNN) Structure (Species-Size) Maps. Second, raw biomass estimates were filtered for feasibility of harvest using the following characteristics: a) spatial isolation (sparse pockets of mortality that can make harvesting expensive were eliminated); b) wilderness designation; and c) average tree volume exceeding chipping capacities. Third, feasibly harvestable biomass was classified based on a) on-site chipping capability (based on average tree volume), and b) terrain slope. A description of the data sources, software used, and a more detailed breakdown of this three-part process follows below.

Data Sources

Aerial Detection Surveys

The Aerial Detection Survey data was obtained from the US Forest Service Pacific Southwest Region (USFS R5) [13]. Aerial Detection Surveys are conducted annually to monitor tree mortality and damage across the state. Surveys are conducted from small aircraft on a 4-mile grid across the majority of forested land in California, including all National Forests, National and State Parks, and most forested private land [14]. The present study uses ADS mortality data, ignoring data on non-mortality damage. Highly trained observers manually record the outlines of mortality areas, recorded as individual polygons, onto digital aerial imagery in computer touch tablets. Mortality is defined as standing dead trees that have died since the last survey [15]. For relatively small pockets of mortality, the concentration of mortality in each ADS polygon is expressed as the total number of dead trees. For larger polygons, mortality is recorded as trees per acre, which is then scaled up to total number of dead trees using the size of the polygon [16]. Generally, areas with < 1 dead tree per acre are considered to have ”background” or ”normal” levels of mortality and are not usually mapped during the flight, unless low levels of mortality are indicative of a localized pest-related event. Areas with mortality in excess of background levels are mapped to the finest resolution practicable.

Forest GNN Structure (Species-Size) Maps

The Gradient Nearest Neighbor (GNN) Structure (Species-Size) Maps were obtained from the Oregon State University Landscape Ecology, Modeling, Mapping, and Analysis (LEMMA) research group website [17]. They use gradient nearest neighbor (GNN) interpolation methods to assign forest structure and species data at a 30m x 30m (1 pixel) resolution. GNN relies on the statistical relationship between USFS Forest Inventory and Analysis field measurements and Landsat-derived inputs as well as other predictor variables (i.e., climate, topography, parent material and location) [18, 19]. The GNN forest structure maps provide critical data for energy feedstock calculations including tree density (TPH) and aboveground live biomass per hectare (BPH) calculated using two different methods: the component ratio method (CRM) [20] and a more simplified method, referred to here as the “Jenkins method.” Digital maps are provided as 30-m-resolution rasters, where each grid value is a unique plot number that links to the plot database containing detailed vegetation data for each plot. The present study uses GNN maps developed in 2014 using 2012 satellite imagery. The GNN models apply only to forest land, defined as areas currently or with the potential to support at least 10 percent tree cover.

Elevation data

Elevation data was obtained from the US Geological Survey USGS National Elevation Data (NED). The NED is derived from diverse source data that are processed to a common coordinate system and unit of vertical measure. The data are available at: https://lta.cr.usgs.gov/NED.

Software

PostGIS

The database created in this study was built and developed using the object-relational system PostreSQL and the geospatial analytics extension PostGIS, for which the documentation is available at https://postgis.net.The clustering command used to develop the database is ST ClusterDBSCAN.

GDAL

The manipulation of raster data was done using the Geospatial Data Abstraction Library (GDAL). GDAL is a computer software library for reading and writing raster and vector geospatial data formats. Two main commands were used: 1) gdaldem, used to calculate the slope values from elevation data, for which the documentation is available at: http://www.gdal.org/gdaldem.html, and 2) gdal_translate, used to average the slope values, for which the documentation is available at: http://www.gdal.org/gdal_translate.html.

DBSCAN

Density Based Scan clustering method is a clustering algorithm based on the notion of density, where clusters are defined as sets of points that lie inside or on the border of high-density regions in spatial databases. Given a set of points in space, DBSCAN groups together points that have many nearby neighbors, marking as outliers points in low-density regions. The algorithm shows good performance on large spatial databases with clusters of arbitrary shapes. The principle behind the method is that a point is density-reachable from another point if it is within ε distance from a cluster of points larger than the minimum number of elements that constitute a cluster. Once a point is considered density-reachable, it is added to the closest cluster [21].

R

Calculations of SD biomass densities combining GNN forest structure maps and ADS data were performed in R 3.4.3 [22].

Analytical Procedure

Calculating Total SD Biomass

For each ADS mortality polygon *P* in year *t*, the GNN forest structure raster was cropped to the size and shape of the polygon. Each grid cell, or pixel, *i* was assigned an estimated number of SD trees $DT_{i,t}$ by distributing the total number of SD trees in the ADS polygon *P* across the forested pixels in *P* based on pixel i's tree density TPH_i relative to tree densities in other pixels in *P*. Because the calculation for $DT_{i,t}$ merged two data sets developed using independent methodologies, discrepancies did occasionally occur in which the number of SD trees in the pixel, $DT_{i,t}$, exceeded the GNN estimate of live trees based on TPH_i. In such cases, it was assumed that $DT_{i,t}$ was limited to the GNN estimate of live trees based on TPH_i, as shown in (1). The constant 0.09 was used to convert TPH_i into number of trees per pixel.

$$DT_{i,t} = \begin{cases} DT_p \frac{TPH_i}{\sum_{iinP} TPH_i} \\ TPH_i * 0.09 \qquad \text{if } DT_{i,t} \geq TPH_i * 0.09 \end{cases} \qquad (1)$$

This calculation assumes that all trees in the GNN data have equal likelihood of mortality, regardless of size, and that ADS detects all trees with equal likelihood.

Dead biomass per pixel per year $DBM_{i,t}$ was estimated by multiplying the number of dead trees $DT_{i,t}$ by the pixel's 2012 live tree biomass quantity, which was calculated by dividing GNN biomass per hectare BPH_i by TPH_i. This calculation is shown in (2).

$$DBM_{i,t} = DT_{i,t} \frac{BPH_i}{TPH_i} \qquad (2)$$

Steps 1-2 were repeated for each year *t* of ADS data from 2012 to 2017 and then summed across years to calculate total dead biomass *TDBMj* for each pixel. For a small fraction of pixels, *TDBMi* exceeded the 2012 GNN live tree biomass for that pixel. In such cases, *TDBMi* was limited to 2012 GNN live biomass as it corresponds to maximum possible biomass in the pixel. The formula is as shown in (3).

$$TDBM_i = \begin{cases} \sum_t DBM_{i,t} \\ BPH_i * 0.09 \quad \text{if } DBM_i \geq BPH_i * 0.09 \end{cases} \qquad (3)$$

This correction was required in fewer than 10 percent of pixels and represents a reduction of only 4 percent on the overall cumulative sum of feedstock over the years.

The potential biomass feedstock was first calculated assuming that SD trees are detected by ADS if they have a diameter at breast height (DBH) of ≥25 cm, since smaller trees are less visible from aircraft [23]. We used GNN forest structure data that describes the subset of live trees with DBH ≥25 cm to match our assumption about ADS detection capability. However, in areas with low tree densities or small average tree size, ADS data may detect SD trees smaller than 25 cm DBH. To address uncertainty resulting from the assumption about ADS detection, we also estimated biomass using GNN forest structure data for all trees with DBH ≥2.5 cm. Biomass densities generated from this subset of GNN data represent a lower bound, or floor, because trees near 2.5 cm DBH are likely to be obstructed from view by larger trees and because the tree die-off event was largely catalyzed by bark beetles, which preferentially target larger trees [24]. The true SD biomass densities are likely closer to the estimates made using the 25 cm DBH GNN map. To address uncertainty related to the conversion of tree size to tree biomass, we also repeated the calculations using both CRM and Jenkins biomass estimators. A more detailed description of this process and results can be found in Chapter 2 and Appendix B.

Filtering SD Biomass for Harvest Feasibility

1. Small, scattered pockets of tree mortality are economically inefficient to harvest for biomass energy. Thus, to refine our estimates of SD biomass feedstock availability, we identified clustered pixels containing SD biomass and removed spatially isolated pixels. The clustering algorithm Density Based Scan Clustering (DBSCAN) [21] was implemented using 112 pixels as the minimum number of pixels per cluster, which is equivalent to approximately 10.1 hectares. Given that a pixel is approximately 0.09 hectares, each cluster can be taken to represent approximately ≥ 10.1 hectares of area containing SD biomass.

The DBSCAN method requires specification of an ε-neighborhood, which represents the local radius for expanding clusters and serves as the upper limit to define a cluster. We performed a sensitivity analysis to identify the optimal ε-neighborhood value, as follows: for each possible value of ε, the amount of scattered biomass that would be removed from the statewide total was calculated and compared to the average standard distance. Standard distance is a measure of the compactness of a cluster, and thus assesses its quality by determining the dispersion amongst members of a cluster [25]. In other words, to belong to a cluster, a pixel must have $TDBM_i > 0$ and be located close to many other pixels.

