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Energy Research and Development Division

FINAL PROJECT REPORT

Linear Generation for Combined Heat and Power

Gavin Newsom, Governor

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PREFACE

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

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

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

Linear Generator for Combined Heat and Power is the final report for the High Compression Ratio Free Piston Engine for CHP project (Grant Number: PIR-13-002) conducted by EtaGen, Inc. The information from this project contributes to the Energy Research and Development Division's Natural Gas Research and Development Program.

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

ABSTRACT

EtaGen has developed a linear generator technology for distributed generation applications that reduces the emissions, maintenance, and cost limitations that hamper existing combined heat and power technologies. This innovative technology is poised to deliver efficient, clean, and cost-effective onsite electricity and heat that is well-matched to commercial and light-industrial facilities. EtaGen's linear generator will address the enormous market potential for CHP that is under-served in California.

With funding support from the California Energy Commission and Southern California Gas Company, EtaGen successfully designed, built, installed, interconnected, operated, and monitored the world's first linear generator system for electricity and heat production. The system was installed outside EtaGen's headquarters in Menlo Park (San Mateo County), and performance was monitored from October 2017 through February 2018. The research team continuously measured electrical performance during all operation and potential thermal performance for combined heat and power applications was measured upon commissioning. The net alternating current power output was 70 kilowatts (kW), and the potential thermal output and overall efficiency were 87 kW and 77 percent, respectively. Third-party emissions testing demonstrated the ability to meet Southern California Air Quality Management District emissions standards in both electric-only and combined heat and power applications. Among the emissions standards applicable to EtaGen's technology, the South Coast Air Quality Management District emissions standards are the most stringent in the world.

With the success of this project and the knowledge gained, EtaGen has a clear development roadmap to a 250-kW commercial product with electric efficiency greater than 45 percent and overall thermal combined heat and power efficiency greater than 80 percent.

Keywords: Combined heat and power, linear generator, HCCI, distributed generation

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TABLE OF CONTENTS

Page

LIST OF FIGURES

Page

LIST OF TABLES

EXECUTIVE SUMMARY

Background

Existing combined heat and power technologies lack the performance and cost attributes to provide a compelling economic solution for most commercial and light-industrial applications. The weaknesses of available combined heat and power technologies vary by type, but include low electric efficiencies, high capital and operating costs, and poor emissions. Low-to-modest combined heat and power electric efficiencies typically lead to electrically under sizing systems or to poor thermal use, and combined heat and power technologies with high electric efficiencies are typically too costly without substantial government and utility subsidies.

EtaGen has developed a ground-breaking linear generator technology for distributed generation applications that reduces the emissions, maintenance, and cost limitations that hamper existing combined heat and power technologies. This innovative technology is poised to deliver efficient, clean, and cost-effective onsite electricity and heat that is well-matched to commercial and light-industrial facilities. EtaGen's linear generator will address the enormous market potential for combined heat and power at commercial and light-industrial facilities that is currently under-served in California.

The aspects of EtaGen's linear generator that have been demonstrated through this project include its innovative and patented architecture, control algorithms, gas seals, and potential for combined heat and power applications. These aspects combine to enable EtaGen's linear generator to operate with high electric and combined heat and power efficiencies, ultra-low emissions, and low capital and maintenance costs.

Project Purpose

EtaGen's linear generator has a center reaction cylinder with two opposed oscillators and outer air springs. Each oscillator has magnets attached to them for directly converting linear motion into electricity using copper coils that surround the magnets. The electricity produced is rectified to direct current power through power electronics, and this direct current power is then converted to three-phase alternating current power using a UL-listed grid-tie inverter. The linear generator is liquid cooled with excess thermal energy being transferred to the surroundings; however, the cooling system can be retrofitted for supplying thermal energy to commercial and industrial facilities.

Several linear generators can be packaged with auxiliary equipment to meet the power needs of commercial and light-industrial businesses. For this demonstration project, only one linear generator module was packaged with auxiliaries into a custom-designed enclosure that is 24′ (L) x 8.5′ (W) x 8′ (H). EtaGen, rebranded as Mainspring Energy in early 2020, developed and packaged its next-generation linear generator modules along with auxiliaries into a slightly smaller package for its first commercial product, which was delivered in the summer of 2020.

Project Approach

Performance data were collected from October 2017 through February 2018. The research team continuously measured electrical performance during all operations, and potential thermal performance for combined heat and power applications was measured upon commissioning. The net AC power output was 70 kilowatts (kW), and the potential thermal output and overall efficiency were 87 kW and 77 percent, respectively. Third-party emissions testing demonstrated the ability to meet Southern California Air Quality Management District emissions standards in both electric-only and combined heat and power applications. Among the emissions standards applicable to EtaGen's technology, the district's standards are the most stringent in the world.

This successful project demonstrated the ability to design, build, install, interconnect, and operate the world's first linear generator while showing the potential of the technology for combined heat and power applications. The engineering steps needed to increase electrical power and efficiency to meet product targets were characterized during this project and are currently being incorporated into EtaGen's next generation design.

The potential exists for more than 7,400 megawatts (MW) of installed combined heat and power capacity in California for systems less than 5 MW. Much of this underserved market is addressable by EtaGen's linear generator technology. With high efficiency, ultra-low emissions, and low capital and maintenance costs, EtaGen's linear generator will offer commercial and light-industrial businesses an onsite electricity and heat solution while reducing their costs and emissions and increasing their resiliency.

Project Results

With the success of this project and the knowledge gained, EtaGen has a clear development roadmap to a 250-kW commercial product with electric efficiency greater than 45 percent and overall combined heat and power efficiency greater than 80 percent. EtaGen's recent private financing was used in combination with continued support from the California Energy Commission and Southern California Gas to launch its first commercial products in the summer of 2020.

Benefits to California

EtaGen's linear generator is projected to provide significant near-term and long-term benefits. For the 10-year period following full commercial production, the cumulative benefits in California include 34 million million British thermal units (MMBTU) of natural gas savings from boilers, $3 billion in electricity and capacity savings, 5,700 metric-ton (1,000 kilograms or 2,205 pounds) reduction in carbon dioxide (CO_2) emissions, and 4 gigawatts (GW) in avoided centralized generation. Although not quantified for this project, other tangible benefits include avoided electric transmission and distribution costs and losses, and a more secure and reliable electricity supply. For installations outside California, EtaGen projects four times the sales and market volumes envisioned for California. The greenhouse gas emissions reductions for installations outside California will be appreciably greater than in California because the avoided grid emissions are significantly higher. In addition, it is estimated that EtaGen's internal employee base will grow to an estimated 3,500 by 2029 (10 years after commercial launch). This increase in employment does not include additional job creation through vendors, suppliers, installers, or other business associated with EtaGen that could easily match EtaGen's internal employment growth.

CHAPTER 1: Introduction

1.1 The Issue

Existing combined heat and power (CHP) technologies lack the performance and cost attributes to provide a compelling economic solution for most commercial and light-industrial applications. The weaknesses of available CHP technologies vary by type, but include lackluster efficiencies, high capital and operating costs, and poor emissions. Low to modest CHP electric efficiencies typically lead to electrically under sizing systems or to poor thermal utilization, and CHP technologies with high electric efficiencies are typically too costly without substantial government and utility subsidies.

1.2 Project Description

An innovative linear generator technology was designed, built, installed, interconnected, operated, and monitored for electric and potential CHP performance. The demonstration project established the near-commercial position of the technology on its performance and cost trajectory toward commercialization. The production readiness plan in Appendix A discusses the planned incremental engineering improvements and manufacturing cost reductions required to achieve product target performance and costs.

1.3 Project Goals and Objective

This project sought to accelerate the development, commercialization, and deployment of EtaGen's efficient, low emission, and cost-effective linear generation technology for CHP applications. The objectives of the project were to:

- Specify and build a fully enclosed linear generator with auxiliaries.
- Install, interconnect with Pacific Gas and Electric Company (PG&E) and permit the system next to EtaGen's facility in Menlo Park (San Mateo County), California.
- Operate and monitor the system with the following performance targets:
    - Greater than 50 kW electric output.
    - Greater than 75 percent potential overall thermal efficiency.
    - Air criteria pollutant emission less than California Air Resources board (CARB) 2007 distributed generation (DG) standards.
- Show pathway to commercial performance goals of:
    - Greater than 100 kW per module electric output.
    - Greater than 45 percent electrical efficiency.
    - Greater than 80 percent overall efficiency.
    - Air criteria pollutant emission less than CARB 2007 DG targets.
    - Share results with the California Energy Commission (CEC) to spur additional linear generator research.

1.4 Project Team

EtaGen, the prime contractor for this project, is a startup in Menlo Park that was founded in the summer of 2010 by Shannon Miller, Matt Svrcek, and Adam Simpson. All three co-founders earned their Ph.D.'s in mechanical engineering from Stanford University. Most of EtaGen's employees have been heavily involved in the project.