To choose the final value of ε, a sensitivity analysis was performed to identify the optimal ε-neighborhood value. For each possible value of ε, the amount of scattered biomass that would be removed from the statewide total was calculated and compared to the average standard distance. Standard distance is a measure of the compactness of a cluster, and thus assesses its quality by determining the dispersion amongst members of a cluster [26]. The ε-neighborhood value used in further analyses was chosen where there was an inflection point in the trade-off curve between biomass reduction and average standard distance.

2. Protected area designation is another relevant criterion to assess feasibility of feedstock supply since it is not legal to harvest in wilderness areas. Hence, we removed SD biomass within land designated as wilderness according to the National Wilderness Preservation System [25]. We also filtered out SD biomass in non-wilderness National Park land because, though harvesting is legal within non-wilderness National Park land, it is less common there than in other land ownership designations [25]. Map pixels were removed from the feasibly harvestable subset of SD biomass if they fell within federally designated wilderness areas and/or National Parks based on geospatial layers obtained from the Bureau of Land Management and USFS [25].

3. Harvesting feasibility is strongly affected by tree size due to equipment limitations and safety considerations [27]. Commercial large drum whole tree chippers have a maximum in-

feed size of 102-127 cm DBH [28], which is associated with a VPT of about 11.32 m^3 for *Pinus ponderosa* or *P. lambertiana*, two species that have been heavily affected by the recent tree die-off [29]. Thus, pixels with $VPT_i \geq 11.32$ m^3 were filtered out from our estimates of potentially feasibly harvestable biomass for energy feedstock. Even though these trees contain substantial biomass, it is technically challenging to turn them into wood chips.

Using data from the GNN structure maps, average VPT per pixel VPT_i was estimated by dividing the GNN total volume of live trees per hectare (VPH_i) by the number of live trees per hectare (TPH_i) as follows in (4):

$$VPT_i = \frac{VPH_i}{TPH_i} \tag{4}$$

Pixels with $VPT_i \geq 11.32$ m^3 (400 ft^3) were removed.

4. Dead tree density also plays a major role in harvest feasibility. Areas with very low tree density can be costly to harvest [27]. If dead tree density is low but live tree density is high, selective removal of dead trees could be difficult due to the need to navigate around live trees.

We converted dead trees per pixel $DT_{i,t}$ calculated in (1) to dead trees per acre for each pixel $DTPA_{i,t}$. We then removed areas with very low dead tree density ($DTPA_{i,t} < 1$) from the potentially feasibly harvestable biomass.

5. The remaining pixels were then classified according to their location within Hazard Zones Tier 1 and High Hazard Zones Tier 2.

Classifying SD Biomass by Factors Related to Expected Cost of Harvest

Although other factors influence harvest costs, we limited our analysis to these two biophysical variables because they are not influenced by decisions made during the logging operation.

1. We classified the remaining pixels into two VPT classes, ≥2.26 m^3 (~80 ft^3), termed "chip trees," and ≤2.26 m^3, termed "small log trees." This cutoff value is based on the maximum volume that can be processed on-site with commercial mechanical equipment [31, 27]. Trees with volumes ≥2.26 m3 must be cut into logs and chipped at saw mills or chipping facilities.

2. Each pixel was then classified based on local terrain slope. Terrain slope strongly affects the cost of harvest, primarily because it determines whether ground-based, cable-yarding, or helicopter-yarding harvest systems may be used [31]. We calculated slope values using the National Elevation Dataset (NED). Slope thresholds used in this study are based on the Fuel Reduction Cost Simulator (FRCS) model, which is used extensively by the US Forest Service and others as the standard cost calculator for biomass supply curves [30]. FRCS includes detailed information on the cost of operations for three harvesting systems: ground-based, cable-yarding, and helicopter-yarding. Ground-based systems are used where conditions allow because they are typically less expensive and cause less damage to reserve trees than cable- or helicopter-yarding. For safety and environmental reasons, however, ground-based systems are generally used only when slope is ≤ 40 percent. Trees located in areas with slopes in the 30 to 40 percent range can employ either ground-based systems or cable-yarding, depending on other factors such as tree size [31]. Cable-yarding can accommodate steeper slopes than

ground-based systems, but the distances trees can be hauled are constrained by a maximum cable length of 400 meters. Steep areas with greater than 400 m hauling distances require helicopter systems, which are the most expensive harvest type and unlikely to be economically viable for SD biomass harvest [28].

GDAL, a GIS analysis package (See Software Section), was used to merge all of the National Elevation Data (NED) tiles for the state of California and calculate slopes. The most relevant slope for harvest operations is the slope over the distance logs need to he hauled. To estimate this, the slope map generated from NED tiles was resampled with the command "gdal translate," setting the outsize parameter at 5 percent. This calculated the average slope over areas 3.4 hectares in size (207x162 meters).

Calculating Energy Conversions

To calculate energy conversions, we assumed that commercial boiler technology is used in the electricity generation process, with a calorific value of bone dry biomass between 18 and 22 $\frac{GJ}{1000kg}$ and a boiler efficiency of 20 percent. The equivalent conversion rate is approximately 1 MWh electricity per 1 BDT biomass [32, 33] (A BDT is defined as 2,000 lbs of woody material at 0 percent moisture content in the form of fuel chips produced by hammermills, chippers, or grinders). However, if small-scale gasification technology is used – a popular option supported by the state – then the conversion rate would be approximately 4.73 $\frac{BDT}{MWh}$ (or 2.365 $\frac{lb}{kWh}$) [34].

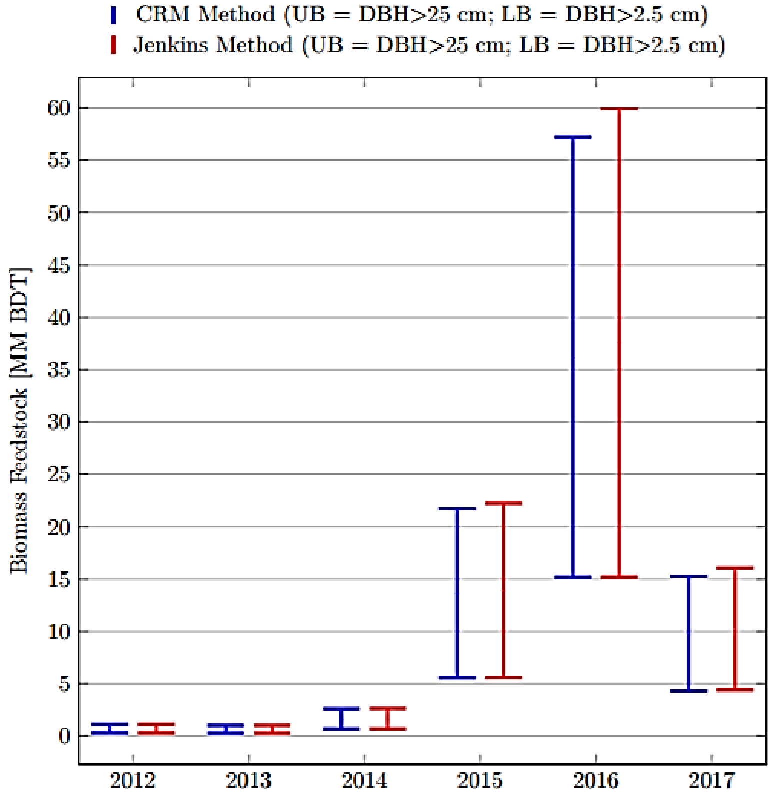
Discussion

Statewide SD tree biomass resulting from forest die-off

This study revealed that in 2012-2017, approximately 95.1 million BDT (million bone- dry tons) of total SD biomass resulted from tree mortality, with a lower bound of 26.2 million BDT, according to the CRM method. Results from the Jenkins method were similar. Mortality reached 100 percent in some areas of the southern Sierra Nevada. Because of the similarities between results using the CRM and Jenkins methods, and because the CRM method is based on a more complex estimation of biomass per tree [20], further results are reported using the CRM method. The largest increase in SD biomass occurred in 2016 (Fig. 1). We found that 1.3 percent to 4.8 percent of the aboveground tree biomass that was alive in 2012 was dead by 2017.

Though the calculations performed in this study used metric units, results were converted from kg to BDT to align with the conventional units of energy feedstock (the resulting dataset is available as part of SI). A BDT is defined as 2,000 lbs of woody material at 0 percent moisture content in the form of fuel chips produced by hammermills, chippers, or grinders.

Figure C-1: Yearly biomass resulting from 2012-2017 tree mortality in California using CRM (blue) and Jenkins (red) biomass estimators.