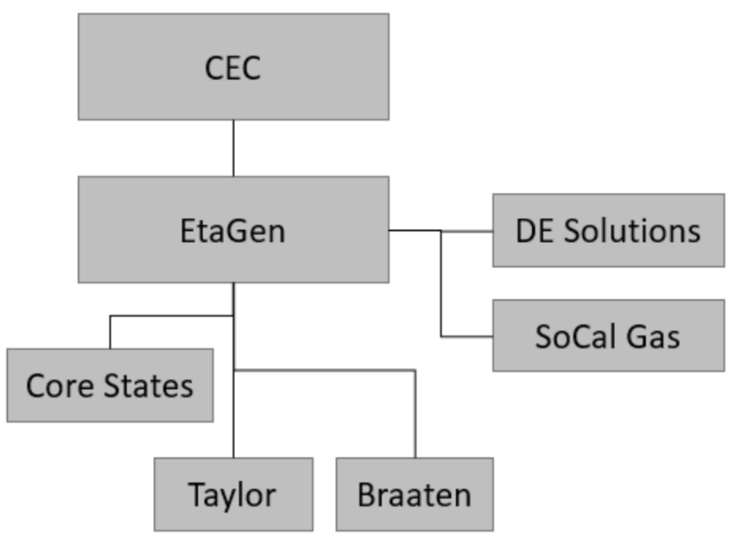
This collaboration involved several key team members, all of whom were committed to the project and related success. Table 1 provides a summary of the various team members and project roles, and Figure 1 provides an organization chart that illustrates the structure of the project team and workflow. All team members are California businesses.

Table 1: Project Team

Organization	Project Role
EtaGen	Prime contractor, project management, equipment supplier, engineering, maintenance, data acquisition
DE Solutions	Technical advisor, administration and project management support, data analysis and findings, report writing
SoCal Gas	Match funder, technical and management advisor
Core States Group	Construction management
Taylor Engineering & Plumbing	Mechanical construction
Braaten Electric	Electrical construction

Source: EtaGen, Inc.

Figure 1: Organization Chart



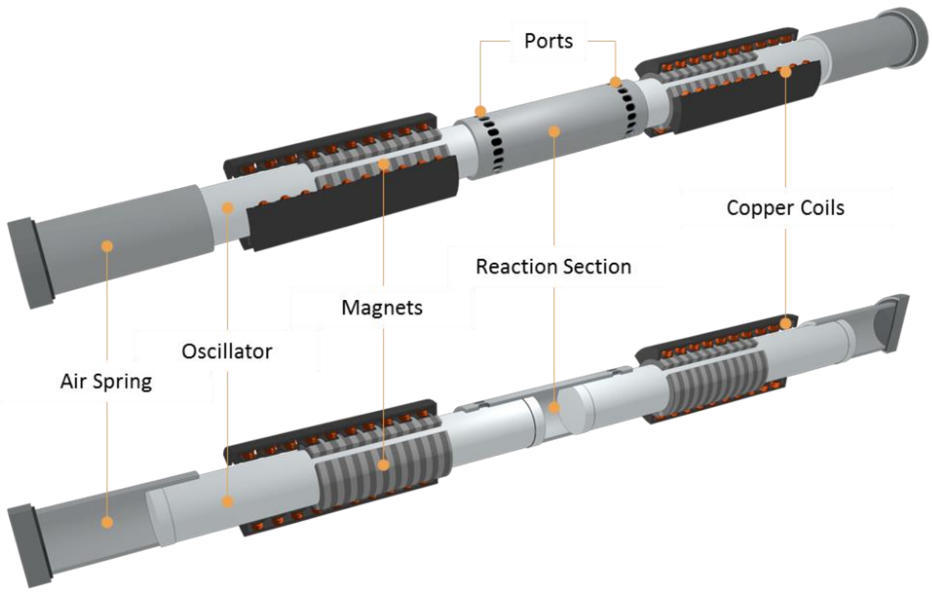
Source: EtaGen, Inc.

CHAPTER 2: Project Approach

2.1 System Description

Figure 2 illustrates the architecture of the linear generator technology developed by EtaGen. The linear generator has a center reaction cylinder with two opposed oscillators and outer air springs. The reaction section has ports for gas exchange, and each oscillator has magnets attached to them for electricity production via the surrounding copper coils. For this report, the combination of the magnets and surrounding copper coils are referred to as the "motor."

Figure 2: Cross Section Illustration of EtaGen's Linear Generator



Source: EtaGen, Inc

Linear generator operation begins with compression of a homogeneous fuel/air mixture that is driven by energy stored in the air springs from a previous cycle. Compression continues until a low-temperature reaction occurs uniformly through the chamber without a flame when the fuel/air mixture reaches the auto-ignition temperature. This form of reaction achieves high thermodynamic efficiency and negligible emissions. The reaction causes the oscillators to move outward, during which a portion of the kinetic energy is directly converted to electricity through the copper coils, and the remaining kinetic energy is stored in the air springs for use during the next compression cycle. Following an expansion stroke, the ports open for gas exchange, which replaces the reaction products with a fresh fuel/air mixture. The electricity produced is rectified to direct current (DC) through power electronics, and this DC is then converted to three-phase alternating current (AC) power via a UL listed grid-tie inverter. Table 2 summarizes the attributes of EtaGen's free-piston linear generator, along with the enabling technological and design drivers.

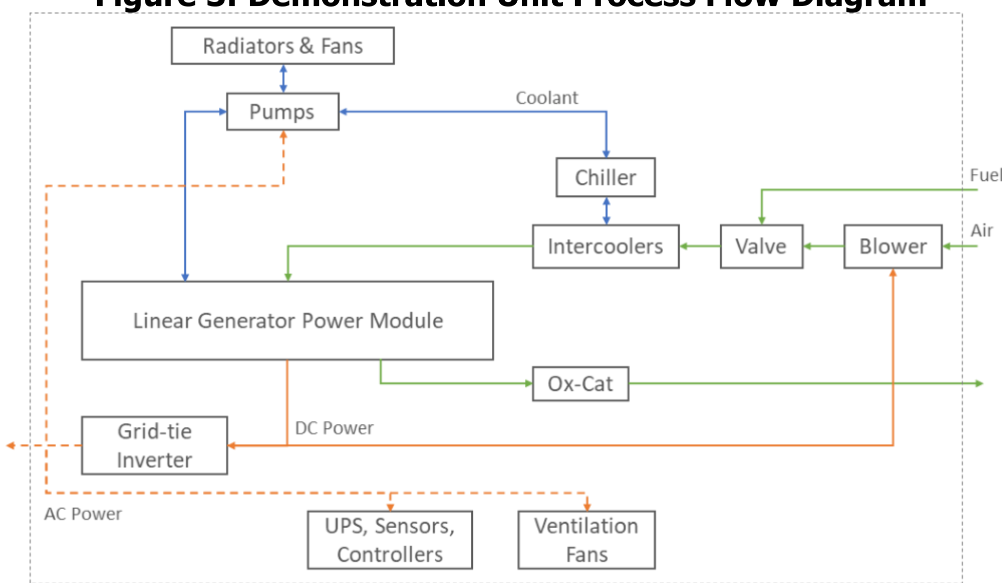
Table 2: Summary of Linear Generator Attributes

Attributes	Enablement
High Electrical Efficiency	High expansion with direct conversion into electricity
Ultra-Low Emissions	Low-temperature reaction without a flame
Low Capital Cost	Standard materials and manufacturing processes
Low Maintenance Cost	Only two moving parts and no oil

Source: EtaGen, Inc

EtaGen's linear generator system was demonstrated at EtaGen's facility and the generated electricity offset power purchases from PG&E. As there is little demand for heat at the facility, the prototype was not equipped with heat-recovery equipment. Rather, multiple recoverable heat sources were monitored (measured for potential heat output and quality) and then rejected to the environment. A process flow diagram of the demonstration system is depicted in Figure 3.

Figure 3: Demonstration Unit Process Flow Diagram



Source: EtaGen, Inc

Figure 4 shows a rendering of the package. The dimensions of the package are 24' (L) x 8.5' (W) x 8' (H), and the package is placed on a poured concrete pad. Natural gas and electrical connections were designed to be made from beneath the package.

Figure 4: EtaGen's Generator System

Source: EtaGen, Inc

2.2 Component Specifications

Key components included in the demonstration system are itemized in Table 3.