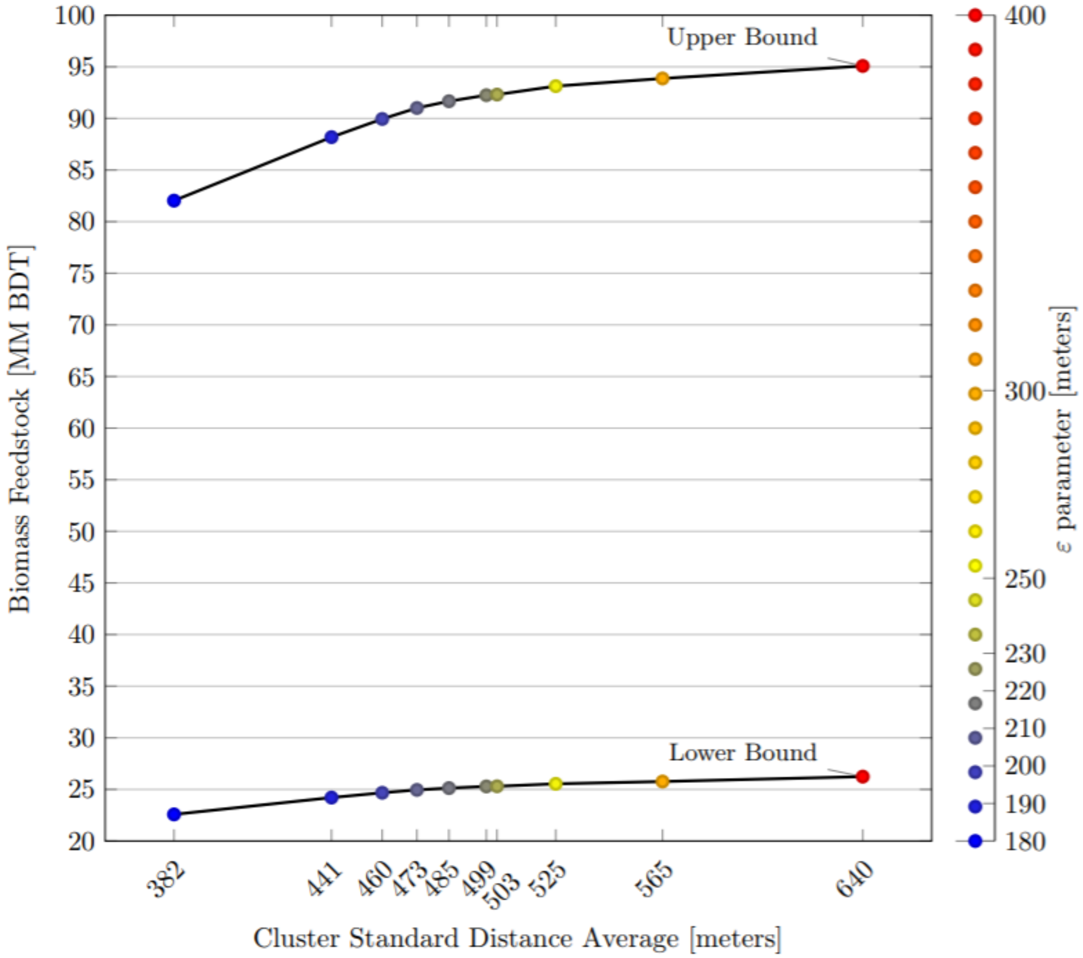
The upper bound estimates (UB), represented by the upper bars, were calculated using the assumption that ADS detects all dead trees ≥25 cm DBH with equal likelihood. The lower bound estimates (LB), represented by the lower bars, were calculated using the assumption that ADS detects all trees ≥2.5 cm DBH with equal likelihood. This figure depicts biomass estimates made before correcting areas with greater total dead biomass estimated across years 2012-2017 than live biomass in 2012.

SD Biomass Filtered for Harvest Feasibility

Harvest feasibility by geography

The sensitivity analysis to select the value of ε showed an inflection point in the trade-off curve between biomass reduction and cluster compactness, measured by average standard distance, at ε = 220 (Figure 2). Filtering out spatially isolated pixels based on this ε-neighborhood parameter reduced the statewide SD biomass upper bound total by 2.7 million BDT, to 92.3 million BDT. The same filtering method reduced the lower bound value by 1.0 million BDT, to 25.3 million BDT.

Figure C-2: The trade-off curve between reduction in total SD biomass and cluster compactness measured by average standard distance, after performing DBSCAN clustering using a range of ε-values and eliminating unclustered pixels.



The upper curve represents biomass estimates using the assumption that ADS detects all dead trees ≥25 cm DBH with equal likelihood, while the lower curve represent the lower bound estimate made using the assumption that ADS detects all trees ≥2.5 cm DBH with equal likelihood. The final ε-value used in DBSCAN clustering was chosen by locating inflection points along these curves, of which the result was ε = 220. The DBSCAN algorithm does not generate clusters using ε-values < 180 because the minimum pixel count of 112 cannot be reached within a radius < 180m. On the other hand, DBSCAN clustering using ε-values >400 does not achieve the goal of filtering out scattered SD biomass that would be inefficient to harvest.

There are 19.9 million BDT SD biomass in wilderness areas or National Parks after filtering out spatially isolated pixels (see Table B-2 and Table B-3 for a detailed breakdown). After subtracting these areas from SD biomass from the totals, our feedstock estimates reduced to 72.3 million DBT, with a lower bound of 19.5 million BDT.

Harvest feasibility by tree size and density

Removing pixels with very large average tree size and low dead tree density resulted in a 3.4 million BDT reduction of the total estimated SD biomass, bringing it to 68.9 million BDT, with a lower bound of 18.4 million BDT.

Assuming typical boiler technology, this quantity of biomass is equivalent to 18.4 - 68.9 TWh of electricity generation. If small-scale gasification technology were used - a popular option supported by the state - the potential electricity production would be 15.6 - 59.2 TWh.

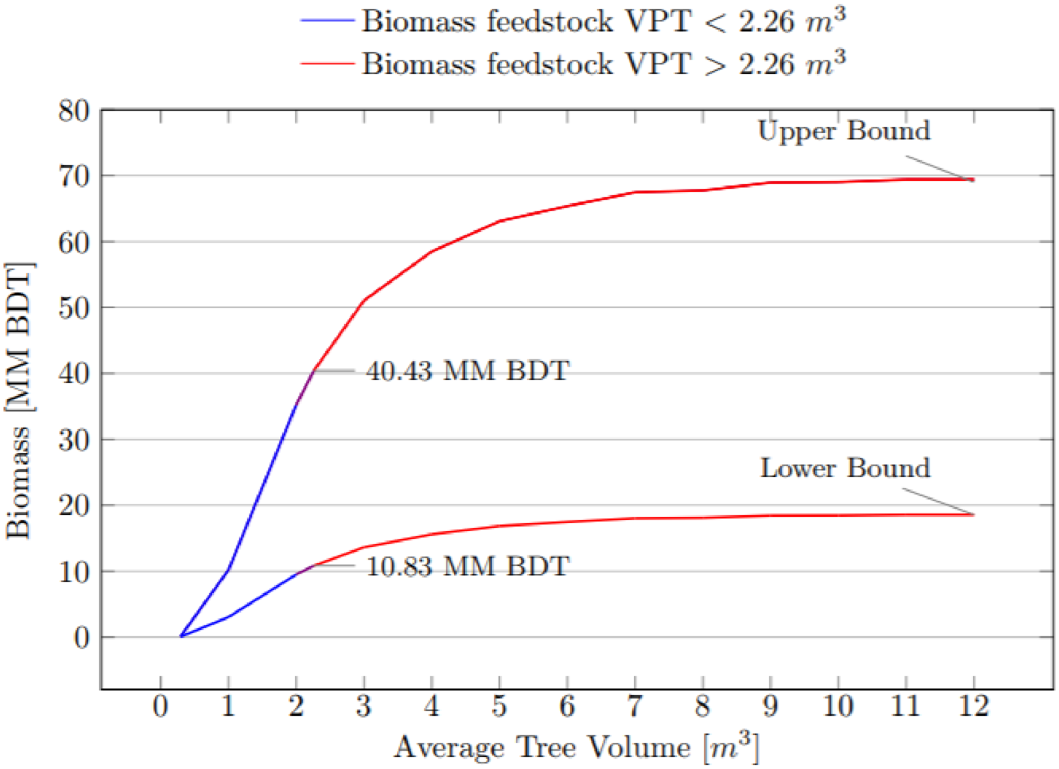
SD Biomass Classified by Factors Related to Expected Cost of Harvest

Classification by tree size

We defined two categories, those with mean VPT ≥2.26 m^3, termed "chip trees," and those with mean VPT ≤2.26 m^3, termed lower-cost or "small log trees."

Of the 69.4 million BDT feasibly harvestable SD biomass, about 40.4 million BDT (lower bound 10.8 million BDT) met the VPT cutoff for being processed on site, while approximately 29.0 million BDT (lower bound 7.82 million BDT) would require intermediate processing (Fig. 3).

Figure C-3: Running cumulative sums of statewide SD biomass with respect to mean VPT per pixel.