Table 3: Key Linear Generator Components

Component	Details
Radiators & Intercoolers	Electrical & cooling jackets share one fan and the chiller & intercoolers share one fan
Fans	Variable--speed drives (VFDs)
Pumps Heads & Motors	Magnetic drive seal-less pumps
Grid-Tie Inverter	UL 1741 listed
Chiller	Operated off of 480V 3-phase
Blower	VFD designed to operate off DC bus
Oxidation Catalyst	Sized to meet CARB DG CO & VOC standards
Power Electronics	Control the motors
Linear Generator Power Module	Designed by EtaGen, contract manufactured
Enclosure	Designed by EtaGen, contract manufactured

Source: EtaGen, Inc

2.3 Performance Expectations

The projected performance targets for this demonstration project along with the projected performance of EtaGen's first commercial product are shown in Table 4. Indicated power and efficiency are the integral of the pressure and volume in the reaction section. It measures how effective the linear generator is at converting fuel energy into linear motion of the oscillators and accounts for heat transfer, reaction, and blow-by losses. Power electronics (PEs) are used to rectify three-phase power from linear generator motors into DC power, and the DC power and efficiency includes losses from the motors and power electronics.

Table 4: Linear Generator- Projected Performance Targets

	CEC Demo Project (Projected)		250 kW Products (2019) (Projected)	
	kW	% LHV	kW	% LHV
Electrical Performance				
Fuel Input	217	100%	557	100%
Indicated Power	128	59%	334	60%
DC Power	103	48%	278	50%
Net AC Power	**88**	**40%**	**254**	**46%**
Recoverable Heat				
Motor & PE	12	6%	29	5%
Cooling Jackets	35	16%	81	15%
Exhaust Sensible HX	27	12%	70	12%
Exhaust Condensing HX	7	3%	17	3%
Total Heat	**81**	**37%**	**197**	**35%**
Overall CHP Performance	**168**	**78%**	**450**	**81%**

Water Supply Temperature	(C)	(F)
Motor & PE	60	140
Cooling Jackets	65	149
Gas Sensible HX	95	203
Gas Condensing HX	60	140

Source: EtaGen, Inc

CHAPTER 3: Fabrication and Assembly

3.1 Major Components

Key components included in the demonstration unit package are listed below include:

- Linear generator components, including motors, cylinders, and oscillators.
- Intake system, including blower, fuel valve, intercooler, and chiller.
- Cooling system, including pumps, radiators, and fans.
- Emissions system, including oxidation catalyst and sound attenuator.
- Motor power electronics and grid-tie inverter.
- Enclosure/package.

3.1.1 Linear Generator Components

EtaGen's linear generator has a center reaction cylinder with two opposed oscillators and outer air springs. The reaction section has ports for gas exchange, and each oscillator has magnets attached to them for electricity production via the surrounding copper coils. The oscillators also have seals for containing the gases in the reaction and air spring cylinders. The cylinders, oscillators, seals, motors, and other proprietary features were developed and designed by EtaGen staff. Fabrication of these parts was outsourced to specialty contract manufacturers, and EtaGen staff assembledthe parts at EtaGen's facility.

3.1.2 Intake System

To increase the power density of the LG performance of the linear generator, an electrically driven blower is used to compresses the inlet air, which is then mixed with natural gas through fuel valve. The air-fuel mixture, which has an increased temperature due to the compression in the blower, is cooled in a two-stage liquid-cooled intercooler. The first stage rejects thermal energy to the surrounding air, and the second stage rejects thermal energy to a chiller with a set-point temperature controlled by EtaGen based on desired performance. In a commercial CHP application, this thermal energy removed in the first stage can be recovered and used for water, space, or process heating. All major components in the intake system—blower, variable -frequency drive (CFD), fuel valve, intercoolers, and chiller— were supplied by third-party vendors.

3.1.3 Cooling System

The linear generator is entirely liquid-cooled, with all excess thermal energy ultimately being rejected to the surrounding air since EtaGen's facility does not have a use for the thermal load. All excess thermal energy from the reaction cylinder, gas spring cylinders, power electronics, chiller, and the first stage of the intercooler is rejected to the surrounding air through radiators and fans. Third-party vendors supplied radiators, pumps, and VFDs. In a commercial CHP application, the thermal energy from all of these systems can be recovered and used for water, space, or process heating.

3.1.4 Emissions System

The two key components in the emissions system include an oxidation catalyst and sound attenuator, both were supplied by third-party vendors. The oxidation catalyst is sized to meet CARB DG emissions standards for carbon monoxide (CO) and volatile organic compound (VOC) emissions (0.1 lb/MWh and 0.02 lb/MWh, respectively) as a result, the oxidation catalyst is also sized to meet SCAQMD emissions standards for CO and VOC emissions (0.2 lb/MWh and 0.1 lb/MWh, respectively). However, the oxidation catalyst is not needed to meet the SCAQMD VOC emissions standard since the emissions from the linear generator are less than 0.1 lb/MWh. Because of EtaGen's low-temperature reaction, no after-treatment is needed to meet SCAQMD's or CARB's DG emissions standard for oxides of nitrogen (NO_x) emissions because the emissions from the linear generator are lower than their standard of 0.07 lb/MWh (for both SCAQMD and CARB DG).

3.1.5 Power Electronics and Inverter

The electricity produced from the generator motors is rectified to DC power through the power electronics. The DC power is then converted to three phase 480 volts (V) alternating current (AC) via a UL-listed inverter tied to the grid. The power electronics and inverter were supplied by third-party vendors. The demonstration unit is controlled by EtaGen proprietary software running on central processing units (CPUs) in the electrical section of the enclosure.

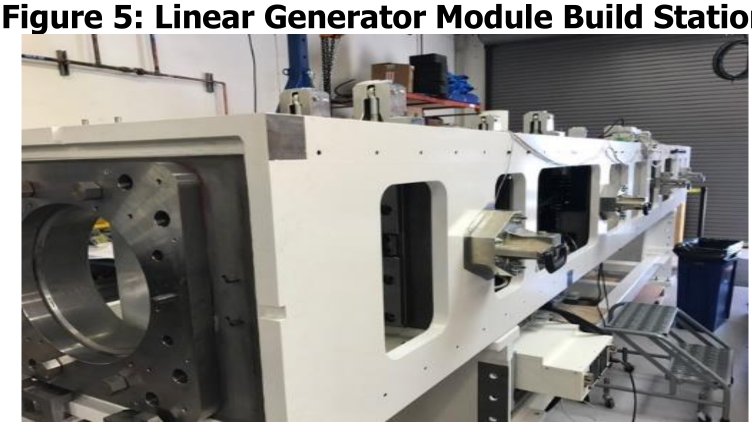
3.1.6 Enclosure/Package

The package was designed by EtaGen and manufactured by a contract manufacturer. The enclosure was designed to attenuate sound such that the sound levels from the system is 70 A-weighted decibels (dBA) at 6 feet. The enclosure and equipment within were UL 2200 field certified.

3.2 System Assembly

The linear generator module was built inside EtaGen's facility and then installed into the base of the package outside the facility. Due to space constraints inside the facility, a temporary tent was erected outside for full system build, including the enclosure. Figures 5-7 show photographs of the various stages of the build and assembly process.

Figure 5: Linear Generator Module Build Station



Source: EtaGen, Inc

Figure 6: Module Side of Package During Build

Source: EtaGen, Inc

Figure 7: Completed and Installed System

Source: EtaGen, Inc

CHAPTER 4: Commissioning

4.1 Instrumentation and Data Acquisition System

Instrumentation used to measure performance parameters described the scope of work is listed in Table 5. The instrumentation was calibrated to confirm manufacturer specified accuracy.

Table 5: Measurement List

Measurement	Metric	Accuracy
Gas temperatures	°C	0.75%
Coolant temperatures	°C	0.75%
Coolant flow rates	LPM	0.2%
Intake air low rate	g/sec	0.7%
Natural gas flow	g/sec	0.1%
DC electric power output	Volt Amp	0.2% 0.2%
AC net electric power output	W	0.2%
NOx emissions	ppm	1.0%
CO emissions	ppm	0.5%

Source: EtaGen, Inc

4.2 Safety

The demonstration system received UL 2200 field certification in December 2017. This standard is for stationary generator set installations 600 volts or less that are also subject to National Electrical Code NFPA-70, the installation code NFPA-37, and NFPA-99 for health care facilities. The system is also equipped with a UL 1741 -listed grid-tie inverter, which covers inverters and interconnection system equipment intended for use in grid-connected and stand-alone power systems. Interconnection with PG&E was completed in January 2018.

4.3 Start-Up and Commissioning

A chronological summary of the start-up and commissioning process follows:

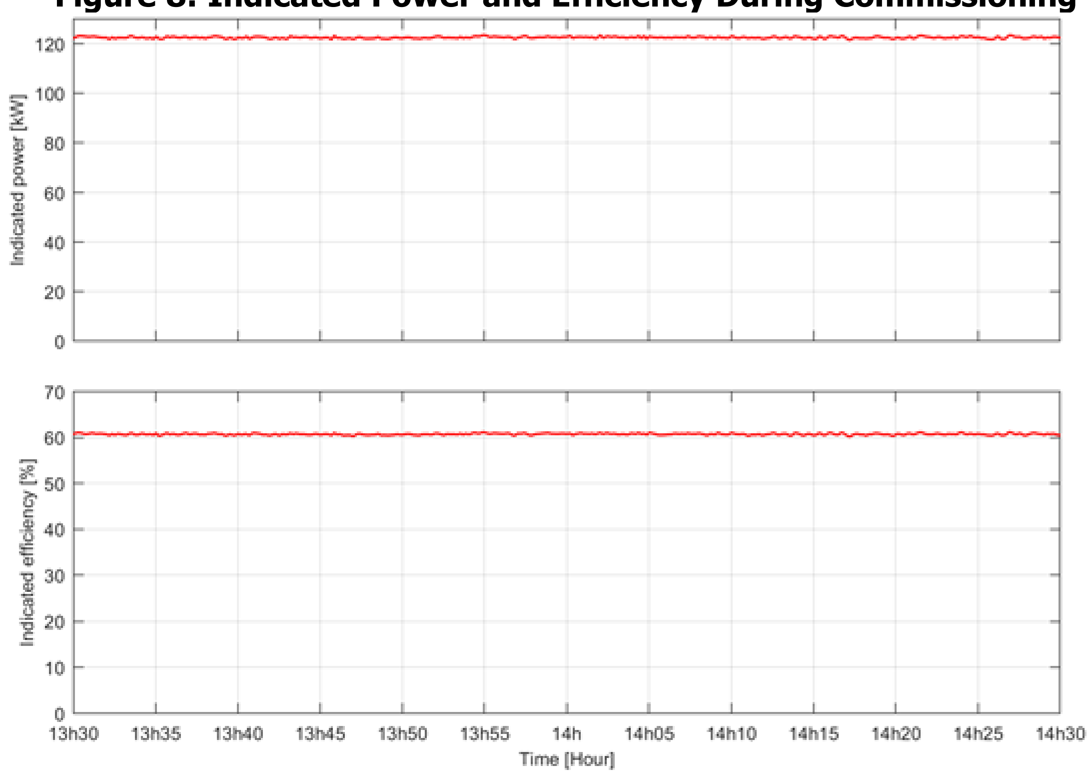
- July:
  - Compression and reaction tests were satisfactorily conducted.
- August:
  - Initial data suggested that gas exchange and performance were not yet optimized.

- September:
    - Adjustments were made to improve the performance and gas exchange issue.
    - While testing the system, an encoder failure occurred, which delayed the completion of performance optimization until October.
- October:
    - Replacement encoder part was received and installed.
    - Remaining performance deficiencies were addressed for the module.
    - Revised projected performance targets were achieved given the lower power output and efficiency capabilities of the motors.

4.4 Initial Performance Tests

Figure 8 shows the indicated power and efficiency, which is a measure of the conversion of fuel input energy to mechanical motion and includes heat transfer, reaction, and gas blow-by losses. The high indicated efficiency of 60 percent provides a glimpse into the potential for the linear generator technology with ongoing improvements to ancillary losses through optimized sizing and efficiency improvements.

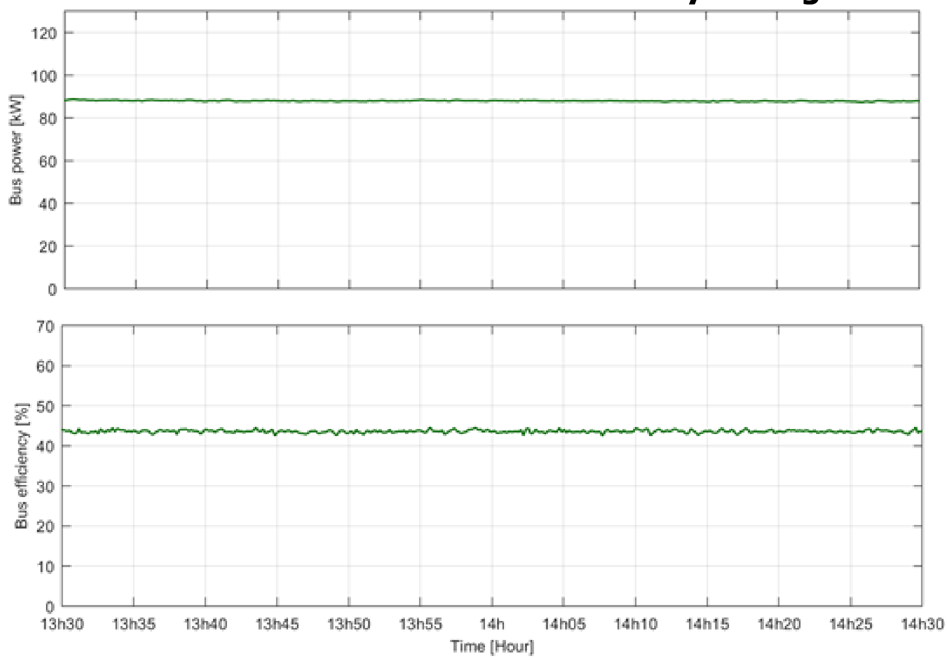
Figure 8: Indicated Power and Efficiency During Commissioning



Source: EtaGen, Inc

Figure 9 shows the power and efficiency at the DC bus. Contributing to the power and efficiency losses from indicated to the DC bus are air spring, friction, motor, and power electronics losses. Each element represents targets for engineering improvements in the next-generation product that are underway, in particular the motor losses, which are discussed in detail.

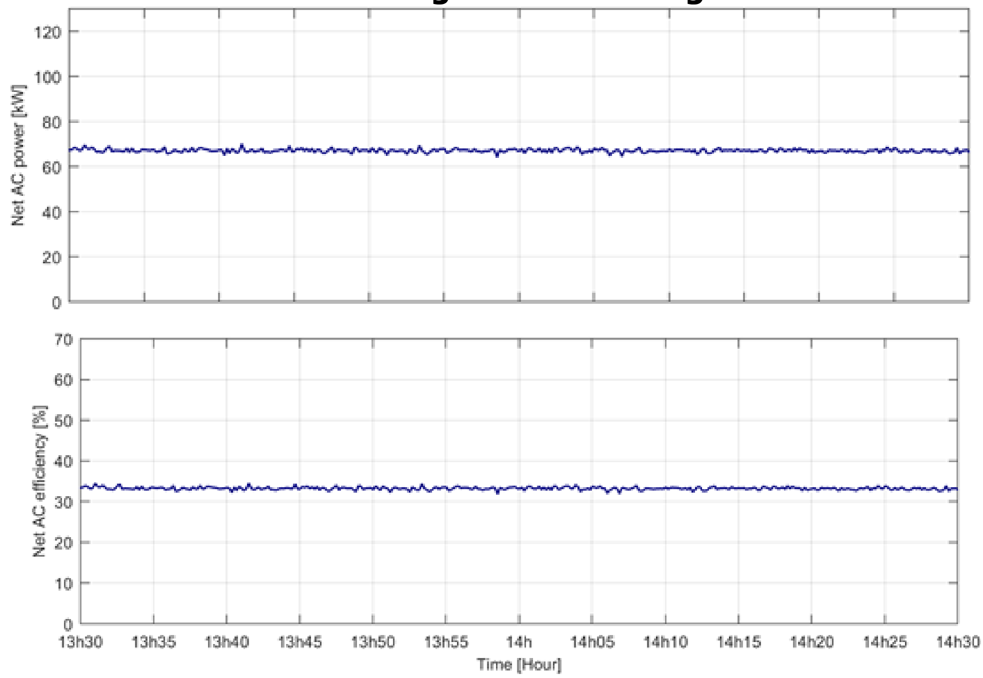
Figure 9: Direct Current Bus Power and Efficiency During Commissioning



Source: EtaGen, Inc

The net AC power output and electric efficiency are shown in Figure 10. Incremental ancillary loads affecting net AC performance include the chiller power, cooling fans and pumps power, and CPU and sensor power. Additional AC loads that were not originally planned include the blower power and motor cooling fans. The blower was planned to be operated off of the DC bus, but due to unanticipated electrical noise issues, it was more time-efficient to simply operate off the AC side of the grid-tie inverter. The motor cooling fans were needed due to the lower-than-expected efficiency of the motors, which is discussed in detail below. Engineering improvements to these components are being addressed for the next-generation systems.