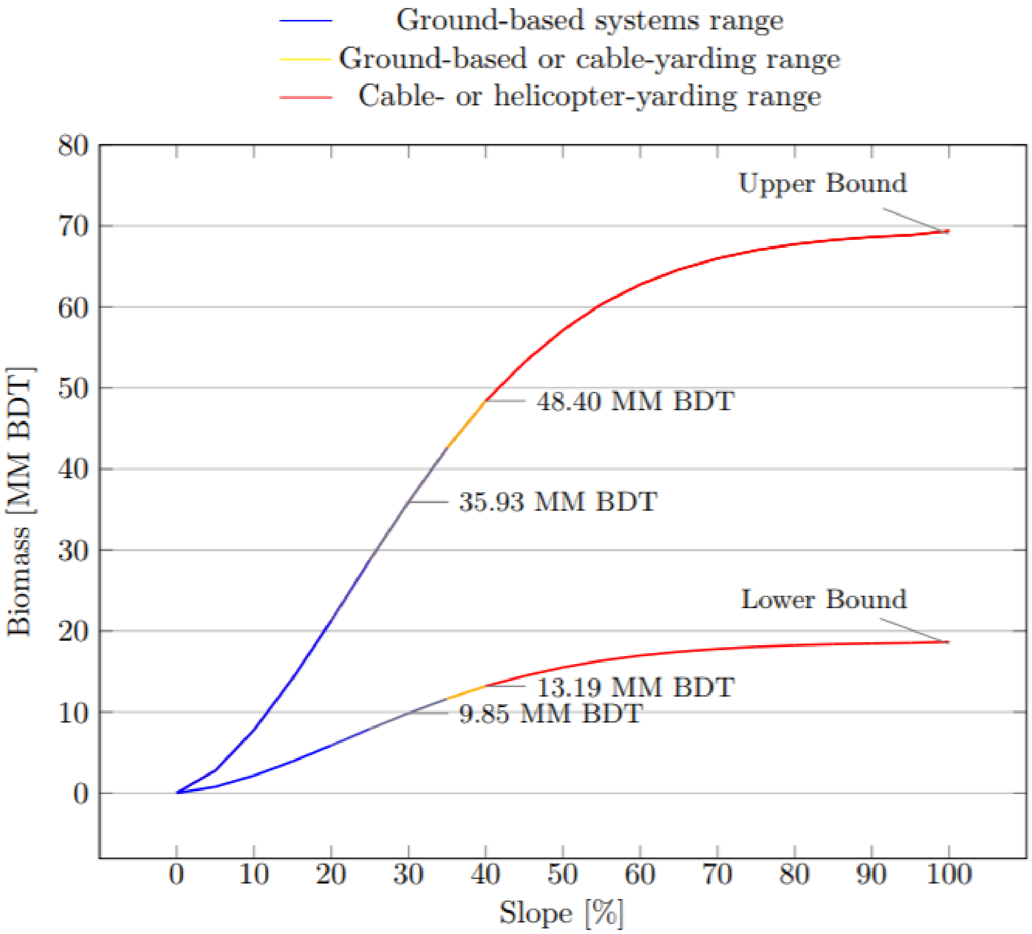


The upper curve represents biomass estimates using the assumption that ADS detects all dead trees ≥25 cm DBH with equal likelihood (UB), while the lower curve represent the lower bound estimate made using the assumption that ADS detects all trees ≥2.5 cm DBH with equal likelihood (LB). Below 2.26 m^3 VPT, biomass can be chipped on-site (blue); whereas, above 2.26 m^3 trees must be chipped at facilities before further processing (red). There are a total of 40.4 million BDT SD biomass, with a lower bound of 10.83 million BDT, in areas where the average VPT is <2.26 m^3. This represents fewer than 60 percent of the total feedstock available.

Classification by terrain slope

Out of the "feasible" feedstock, as estimated according to the above methods, 35.9 million BDT (lower bound 9.9 million BDT) SD biomass is in areas with slopes <30%, allowing for ground-based systems. An estimated 5.8 to 21.6 million BDT fall within areas with slopes greater than 40 percent where harvesting is likely cost prohibitive due to the need to use cable- or helicopter-yarding (Figure C-4).

Figure C-4: Running cumulative sums of statewide SD biomass with respect to slope



The upper curve represents biomass estimates using the assumption that ADS detects all dead trees ≥25 cm DBH with equal likelihood (UB), while the lower curve represent the lower bound estimate made using the assumption that ADS detects all trees ≥2.5 cm DBH with equal likelihood (LB). Less than 30 percent slope, ground-based harvesting can be used (blue), whereas in terrain with slopes 30 to 40 percent, either ground-based or cable-yarding systems may be used depending on other factors (yellow). Greater than 40 percent slope, cable- or helicopter-yarding systems must be used (red).

The tables below give a snapshot of the available biomass due to tree mortality.

Table C-1: Standing Dead Biomass Feedstock available in the Counties most Affected by tree Die-off*

County	Gross [1000 BDT]		Feasible [1000 BDT]		Cost-Effective [1000 BDT]		Cost-Effective out of Gross [%]	
	CRM, DBH > 25 cm (UB)	**CRM, DBH > 2.5 cm (LB)**	**CRM, DBH > 25 cm (UB)**	**CRM, DBH > 2.5 cm (LB)**	**CRM, DBH > 25 cm (UB)**	**CRM, DBH > 2.5 cm (LB)**	**CRM, DBH > 25 cm (UB)**	**CRM, DBH > 2.5 cm (LB)**
Tulare[†]	22,866	6,739	12,619	3,634	3,554	1,057	15.54	15.68
Fresno[†]	15,137	4,701	11,410	557.8	3,942	1,293	26.04	27.50
Madera[†]	10,134	3,192	8,595	2,714	3,460	1,082	34.14	33.90
Tuolumne[†]	7,734	1,879	6,339	1,492	2,583	636	33.40	33.85
Mariposa[†]	7,401	1,883	4,480	1,010	1,849	423	24.98	22.46
Kern[†]	3,673	1,072	3,220	912	1,213	349	33.02	32.56
Siskiyou	3,483	895	2,579	639	1,220	314	35.03	35.08
Calaveras[†]	2,468	535	2,365	509	1,029	232	41.69	43.36
El Dorado[†]	2,392	601	2,230	552	1,068	273	44.65	45.42
Modoc	2,355	706	2,191	641	1,745	503	74.10	71.25
Plumas	2,089	485	1,809	409	888	211	42.51	43.51
Lassen	1,414	341	1,258	293	1,093	255	77.30	74.78
Total	81,146	23,028	59,094	16,362	23,644	6,627		

* More detail on Table 1 in Appendix A

[†] These counties have been identified as High Priority Counties by the Tree Mortality Task Force

The column "Gross Total" lists SD biomass before filtering. The column "Feasible" lists SD biomass after filtering for scattered pixels, wilderness/National Parks, VPT > 11.32 m^3, and DTPA < 1. The column "Cost Effective Total" lists feasibly harvestable SD biomass available at slopes less than 40 percent and average tree volumes less than 2.26 cubic meters.

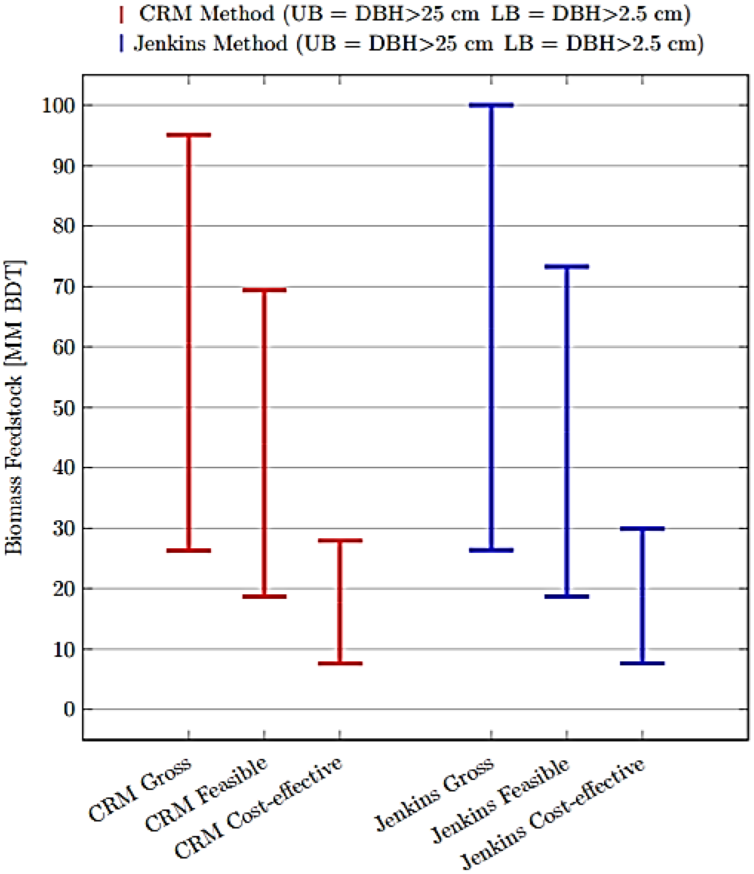
After the classification process, we estimated that 27.9 million BDT of SD biomass, with a lower boundary of 7.6 million BDT, meet criteria for potentially economically feasible harvest, including mean tree volumes <2.26 m^3 and slopes less than 40 percent (Figures 5 and 6). We termed this subset of SD biomass the "cost-effective" feedstock supply. Table C-2 identifies the SB biomass in the counties most affected by tree die-off.

Table C-2: SD biomass in the counties most affected by tree die-off, by HHZ, after filtering for harvest feasibility and cost effectiveness

	FEASIBLE [1000 BDT]		COST EFFECTIVE [1000 BDT]	
COUNTY	HHZ Tier 1	HHZ Tier 2	HHZ Tier 1	HHZ Tier 2
TULARE	**1,072.4**	**9,640.2**	**464.1**	**2,607.5**
FRESNO	**496.8**	**9,777.1**	**200.9**	**3,536.5**
MADERA	**683.1**	**8,121.0**	**385.7**	**3,264.2**
TUOLUMNE	**1,219.7**	**6,012.3**	**563.1**	**2,453.7**
MARIPOSA	**842.5**	**3,706.7**	**432.1**	**1,592.1**
KERN	**327.1**	**2,013.3**	**144.9**	**709.7**
SISKIYOU	**154.8**	**1,988.6**	**92.8**	**1,002.8**
CALAVERAS	**1,017.1**	**2,308.1**	**482.6**	**1,002.4**
EL DORADO	**318.8**	**1,853.7**	**158.6**	**899.0**
MODOC	**175.9**	**1,882.9**	**152.4**	**1,489.4**
PLUMAS	**291.5**	**1,568.8**	**164.3**	**765.1**
LASSEN	**86.1**	**1,136.0**	**72.9**	**984.0**

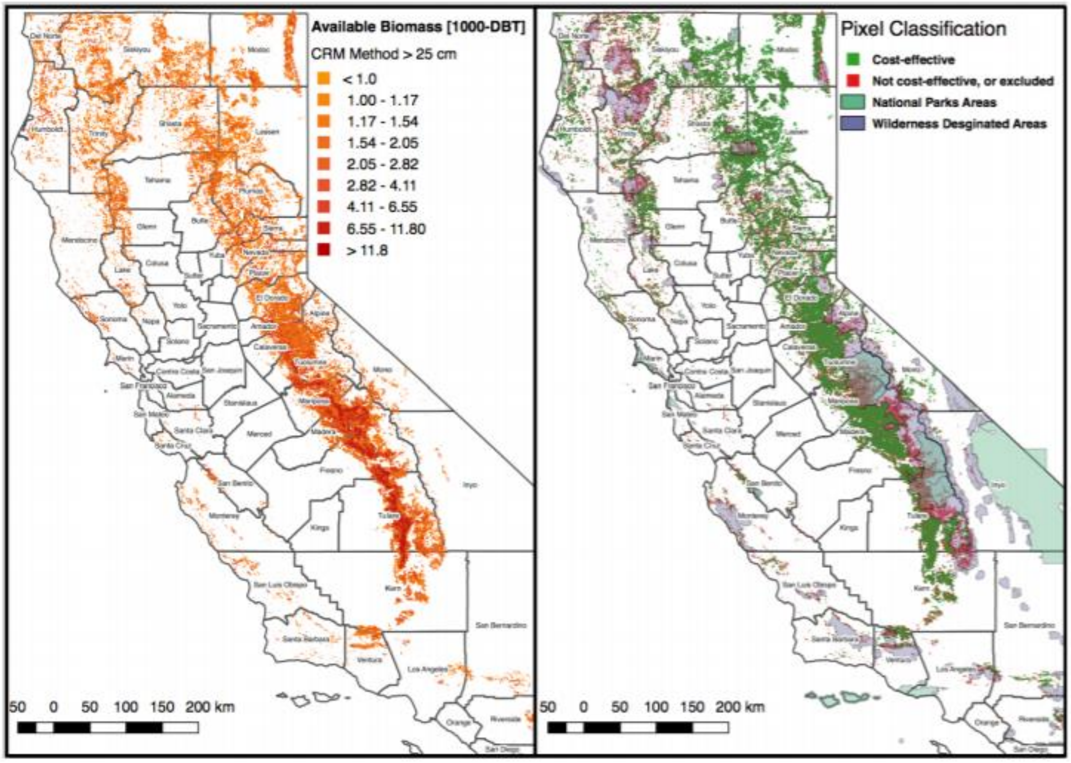
The column "Feasible" lists SD biomass after filtering for scattered pixels, wilderness/National Parks, VPT > 11.32 m^3, and DTPA < 1. The column "Cost Effective Total" lists feasibly harvestable SD biomass available at slopes less than 40 percent and average tree volumes less than 2.26 cubic meters.

Figure C-5: Total SD biomass that has resulted from 2012-2017 tree mortality in California



"Gross" values show total SD biomass. "Feasible" bars show the subset of SD biomass lacking characteristics likely to impede harvest feasibility, including geographic isolation, wilderness or National Park designation, and tree volumes exceeding standard chipping capacities. "Cost-effective" bars show the subset of "Feasible" biomass that is in areas with mean tree volumes < 2.26 m^3 and slopes less than 40 percent. The upper bars (UB) represent biomass estimates using the assumption that ADS detects all dead trees ≥ 25 cm DBH with equal likelihood, while the lower bar (LB) represent the lower bound estimate made using the assumption that ADS detects all trees ≥ 2.5 cm DBH with equal likelihood. Filtering for harvest feasibility resulted in a 30 percent reduction in the UB available feedstock and filtering for cost-effectiveness resulted in a 70 percent reduction.

Figure C-6: Dead aboveground tree biomass resulting from tree die-off in 2012-2017



(Left) Dead aboveground tree biomass (upper bound estimates assuming ADS detection of trees >25 cm DBH) resulting from tree die-off in 2012-2017 in 1000s of bone dry tons (BDTs). (Right) Comparison of the "cost-effective" areas to excluded or economically infeasible areas of SD biomass. Black lines represent county boundaries.

To put our results into context, California's economically recoverable supply of biomass for energy production from regular forest residues and thinning was previously estimated at about 33 million BDT/year [35]. The database created from these SD biomass calculations can be used to identify geographic areas of California with the highest total SD biomass feedstock availability.

Energy Conversions

We then estimated the total energy that could potentially be generated with the SD biomass classified as "cost-effective." The upper boundary of "cost-effective" energy potential using the CRM method and DBH > 25 cm is 27.9 TWh, while the lower boundary value, using DBH > 2.5 cm, is 7.6 TWh. For context, California generated a total of 198 TWh of energy of all types in-state in 2016 (

Table **B-5**).

Classification by High Hazard Zones

Of the 26.2-95.1 million BDT of gross total SD biomass located in this study (before filtering for any factors related to economic feasibility), 21.1-76.2 million BDT are located in Tier 2 High Hazard Zones (HHZs) and 2.4-9.6 million BDT are located in Tier 1 HHZs.

Of the 19.5-72.3 million BDT of "feasible" SD biomass (which remain after filtering for spatial scatter, wilderness or National Park status, VPT < 11.32 m^3, and (DTPA > 1), only 1.8-7.4 million BDT fall outside of a HHZ Tier 1 or 2. There are 15.4-57.2 million BDT of "feasible" SD biomass in Tier 2 HHZs and 2.0-8.3 million BDT in Tier 1 HHZs.

Of the 7.6-27.9 million BDT of "cost-effective" SD biomass (after removing areas with VPT > 2.26 m^3 and slope greater than 40 percent), 0.9-3.7 million BDT fall outside of a High Hazard Zone, while 6.4-23.6 million BDT are in Tier 2 HHZs and 1.0-4.1 are in Tier 1 HHZs.

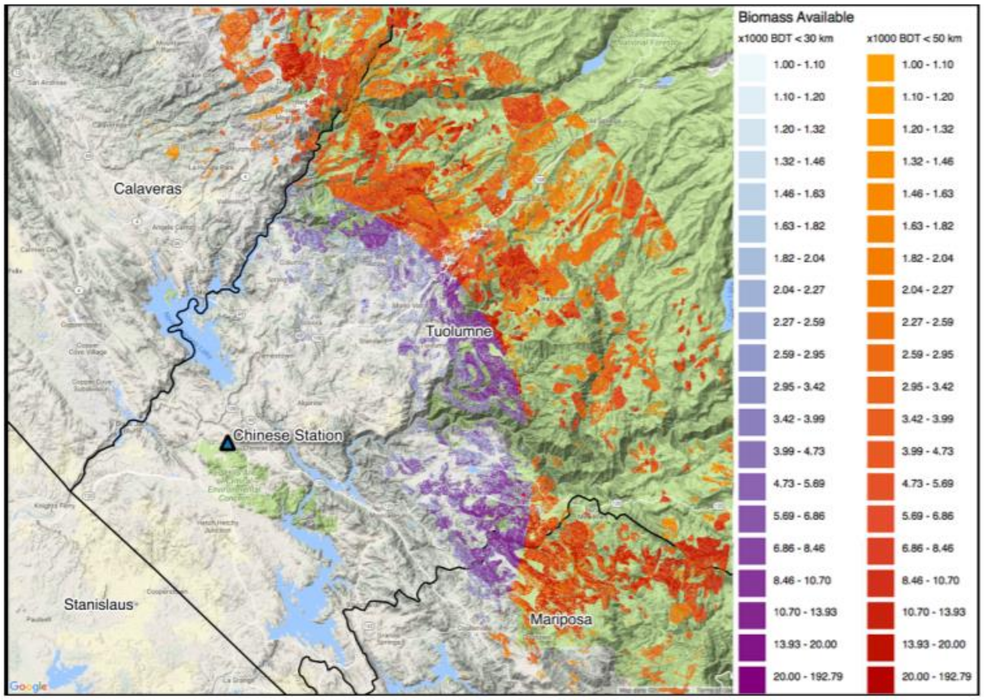
Example application

The Pacific Ultrapower Chinese Station (PUCS) is a biomass power plant located in Central California. The facility, which has a 25 MW production capacity, was built to use woody biomass from forest management operations and could potentially be used to process waste from SD trees.