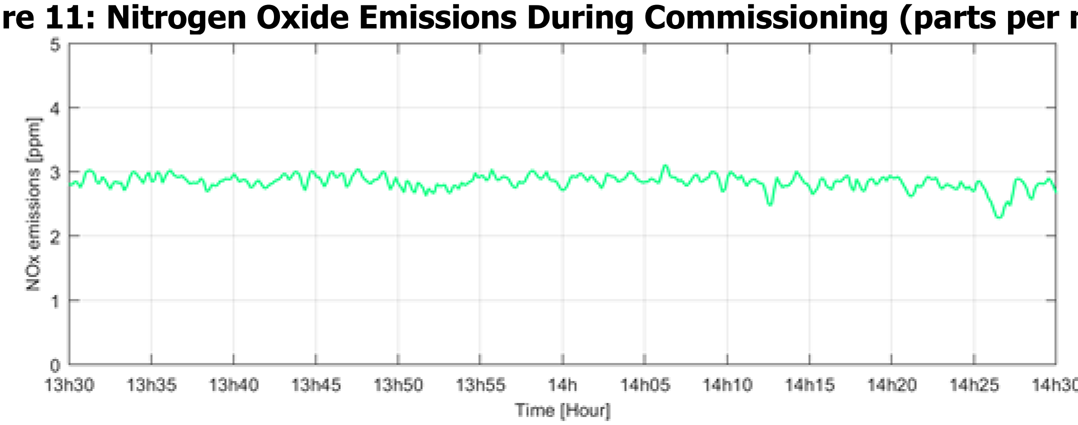
Figure 10: Net Alternating Current Power Output and Efficiency During Commissioning



Source: EtaGen, Inc

Figure 11 shows the NOx emissions measured using an in-house analyzer. The NOx emissions were between 2.8-3.0 parts per million (ppm) during commissioning. All emissions testing during commissioning was done using NOx and CO analyzers owned by EtaGen, measured at a location before the oxidation catalyst. While the oxidation catalyst minimally affects NOx emissions, it significantly impacts CO emissions. Adjustments to the analyzer port locations were needed to gather CO emissions post catalyst, which was completed in December 2017. A third-party emissions testing firm, BlueSky Environmental, took measurements in January 2018 to validate NOx, CO, and VOC emissions both pre- and post-catalyst. Results are discussed in Chapter 5.

Figure 11: Nitrogen Oxide Emissions During Commissioning (parts per million)



Source: EtaGen, Inc

The DC and net AC power output and efficiency of the system were lower than originally anticipated due to the motors having a lower-than-expected efficiency, which limits the amount of fuel into the system and creates the need for motor cooling fans that increase auxiliary power loads. The motor efficiency was expected to be 92 percent, similar to motors in the first-generation systems operating in EtaGen’s laboratory with more than 10,000 hours of operation. Upon commissioning and diagnostics, the research team discovered that the motor efficiency is 92 percent at low loads but drops to 84 percent at full load. A motor program began in June 2017 to design and test improved motors for the next-generation product; however, these motor improvements were not incorporated into this demonstration system.

The demonstration system was designed to operate using a chiller to cool the intake fuel/air mixture and increase the power output and efficiency of the system. However, out-of-system tests showed that chiller power consumption was higher than anticipated, leading to a projected net loss to system performance. Furthermore, the less-than-expected motor efficiency further reduced the benefits of the chiller by limiting the amount of fuel energy that could be input to the system. Since the chiller does not pay for itself energetically, the next-generation product will not include a chiller. As mentioned, due to some unanticipated electrical noise issues, it was more favorable based on schedule to simply operate the blower of the AC side of the grid-tie inverter, which incurs another 2-3 percent in blower power consumption. Moreover, the blower has shown higher-than-expected mechanical losses compared to the manufacturer’s specifications. The manufacturer and an internal team are working to reduce mechanical losses such that the blower performance meets the revised projected performance.

Table 6 shows the measured performance of the demonstration system alongside the projected performance of the system with motor improvements and without operating with the chiller. Operating without the chiller slightly reduces the indicated efficiency by about 1 percentage point but is a net gain on AC power output and efficiency. EtaGen’s first-generation systems have motor efficiencies greater than 92 percent, and the motor program that began in June 2017 has yielded results showing that the next-generation product should have efficiencies higher than 92 percent. Tests have been performed to confirm these performance improvements; however, they were not retrofitted into this demonstration system, but will be incorporated into the next-generation product. As illustrated, the motor efficiency is the key to meeting EtaGen’s performance targets.

Table 6: Measured Performance and Projected Performance with Motor Fix

	CEC Demo Initital Run Data (Oct 17)		CEC Demo with Motor Fix (Projected)		
	kW	% LHV	kW	% LHV	Notes
Electrical Performance					
Fuel Input	203	100%	216	100%	
Indicated Power	122	60%	128	59%	
DC Power	89	44%	101	47%	Improved motor efficiency (92% vs 84%)
Net AC Power	**69**	**34%**	**87**	**40%**	Removed chiller reduces auxiliary losses
Recoverable Heat					
Motor & PE	18	9%	12	6%	60 C supply temperature (140 F)
Cooling Jackets	34	17%	36	17%	65 C supply temperature (149 F)
Gas Sensible HX	28	14%	27	12%	95 C supply temperature (203 F)
Gas Condensing HX	7	3%	7	3%	60 C supply temperature (140 F)
Total Heat	**87**	**43%**	**82**	**38%**	
Overall CHP Performance	**156**	**77%**	**169**	**78%**	

Source: EtaGen, Inc

Table 7 shows the projected performance targets of the next-generation product relative to the projected performance of the demonstration system with a motor retrofit and without operating the chiller. Out-of-system testing and analysis have confirmed that these performance targets are easily achievable. The increase in performance is due primarily to improved motor efficiency, and to the increase in indicated efficiency. The indicated efficiency is expected to increase back to 60 percent (the same as the demo with the chiller) because the product has a larger cylinder diameter and higher operating frequency (i.e., better surface-to-volume ratio and less time for heat transfer). The motor efficiency is increased due to design improvements that have already been validated by experimental data.

Table 7: Projected Performance with Motor Fix and Product Performance

	CEC Demo with Motor Fix (Projected)		250 kW Products (2019) (Projected)		
	kW	% LHV	kW	% LHV	Notes
Electrical Performance					
Fuel Input	216	100%	557	100%	
Indicated Power	128	59%	334	60%	Larger cylinders, higher frequency
DC Power	101	47%	278	50%	Improved motor efficiency (92.5%)
Net AC Power	**87**	**40%**	**254**	**46%**	Improved auxiliary performance with scaling
Recoverable Heat					
Motor & PE	12	6%	29	5%	60 C supply temperature (140 F)
Cooling Jackets	36	17%	81	15%	65 C supply temperature (149 F)
Gas Sensible HX	27	12%	70	12%	95 C supply temperature (203 F)
Gas Condensing HX	7	3%	17	3%	60 C supply temperature (140 F)
Total Heat	**82**	**38%**	**197**	**35%**	
Overall CHP Performance	**169**	**78%**	**450**	**81%**	

Source: EtaGen, Inc

With the support of Energy Commission funding, EtaGen has successful designed, built, installed, and commissioned the world's first fully packaged and UL-certified linear generator. While the performance is slightly lower than anticipated, the improvements necessary to meet the next-generation product performance targets are completely understood and attainable.

CHAPTER 5: Performance Results

5.1 Performance Metrics

The key performance parameters monitored include:

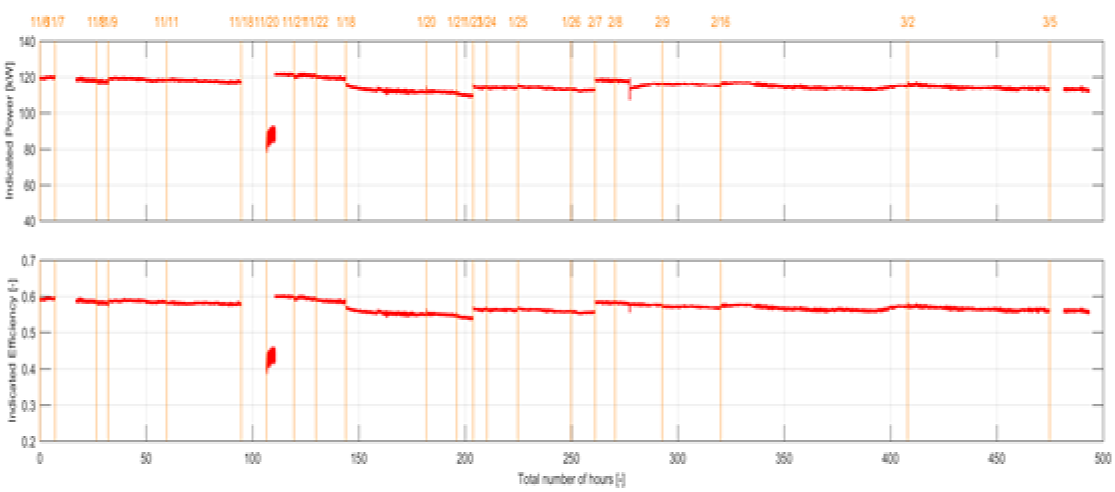
- Indicated power and efficiency.
- DC bus power and efficiency.
- Net AC power and efficiency.
- Criteria emissions – NOx, CO, and VOCs.