Using the database created from this study, we estimated that the biomass feedstock available to PUCS (after removing scattered biomass, dead trees in wilderness areas or National Parks and prohibitively large trees) is 0.4-1.6 million BDT within a 30 km radius, and 1.3-6.1 million BDT within a 50 km radius (Fig. 7).

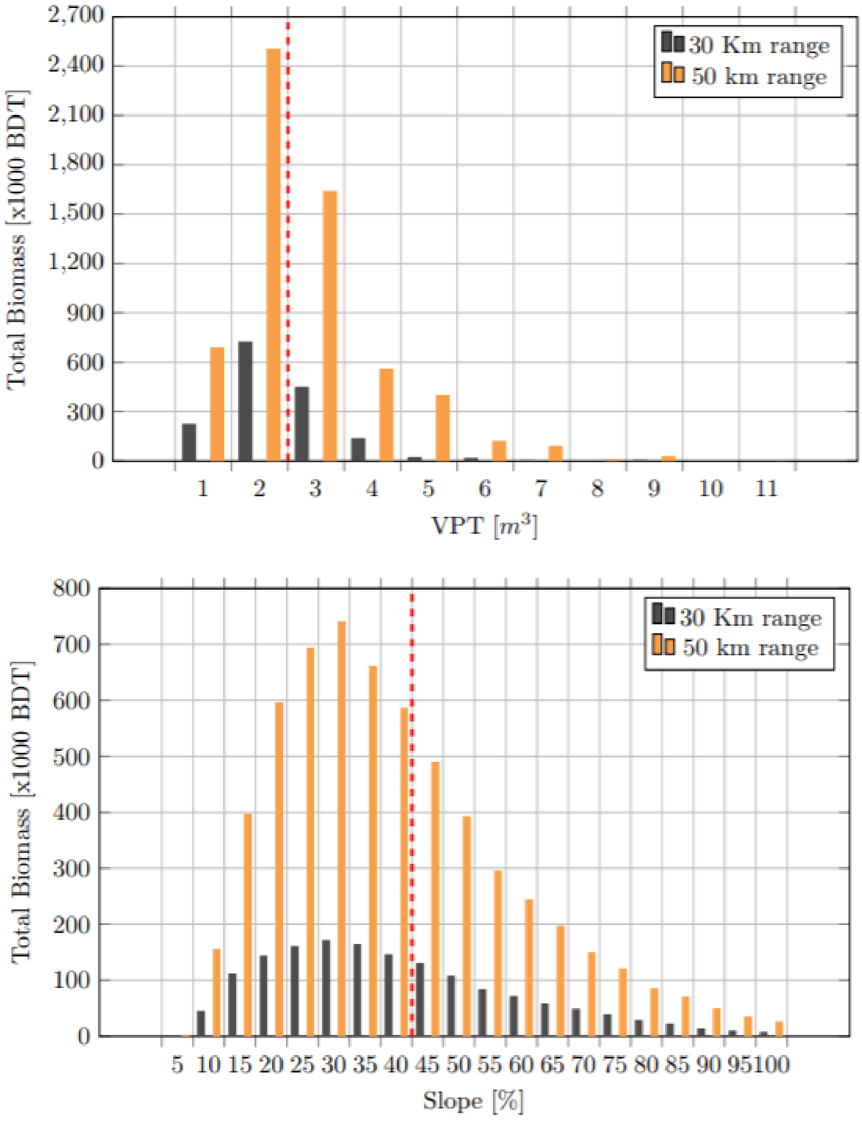
PUCS can produce approximately 175.2 GWh of energy per year, assuming an 80 percent capacity factor (that is, assuming it runs 80 percent of the time). This study shows that there is sufficient economically recoverable feedstock for electricity generation potential of 200 - 700 GWh within a 30 km radius of the facility, using cost-effective feedstock. Thus, PUCS could operate for up to 1-4 years relying only on the most accessible SD biomass within 30 km. If the 50 km radius is considered, the potential increases to 600 - 2500 GWh, which translates to 3-14 years of operation. Details and assumptions used in this energy analysis are provided in Appendix B.

Figure C-7: SD biomass within 30 km (purple) and 50 km (red) of Pacific Ultrapower Chinese Station.



Approximately 1.1 million BDT within 30 km (lower bound 0.3 million BDT) and 4.3 million BDT within 50 km (lower bound 1.0 million BDT) of potential feedstock near PUCS are located in terrain with slope less than 40 percent, enabling the likely use of ground-based harvesting systems (Figure 8). Taking both slope and tree size criteria into consideration simultaneously (less than 40 percent slope and less than 2.67 square meters VPT), there are 0.2 to 0.7 million BDT and 0.6 to 2.5 million BDT of potential "cost-effective" feedstock within 30 and 50 km, respectively, of PUC.

Figure C-8: Feedstock Characteristics of the Area Surrounding Pacific Ultrapower Chinese Station.



Histograms showing the distributions of mean volume per tree (top) and slope (bottom) of the feedstock available for PUCS at the 30 km and 50 km radius, using the upper bound feedstock estimates. The red line indicates the limit for the "cost-effective" biomass classification.

Conclusion

This study's geographically explicit assessment of SD biomass enables detailed estimations of biomass densities for large land areas of California. Furthermore, we developed a method that is suitable for assessing biomass and biomass extraction potential for other forest systems worldwide. Using a novel method to estimate the SD biomass available for electricity generation in California from the 2012-2017 tree mortality, we show that there are 18.7-69.4 million BDT of feasibly harvestable SD biomass feedstock, with the true value likely closer to the upper bound of that range. The largest quantities of SD biomass in California are found in the southern Sierra Nevada and SD biomass is largely concentrated in only 12 counties (Fig. 6 and Table 1). Together, these 12 most affected counties contain over 85 percent of the total SD biomass resulting from recent tree die-off.

The amount of SD biomass that can be considered "cost-effective" for electricity generation is 7.6-27.9 million BDT. This cost-effective estimate represents only about 30 percent of the total SD biomass in the state resulting from 2012-2017 mortality. In some high-biomass counties, even less of SD biomass is "cost-effective" to harvest. For example, in Tulare County, which has the highest gross SD biomass and is a High Priority County according to the Tree Mortality Task Force (Table 1), the "cost-effective" SD feedstock is less than 16 percent of the total.

Efforts to mitigate the tree mortality crisis focus on High Hazard Zones (HHZs) Tiers 1 and 2, in that order of priority. This study found that of the 21.1-76.2 million BDT of SD biomass in Tier 2 HHZs, only 6.4-23.6 million BDT are "cost-effective" (~30 percent) and of the 2.4-9.6 million BDT located in Tier 1 HHZs, only 1.0-4.1 are "cost-effective" (~42 percent). Thus, harvesting SD trees for energy feedstock is not a comprehensive solution for removing the bulk of recently dead trees in California, nor for removing the SD tree in areas of highest priority to the state of California. Given that other factors, such as transport costs, are not included in the present feasibility assessments, the actual quantity of SD biomass that is economically harvestable is likely lower than the present estimates. However, it is worth noting that the state-wide "cost-effective" SD biomass estimate is equivalent to 4 to 14 percent of California's annual in-state electricity generation.

This study provides the first estimate of live tree carbon loss resulting from the 2012-2015 California drought. Our estimates of total SD biomass are equivalent to 11.2-40.6 Tg C across all areas surveyed by ADS, or roughly 1.1 to 3.8 percent of total aboveground forest carbon in California [36]. As these SD trees decay over time, their carbon will transition to the atmospheric pool. This study's estimates of the biomass contained in SD trees will aid in the statewide carbon accounting needed for California to reach its climate change mitigation goals. The method introduced here can also be used to improve calculations of aboveground live carbon losses due to tree die-off elsewhere, as previous attempts to estimate biomass and carbon loss from tree mortality events applied simple conversion factors for all trees of a given species, ignoring fine-scale variation in tree sizes [37, 38]. This study shows that state policies to address risk in high-mortality counties may need a comprehensive approach including other approaches in addition to electricity generation.