5.2 Performance Summary

From October 2017 through February 2018, the system accumulated nearly 500 hours of run time dedicated to this project. The system operated an additional 300 hours for testing various components to inform the next-generation product design decisions, but those operating hours were not counted towards this project.

Figure 12 shows indicated power and efficiency, which is a measure of the conversion of fuel input power to mechanical motion and includes losses from heat transfer, reaction, and gas blow-by. The high indicated efficiency near 60 percent provides a glimpse into the potential for the linear generator technology with ongoing improvements to ancillary losses through sizing and efficiency improvements.

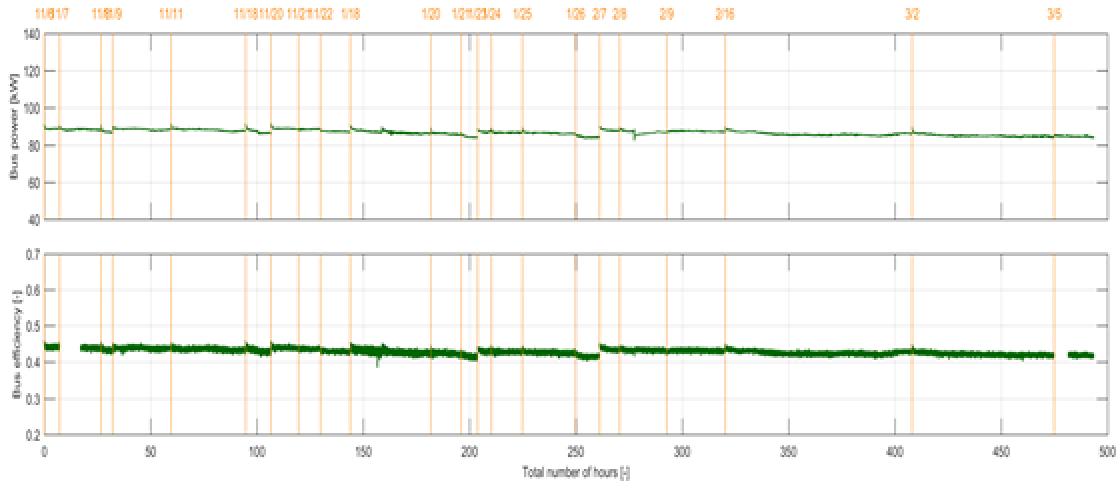
Figure 12: Indicated Power and Efficiency



Source: EtaGen, Inc

Figure 13 shows the power and efficiency at the DC bus. Contributing to the power and efficiency losses from indicated measurements to the DC bus are motor, friction, air spring, and power electronics losses. DC bus power levels are 85–90 kW, and efficiencies are 43–45 percent. The DC performance represents targets for engineering improvements in the next - generation product, in particular, the motor losses.

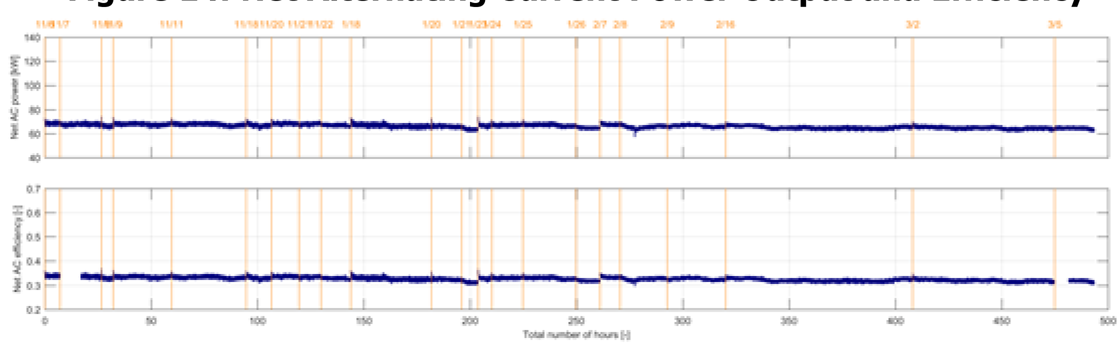
Figure 13: Direct Current Power Bus



Source: EtaGen, Inc

The net AC power output and electric efficiency are shown in Figure 14. Incremental ancillary loads affecting net AC performance include the chiller power, cooling fans, pumps, and CPU and sensor power. Net AC power and efficiency are about 70 kW and 34 percent, respectively. Engineering improvements to these components are also being addressed for the next -generation product. Spot measurements during commissioning of the heat recovery potential yield overall efficiencies around 77 percent, as shown and discussed in Chapter 4.

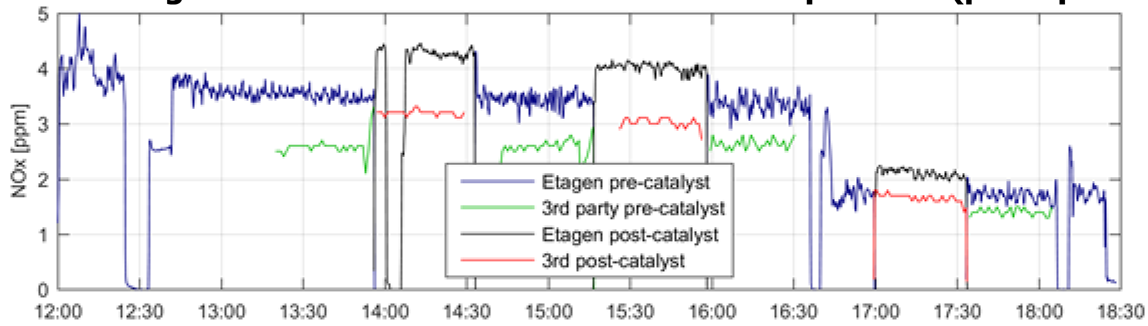
Figure 14: Net Alternating Current Power Output and Efficiency



Source: EtaGen, Inc

Figure 15 shows the NOx emission comparison between EtaGen's in-house analyzer and measurement taken by BlueSky Environmental, an independent emission testing firm. The plot shows that over the four samples, EtaGen's in-house analyzer over-estimated NOx emissions by 15-30 percent both pre- and post-catalyst. The first three samples were taken with the system operating with a controller set point of 3.5 ppm pre-catalyst NOx emissions, and the fourth sample was taken with the system operating with controller set point of 1.8 ppm pre-catalyst NOx emissions. Both set points were based on EtaGen's in-house analyzer.

Figure 15: Nitrogen Oxide Emissions Measurement Comparisons (parts per million)



Source: EtaGen, Inc

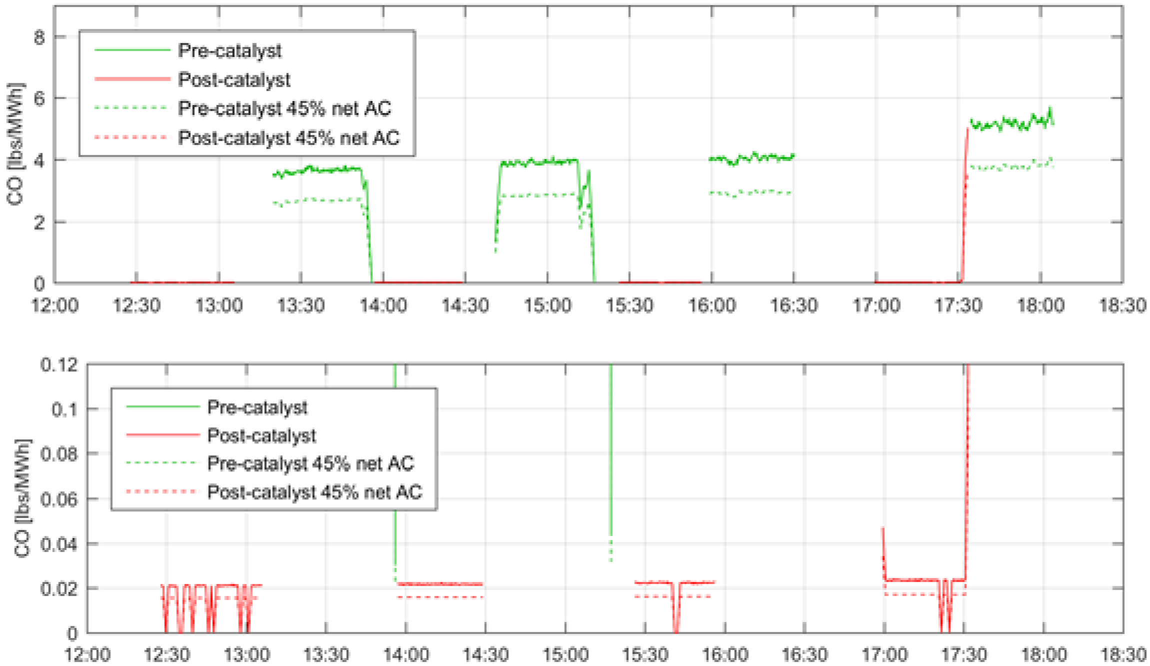
Figure 16 shows the NOx emissions using BlueSky test data in pounds per megawatt hour (lb/MWh) for ease of comparison with SCAQMD and CARB DG emissions standards (both 0.07 lb/MWh). Post-catalyst NOx emissions for the demonstration system were 0.10-0.12 lb/MWh for the first three samples and 0.06-0.07 lb/MWh for the fourth sample. Also shown on the plot are the emissions if the demonstration system was performing with 45 percent efficiency, which is the expected performance of the next-generation product. Based on the first three samples, the demonstration system would be able to meet the SCAQMD and CARB DG emissions standards by either taking credit for waste-heat utilization in CHP applications or by meeting the planned electric efficiency improvements. The fourth sample illustrates the demonstration system can meet both SCAQMD and CARB DG emissions standards in electric-only applications without any efficiency improvement and only with a change in controller set point.