GLOSSARY

Term	Definition
EPIC	Electric Program Investment Charge
Smart Grid	Smart Grid is the thoughtful integration of intelligent technologies and innovative services that produce a more efficient, sustainable, economic, and secure electrical supply for California communities.
ADS	Aerial Detection Surveys
Biomass feedstock	Biomass feedstock are plant and algal materials used to derive fuels like ethanol, butanol, biodiesel, and other hydrocarbon fuels.
BPH	Biomass per hectare is defined as 2,000 lbs of woody material at 0 percent moisture content in the form of fuels chips produced by hammermills, chippers, or grinders
Cable yarding	Cable yarding consists of a system that uses cables to transport material from the woods to the landing.
CEC	California Energy Commission
CRM	Component Ratio Method
DBH	Diameter at Breast Height
DBSCAN	Density Based Spatial Clustering of Applications with noise is a data-clustering algorithm.
FRCS	Fuel Reduction Cost Simulator
GDAL	Geospatial Data Abstraction Library
GNN	Gradient Nearest Neighbor
GWh	Gigawatt Hours
LEMMA	Landscape Ecology, Modeling, Mapping, and Analysis
Mortality	Mortality is defined as standing dead trees that have died since th last survey
NED	National Elevation Data
PostGIS	PostGIS is an open source software program that adds support for geographic objects to the PostgreSQL object-relational database.
PUCS	Pacific Ultrapower Chinese Station
SD	Standing dead
TPH	Tree density

Term	Definition
TWh	Terawatt Hours
USFS	United States Forest Service
VPT	Mean volume per tree

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APPENDIX A:

Table A-1: Upper bound SD biomass feedstock by HHZ in all counties

	Feasible [1000 BDT]		***Cost Effective [1000 BDT]***	
County	***HHZ Tier 1***	***HHZ Tier 2***	***HHZ Tier 1***	***HHZ Tier 2***
Tulare	1,072.4	9,640.2	464.1	2,607.5
Fresno	496.8	9,777.1	200.9	3,536.5
Madera	683.1	8,121.0	385.7	3,264.2
Tuolumne	1,219.7	6,012.3	563.1	2,453.7
Mariposa	842.5	3,706.7	432.1	1,592.1
Kern	327.1	2,013.3	144.9	709.7
Siskiyou	154.8	1,988.6	92.8	1,002.8
Calaveras	1,017.1	2,308.1	482.6	1,002.4
El Dorado	318.8	1,853.7	158.6	899.0
Modoc	175.9	1,882.9	152.4	1,489.4
Plumas	291.5	1,568.8	164.3	765.1
Lassen	86.1	1,136.0	72.9	984.0
Shasta	137.4	821.9	103.4	573.8
Placer	163.6	891.9	96.6	428.2
Trinity	158.2	749.6	51.9	206.8
Tehama	163.9	735.3	83.7	330.8
Humboldt	29.8	221.3	13.7	76.8
Amador	275.4	565.4	135.9	270.1
Sierra	69.4	532.4	28.5	185.3
Nevada	127.2	508.1	70.7	240.3
Butte	98.3	491.0	46.2	189.5
Del Norte	2.9	52.5	0.7	10.1
Mendocino	9.2	152.8	3.1	54.7
Mono	73.6	207.0	37.7	135.6
Glenn	5.1	119.1	2.8	50.2
Yuba	52.9	202.6	27.2	83.1
Sonoma	15.9	88.8	3.7	19.2
Ventura	7.7	176.9	4.8	88.2
Lake	40.3	131.7	26.1	78.9
Alpine	44.4	111.5	14.4	37.2
San Bernardino	29.0	69.9	16.6	35.8
San Luis Obispo	20.1	42.5	16.1	25.5
San Benito	7.4	80.1	3.5	31.7
Monterey	9.2	42.7	4.0	13.1
Santa Barbara	4.5	31.8	2.1	10.9
Los Angeles	7.7	37.9	3.0	10.5
Riverside	11.1	24.3	4.2	8.7
Colusa	1.0	38.6	0.5	19.2
San Diego	6.1	29.0	3.8	17.8
Inyo	0.3	19.5	0.2	7.6
Marin	0.7	0.0	0.1	-
Santa Clara	1.5	5.8	0.5	2.2
Alameda	3.3	7.6	1.0	3.0

	Feasible [1000 BDT]		Cost Effective [1000 BDT]	
County	***HHZ Tier 1***	***HHZ Tier 2***	***HHZ Tier 1***	***HHZ Tier 2***
Napa	1.3	2.6	0.7	1.6
Santa Cruz	1.4		0.4	-
San Mateo	0.0		0.0	-
Yolo		0.2	-	0.1
Contra Costa	0.1		0.1	-
San Joaquin	0.0		0.0	-

The column "Feasible" lists SD biomass after filtering for scattered pixels, wilderness/National Parks, VPT > 11.32 m^3, and DTPA < 1. The column "Cost Effective Total" lists feasibly harvestable SD biomass available at slopes less than 40 percent and average tree volumes less than 2.26 cubic meters. These values are all from the CRM biomass method using the upper bound (UB) values, under the assumption that ADS detects all trees > 25 cm DBH with equal likelihood.

APPENDIX B:
SUPPLEMENT TABLES

Table B-1: SD biomass for all counties

	Gross [1000-BDT]		Feasible [1000-BDT]		Cost-effective [1000-BDT]	
County	CRM, DBH > 25 cm (UB)	CRM, DBH > 2.5 cm (LB)	CRM, DBH > 25 cm (UB)	CRM, DBH > 2.5 cm (LB)	CRM, DBH > 25 cm (UB)	CRM, DBH > 2.5 cm (LB)
Tulare	22,865.97	6,739.32	12,619.35	3,634.05	3,553.94	1,056.64
Fresno	15,137.39	4,700.47	11,410.03	3,557.83	3,941.96	1,293.08
Madera	10,134.32	3,191.55	8,595.20	2,713.83	3,460.22	1,081.50
Tuolumne	7,733.82	1,879.19	6,339.31	1,492.30	2,582.93	635.80
Mariposa	7,401.15	1,883.15	4,479.77	1,010.20	1,849.42	423.05
Kern	3,672.66	1,071.61	3,219.61	911.54	1,212.66	348.48
Siskiyou	3,482.85	895.16	2,578.79	638.54	1,219.69	313.49
Calaveras	2,468.00	534.67	2,365.04	509.03	1,028.68	231.78
El Dorado	2,391.92	601.44	2,229.64	551.76	1,067.90	273.28
Modoc	2,354.69	705.73	2,190.76	640.91	1,745.37	502.94
Plumas	2,089.01	485.11	1,808.52	409.45	888.26	211.09
Lassen	1,413.83	340.69	1,258.00	292.82	1,093.35	255.43
Shasta	1,477.03	322.21	1,056.86	221.04	720.81	154.56
Placer	1,102.86	262.59	959.07	217.31	455.13	111.59
Trinity	1,594.36	337.44	874.20	169.13	244.93	48.98
Tehama	1,067.60	243.20	874.16	193.02	381.19	85.38

	Gross [1000-BDT]		Feasible [1000-BDT]		Cost-effective [1000-BDT]	
Humboldt	1,158.92	247.33	788.25	152.87	362.96	70.69
Amador	869.67	194.01	741.12	154.24	343.70	74.94
Sierra	811.11	192.20	702.01	160.10	250.34	61.15
Nevada	663.05	148.96	555.52	113.32	260.96	56.89
Butte	584.78	98.04	524.70	84.74	205.12	35.93
Del Norte	422.17	81.41	282.28	43.01	87.84	14.77
Mendocino	436.15	107.49	281.57	61.84	99.27	23.78
Mono	456.28	118.23	245.75	68.14	157.35	46.60
Yuba	241.13	37.20	217.57	32.72	90.75	14.36
Glenn	249.81	59.21	219.16	48.64	89.15	20.62
Sonoma	277.49	51.68	215.69	35.94	46.60	8.09
Ventura	357.69	78.19	204.60	47.47	99.89	24.06
Lake	267.77	60.32	187.17	37.59	99.25	20.19
Alpine	448.46	133.03	172.46	47.16	54.95	15.70
San Bernardino	161.56	46.70	105.64	26.08	44.31	11.23
San Benito	132.35	50.28	100.40	36.06	41.51	15.03
San Luis Obispo	184.19	64.88	100.72	35.18	50.85	19.54
Monterey	180.77	45.86	83.52	22.45	25.22	8.29
Santa Barbara	117.83	36.79	68.11	19.32	20.93	7.44
Los Angeles	128.35	25.89	61.25	9.38	19.50	3.26
Riverside	90.02	24.55	42.09	9.85	14.61	3.59

	Gross [1000-BDT]		Feasible [1000-BDT]		Cost-effective [1000-BDT]	
Colusa	50.34	9.57	40.08	6.53	19.40	3.29
San Diego	114.86	42.89	38.34	9.39	23.16	6.16
Inyo	133.38	37.76	24.75	4.69	10.53	1.75
Marin	62.12	19.41	16.71	2.42	0.68	0.13
Santa Clara	27.55	9.95	11.22	3.34	3.95	1.25
Alameda	13.01	4.10	10.91	3.40	4.04	1.31
Napa	13.07	3.17	8.96	1.76	5.05	1.02
Santa Cruz	13.17	4.74	7.74	2.60	1.78	0.59
San Mateo	15.3	4.8	3.8	1.3	0.9	0.3
Yolo	5.9	1.9	2.6	1.0	1.2	0.7
Contra Costa	1.9	0.4	1.0	0.2	0.3	0.1
San Joaquin	0.1	< 0.1	0.1	< 0.1	< 0.1	< 0.1
Stanislaus	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Orange	3.0	2.5	0.0	0.0	0.0	0.0
Salano	0.2	0.1	0.0	0.0	0.0	0.0
Sacramento	0.1	0.1	0.0	0.0	0.0	0.0
Merced	< 0.1	< 0.1	0.0	0.0	0.0	0.0
Kings	< 0.1	< 0.1	0.0	0.0	0.0	0.0

Table B-2: SD biomass available in National Park Service (NPS) areas outside of wilderness designated areas

National Park	CRM, DBH > 25 cm (UB) [x10^6-BDT]	CRM, DBH > 2.5 cm (LB) [x10^6-BDT]	Jenk, DBH > 25 cm (UB) [x10^6-BDT]	Jenk, DBH > 2.5 cm (LB) [x10^6-BDT]
Sequoia	1,341.2	429.1	1,385.2	431.3
Yosemite	941.0	210.1	958.8	210.2
King Canyon	211.4	63.6	224.3	63.8
Lassen Volcanic	76.8	18.7	77.0	18.8
Redwood	76.6	16.3	77.0	16.3
Whiskeytown-Shasta-Trinity	57.0	10.1	57.6	10.2
Point Reyes	9.5	3.7	9.6	3.7
Golden Gate	6.9	2.2	6.9	2.2
Pinnacles	0.5	0.1	0.5	0.1
Lava Beds	0.1	0.1	0.1	0.1
Devils Postpile	0.1	< 0.1	0.1	< 0.1
Muir Woods	< 0.1	< 0.1	< 0.1	< 0.1
Death Valley National Park	< 0.1	< 0.1	< 0.1	< 0.1

Table B-3: SD biomass in federally designated wilderness areas

Wilderness area	CRM, DBH > 25 cm (UB) [x10^6-BDT]	CRM, DBH > 2.5 cm (LB) [x10^6-BDT]	Jenk, DBH > 25 cm (UB) [x10^6-BDT]	Jenk, DBH > 2.5 cm (LB) [x10^6-BDT]
Sequoia-Kings Canyon	4282.2	1298.3	4528.1	1300.0
Yosemite	3331.9	1026.7	3384.5	1029.0
Ansel Adams	1824.3	539.5	1885.4	544.0
John Krebs	1357.6	402.2	1511.3	402.4
Golden Trout	1229.5	405.1	1266.1	407.9
John Muir	1106.6	336.7	1126.9	339.6
Trinity Alps	712.2	160.5	722.1	161.5
Kaiser	504.9	148.6	525.0	148.6
Marble Mountain	332.2	93.4	341.8	93.8
Carson-Iceberg	234.2	70.7	246.4	71.4
Yolla Bolly-Middle Eel	229.7	59.4	235.5	59.8
Lassen Volcanic	216.6	45.9	218.2	46.1
Domeland	210.9	78.9	217.5	79.3
Monarch	200.8	54.7	205.2	54.7
Siskiyou	157.2	42.3	161.9	42.8
Mokelumme	144.9	44.9	150.2	45.1
Owens Peak	116.1	25.9	123.2	26.1
Jennie Lakes	114.1	24.1	114.2	24.1
South Warner	109.3	42.2	114.2	44.7
Owens River Headwaters	102.2	23.1	103.6	23.1
Sespe	90.7	13.3	98.8	13.3
Chimney Peak	87.6	26.5	93.5	27.4
Kiavah	82.2	30.8	89.0	30.9
South Sierra	65.0	25.3	67.5	26.4
Emigrant	64.8	18.6	65.4	18.7
Bucks Lake	63.5	16.3	66.0	16.3
Chumash	59.2	15.2	59.8	15.2
Dinkey Lakes	55.8	16.1	55.8	16.2

Wilderness area	CRM, DBH > 25 cm (UB) [x10^6-BDT]	CRM, DBH > 2.5 cm (LB) [x10^6-BDT]	Jenk, DBH > 25 cm (UB) [x10^6-BDT]	Jenk, DBH > 2.5 cm (LB) [x10^6-BDT]
Sacatar Trail	54.6	17.0	55.3	17.0
Thousand Lakes	51.9	12.5	55.1	12.7
Ventana	49.3	5.9	50.5	6.0
Caribou	39.7	8.9	39.7	8.9
Hoover	38.2	8.5	40.6	9.1
San Jacinto	36.7	11.2	41.6	11.4
Snow Mountain	31.9	8.5	32.8	8.6
Mt. Shasta	27.6	10.8	29.0	10.8
Phillip Burton	27.6	10.5	27.9	10.7
Inyo Mountains	26.3	9.8	33.8	10.0
Desolation	21.6	5.7	22.3	5.9
Yuki	20.9	4.1	21.0	4.1
Pleasant View Ridge	20.7	4.0	24.0	4.0
Granite Chief	20.2	5.0	20.4	5.2
Garcia	18.0	5.8	18.4	5.8
Russian	15.7	3.9	15.7	3.9
San Rafael	15.2	3.0	16.8	3.0
Ishi	14.5	2.0	14.5	2.0
Sheep Mountain	13.9	2.7	16.1	2.8
Cucamonga	12.4	3.5	13.9	3.5
Silver Peak	11.3	3.4	11.3	3.4
Santa Lucia	8.1	2.5	8.2	2.5
San Gabriel	7.0	1.0	7.8	1.0
Chanchelulla	6.4	1.5	6.4	1.5
Machesna Mountain	6.3	1.9	6.6	1.9
Dick Smith	6.1	1.3	6.8	1.3
King Range	5.0	1.0	5.0	1.0
San Gorgonio	4.4	1.2	5.0	1.0
Cache Creek	2.1	0.2	2.7	0.2

Wilderness area	CRM, DBH > 25 cm (UB) [x10^6-BDT]	CRM, DBH > 2.5 cm (LB) [x10^6-BDT]	Jenk, DBH > 25 cm (UB) [x10^6-BDT]	Jenk, DBH > 2.5 cm (LB) [x10^6-BDT]
North Fork	1.8	0.3	1.8	0.3
South Fork San Jacinto	1.3	0.4	1.4	0.4
Bighorn Mountain	1.1	0.3	1.1	0.4
Matilija	0.7	0.1	0.7	0.1
White Mountains	0.7	0.5	0.9	0.7
Bright Star	0.6	0.1	0.6	0.1
Pine Creek	0.6	0.2	0.7	0.2
Hain	0.5	0.1	0.5	0.1
Sanhedrin	0.5	0.3	0.6	0.3
Elkhorn Ridge	0.5	0.1	0.5	0.1
Cedar Roughs	0.2	< 0.1	0.2	< 0.1
Agua Tibia	0.1	0.1	0.1	0.1
Magic Mountain	0.1	< 0.1	0.1	< 0.1
Mount Lassic	0.1	< 0.1	0.1	< 0.1
Lava Beds	< 0.1	< 0.1	< 0.1	< 0.1
Cahuilla Mountain	< 0.1	< 0.1	< 0.1	< 0.1
South Fork Eel River	< 0.1	< 0.1	< 0.1	< 0.1
San Mateo Canyon	< 0.1	< 0.1	< 0.1	< 0.1
Santa Rosa	< 0.1	< 0.1	< 0.1	< 0.1
Hauser	< 0.1	< 0.1	< 0.1	< 0.1
Sawtooth Mountains	< 0.1	< 0.1	< 0.1	< 0.1
Piper Mountain	< 0.1	< 0.1	< 0.1	< 0.1

Table B-4: Dead and live biomass in the ADS surveyed areas organized by method of estimation

Total	CRM, DBH > 25 cm (UB) [x10^6-BDT]	CRM, DBH > 2.5 cm (LB) [x10^6-BDT]	Jenk, DBH > 25 cm (UB) [x10^6-BDT]	Jenk, DBH > 2.5 cm (LB) [x10^6-BDT]
Live	470.0	533.6	620.1	720.0
Dead	95.1	26.2	100.0	26.3
Percent	20.2%	4.9%	16.1%	3.7%

Table B-5: California energy mix of 2016

Fuel Type	California In-State Generation	California In-State Generation (%)	Northwest Import	Southwest Imports	California Energy Mix	California Power Mix
Coal	324	0.16%	373	11,310	12,006	4.13%
Large Hydro	24,410	12.31%	3,367	1,904	29,681	10.21%
Natural Gas	98,831	49.86%	41	7,120	105,992	36.48%
Nuclear	18,931	9.55%	0	7,739	26,670	9.18%
Oil	37	0.02%	0	0	37	0.01%
Other	394	0.20%	0	0	394	0.14%
Renewables	55,300	27.90%	11,710	6,952	73,961	25.45%
Biomass	5,868	2.96%	659	25	6,553	2.26%
Geothermal	11,582	5.84%	96	1,038	12,717	4.38%
Small Hydro	4,567	2.30%	229	1	4,796	1.65%
Solar	19,783	9.98%	0	3,791	23,574	8.11%
Wind	13,500	6.81%	10,725	2,097	26,321	9.06%
Unspecified	N/A	N/A	26,888	14,937	41,825	14.39%
Total	198,227	100.00%	42,378	49,963	290,567	100.00%

All values in GWh, unless otherwise specified. Table contents were obtained from http://www.energy.ca.gov/almanac/electricity_data/total_system_power.html.