Figure 16: Nitrogen Oxide Emissions (pounds per megawatt-hour)

Source: EtaGen, Inc

Figure 17 shows the CO emissions using BlueSky Environmental test data in pounds per megawatt hour (lb/MWh) for ease of comparison with the SCAQMD emissions standard (0.20 lb/MWh) and the CARB DG emissions standard (0.10 lb/MWh). Post-catalyst CO emissions for the demonstration system were around 0.02 lb/MWh for all four samples, which easily meets both standards.

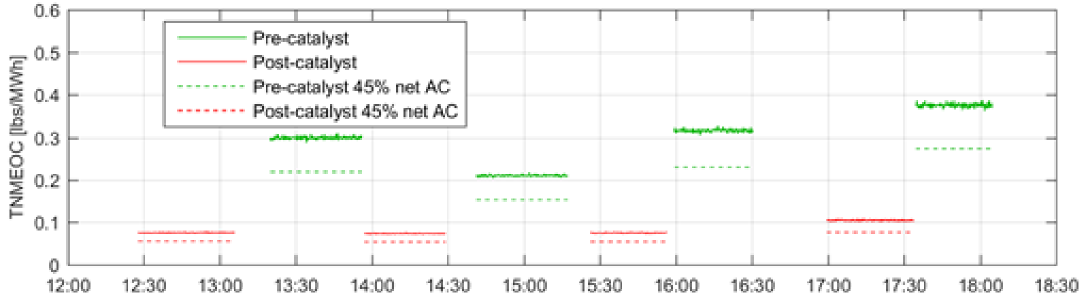
Figure 17: Carbon Monoxide Emissions (pounds per megawatt-hour)



Source: EtaGen, Inc

Figure 18 shows the VOC emissions using BlueSky test data in pounds per megawatt -hour (lb/MWh) for ease of comparison with the SCAQMD emissions standard (0.10 lb/MWh) and CARB DG emissions standard (0.02 lb/MWh). Post-catalyst NOx emissions for the demonstration system were 0.08 lb/MWh for the first three samples and 0.10 lb/MWh for the fourth sample. Based on the first three samples, the demonstration system would easily meet the SCAQMD emissions standards. The increase in VOC emissions in the fourth sample is due to the trade-off between NOx and VOC emissions. While the VOC emissions in the fourth sample are higher than the first three samples, the demonstration system would still be able to meet SCAQMD emissions standards. The oxidation catalyst was sized to provide greater than 93 percent reduction in VOCs at the research team’s gas temperatures; however, based on the data shown in Figure 23, the catalyst only provides only a 60-75 percent reduction in emissions. This lower-than-expected reduction does not reduce VOC emissions to the level required for meeting the CARB DG emissions standard in electric-only applications, but it can meet the standard in CHP applications. However, if the catalyst had performed as expected, the CARB DG standard can be achieved with the planned efficiency improvements for all four samples. EtaGen is working with the catalyst vendor to determine the cause for the lower-than-expected reduction in VOC emissions.

Figure 18: Volatile Organic Compounds Emissions (pounds per megawatt-hour)



Source: EtaGen, Inc

CHAPTER 6: Benefits to Ratepayers

6.1 Benefit Analysis

The linear generator technology being developed by EtaGen will address the enormous market potential that resides in California's commercial and industrial sectors. Since California is unique in its stringent emission requirements, the market for behind-the-meter natural gas generation, especially with CHP, has deteriorated relative to the markets in other parts of the United States. The remaining market potential in California for CHP systems less than 5 MW in size, which is the addressable market for EtaGen's technology, is more than 9,000 MW.2

EtaGen's technology offers high electric efficiency without compromising overall thermal efficiency, which provides electric-only and CHP solutions for customers that have low-to-modest thermal-to-power ratios, which is typical in the commercial and light-industrial sectors. In addition, EtaGen's technology operates with air criteria pollutant emissions below SCAQMD emissions standard without the use of NOx after-treatment equipment. Since the linear generator has only two moving parts and does not use oil or spark plugs, the maintenance cost is significantly lower, and the reliability/availability is significantly higher than existing prime movers. The combination of high electrical efficiency and low capital and maintenance costs yields economic returns that are substantially higher than existing prime movers, providing customers with an unmatched combination of economic value, resiliency, near-zero emissions, and carbon savings. The linear generator is capable of operating on biogas without requiring expensive fuel treatment, as is required for fuel cells and engines with catalysts. Moreover, the linear generator is well-suited for flexible operation and can be paired with storage to best support the grid with local power when it is most valuable.

EtaGen's linear generator technology will significantly increase the deployment of electric-only and CHP onsite generation in the lower size range of the market. California ratepayers benefit from onsite generation in three key ways: 1) customers with onsite generation benefit from energy cost savings, which enables greater spending on their core business, 2) all ratepayers benefit from the reduction in air criteria pollutants and greenhouse gases, and 3) the use of localized clean onsite generation reduces the growth in demand for central power generation, transmission, and distribution.

As shown in Table 8, the EtaGen's linear generators will provide significant near-term and long-term benefits. For the 10-year period following full commercial introduction, the cumulative benefits in California include: 34 million MMBTU of natural gas savings from boilers, $3 billion in electricity and capacity savings, 5,716 metric-ton reduction in CO2 emissions, and 4 GW in avoided centralized generation. Although not quantified here, other tangible benefits include avoided electric transmission and distribution costs and losses, and a more secure and reliable electricity supply. For global installations outside of California, EtaGen projects four (4) times the sales and market volumes envisioned for California. The GHG emissions reductions for installations outside of California will be appreciably greater than in California because the avoided grid emissions are significantly higher. In addition, it is estimated that EtaGen's internal employee base will grow to an estimated 3,500 by 2029 (10ten years after commercial launch). It should be noted that this increase in employment does not include additional job creation through vendors, suppliers, installers, or other business associated with EtaGen that could readily match EtaGen's internal employment growth.

Table 8: California Benefits Summary

	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	10 yr Total
Inputs											
Efficiency (LHV)	48.0%	48.0%	48.1%	48.2%	48.3%	48.4%	48.5%	48.6%	48.7%	48.8%	N/A
CHP Efficiency (LHV)	88.0%	88.0%	88.0%	88.0%	88.0%	88.0%	88.0%	88.0%	88.0%	88.0%	N/A
Fleet Avg. Capacity Factor	88.0%	86.0%	84.0%	82.0%	80.0%	78.0%	76.0%	74.0%	72.0%	70.0%	N/A
Natural Gas Price ($/MMBTU HHV)	$5.00	$5.10	$5.20	$5.31	$5.41	$5.52	$5.63	$5.74	$5.86	$5.98	N/A
Biogas Price ($/MMBTU HHV)	$11.00	$11.22	$11.44	$11.67	$11.91	$12.14	$12.39	$12.64	$12.89	$13.15	N/A
% CHP of Installations	10%	15%	20%	25%	30%	35%	40%	45%	50%	50%	N/A
% Biogas of Installations	5%	10%	13%	15%	18%	20%	23%	25%	28%	30%	N/A
Savings											
Grid Electricity (GWh)	110	585	777	1,534	2,244	3,063	3,880	4,534	4,853	5,190	26,769
Grid Capacity (MW)	14	78	106	214	320	448	583	699	769	846	4,077
Boiler Fuel (thousand MMBTU)	35	280	494	1,214	2,122	3,363	4,846	6,341	7,506	7,991	34,192
CO2 (tonnes)	6	54	92	219	372	576	813	1,042	1,210	1,332	5,716
Value of Savings ($M)											
Grid Electricity	$12	$64	$84	$162	$231	$309	$381	$434	$452	$470	$2,600
Grid Capacity	$1	$8	$11	$21	$32	$45	$58	$70	$77	$85	$408
Boiler Fuel	$0	$1	$3	$6	$11	$19	$27	$36	$44	$48	$196
CO2	$0	$2	$3	$7	$11	$17	$24	$31	$36	$40	$171
Total	**$14**	**$75**	**$99**	**$196**	**$286**	**$389**	**$491**	**$572**	**$610**	**$642**	**$3,376**

Global Inputs	
Avoided CO2 (kg/MWh)	474.7
Displace Boiler Eff. (LHV)	89%
NG CO2 Factor (kg/MMBTU)	53.0
Energy Value (cents/kWh)	16.20
NG Fuel Cost ($/MMBTU HHV)	$5.00
Biogas Cost ($/MMBTU HHV)	$11.00
Value of CO2 ($/tonne)	$30
Value of Grid Capacity ($/kW)	$100
Escalators	
O&M	2%
Natural Gas	2%
Biogas	2%

Source: EtaGen, Inc

The commercialization of EtaGen's ultra-clean, high-efficiency, and cost-effective linear generator products will appreciably further the goals of Assembly Bill 32 (Núñez, Chapter 488, Statutes of 2006), as well as demonstrably support the PIER Natural Gas program, the Governor's Clean Energy Jobs Plan of 12,000 MW of localized generation by 2020, the Integrated Energy Policy Report, the Renewables Portfolio Standard, and the Bioenergy Action Plan. Furthermore, the EtaGen's technology provides a basis for forming future energy policy to continue to improve the efficiency, security, and reliability of California's energy grid system.

Funding has accelerated the time to commercial introduction and increased the probability for sustainable commercial success. Venture capital investment has carried the development of the technology to date; however, venture capital investment in the energy sector has retreated over the past several years. Government support is critical for the early commercial success of EtaGen's products in California.

Beyond the long-term success of EtaGen and the benefits its products can provide to California, there are short-term benefits from disseminating of information from this project. First, the successes and lessons learned from this project will support new and ongoing research in linear generator control and power electronics. Second, proving the viability of EtaGen's technology through this project will dramatically enhance the engagement process with potential customers that have evaluated onsite generation in the past but could not make the economics work with existing technologies. This segment, currently without a viable onsite generation solution unless EtaGen's technology succeeds, will provide early market penetration since it is familiar with project evaluation. Lastly, successful commercialization of this technology will help attract private capital to build a sales and marketing team to broaden EtaGen's customer base.

CHAPTER 7: Conclusions and Recommendations

7.1 Benefit Analysis

There exists the potential for more than 7,400 MW of installed combined-heat-and-power (CHP) capacity in California for systems less than 5 MW.[1] Much of this underserved market is addressable by EtaGen's linear generator technology. With high efficiency, ultra-low emissions, and low capital and maintenance costs, EtaGen's linear generator will offer commercial and light-industrial businesses an onsite electricity and heat solution while reducing their costs and emissions and increasing their resiliency.

With funding support from the Energy Commission and SoCal Gas for this demonstration project, EtaGen successfully designed, built, installed, interconnected, operated, and monitored the world's first linear generator for onsite electricity and heat production. With the success of this project and the knowledge gained, EtaGen has a clear development roadmap to a 250-kW commercial product with an electric efficiency greater than 45 percent and an overall thermal efficiency greater than 80 percent. EtaGen's recent private financing was used in combination with continued support from the Energy Commission and SoCal Gas to launch its first commercial products in the summer of 2020.

7.2 Recommendations

The proposed recommendations consider the following areas:

Technology Verification and Advancement

- Design, fabricate, and demonstrate EtaGen's next generation commercial system.
- Conduct research and development on advanced components including, but not limited to, linear motors.

Outreach and Communication

- Preparation and circulation of case studies and project profiles.
- Continued outreach to prospective customers and targeted industry associations.
- Presentations and dialogue with state and federal officials in support of:
  - Technology neutral laws, policies, and regulations toward DG technologies.
  - Start-up support for promising California small businesses.

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[1] *Combined Heat and Power Technical Potential in the United States*, Anne Hampson, Rick Tidball, Michael Fucci, and Rachel Weston, ICF International, prepared for The U.S. Department of Energy.

LIST OF ACRONYMS

Term	Definition
AC	Alternating Current
CHP	Combined Heat and Power
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CPU	Control Processing Unit
DC	Direct Current
DG	Distributed Generation
kW	Kilowatt
kWh	Kilowatt-hour
MW	Megawatt
MWh	Megawatt-hour
NOx	Nitrogen Oxide
SCAQMD	Southern California Air Quality Management District
VFD	Variable Speed Drives
VOC	Volatile Organic Compounds

APPENDIX A: Technology/Knowledge Transfer

A-1.1 Addressable Market

The high electrical and overall efficiencies of EtaGen's linear generator allow it to have a broader application reach than other CHP technologies in the 250 kW to 2 MW size range. Drawing from a 2016 DOE assessment of the technical potential for CHP in the United States, Table: A-1 illustrates the potential number of suitable sites for EtaGen's 250 kW product in California and in the entire United States without regard for energy prices and incentives.[4]

Table A-1: Market Potential Summary

Potential	California	United States
Number of Sites	7,771	84,009
Number of Units	14,514	164,752

Source: EtaGen, Inc

The economic market potential for CHP applications is typically where the spark spread between electricity and natural gas prices are sufficiently large and where favorable distributed generation policies combine to allow customers to achieve attractive economic returns. Regions of the United States that are most conducive for early EtaGen products include California and the Northeast and Mid-Atlantic States. The Northeast States include Connecticut, Massachusetts, Maine, New Hampshire, New York, Rhode Island, and Vermont. Targeted Mid-Atlantic States include District of Columbia, Delaware, Maryland, New Jersey, and Virginia.

In a CHP assessment conducted for the American Gas Association5, the economic potentials in California, and the Northeast and Mid-Atlantic regions were 76 percent, 85 percent, and 31 percent, respectively. Table: A-2 illustrates the economic potential in these priority CHP regional markets by multiplying the technical potential by respective economic percentage.

Table A-2: Priority Combined Heat and Power Regional Market and Economical Potential

Priority Technical Potential - # Units				
	250-500 kW	**0.5-1 MW**	**1-2 MW**	**Total**
California	3,218	7,644	3,652	7,771
Northeast	3,288	10,028	5,372	9,376
Mid-Atlantic	3,888	10,904	5,886	10,517
Total	**10,394**	**28,576**	**14,910**	**27,664**
Priority Economic Potential - # Units				
	250-500 kW	**0.5-1 MW**	**1-2 MW**	**Total**
California	2,454	5,829	2,785	4,818
Northeast	2,812	8,576	4,594	5,813
Mid-Atlantic	1,189	3,336	1,801	6,520
Total	**6,456**	**17,742**	**9,180**	**17,152**

Source: EtaGen, Inc

With the high electrical and overall efficiencies of EtaGen's products, the linear generator can serve customers with coincident electricity and heating loads in a CHP mode or it can serve customers with little or no thermal loads in an electric-only mode. Targeted early -entry market customers are national and multi-national organizations with numerous plants in the priority regions. Key early market customer verticals include data centers, big box retail, grocery, utility, banking, logistics, telecom, commercial office, government, health care, educational, manufacturing, and food processing and packaging.

A-1.2Commercial Deployment Challenges

A number of regulatory, institutional, and market barriers continue to restrict the distributed generation marketplace. These market barriers include:

- Market acceptance with a new technology lacking a commercial track record.
- Local, state, and federal regulations, building codes, and utilities that do not yet recognize the value of distributed generation.
- Time and expense to obtain grid interconnection agreements.
- Utility tariffs that include unavoidable "non-by passable charges" for select technologies.
- Access to equity financing to support the development of new and innovative technology development.
- Access to project financing for new technologies to reduce customer risk.

A-1.3 Commercial Deployment Solutions

Advocacy, technical and economic benchmarking, and outreach to spur implementation of EtaGen's products in California are described below.

A-1.4 Technology Advancement and Economic Analysis

- Demonstration system was successfully designed, built, installed, interconnected, and operated

- Instrumentation, data collection, and analysis of key performance metrics werecompleted
- Design and build of the next--generation product are ongoing.
- Economic analysis
- Capital cost estimates for entry and mature products have been completed.
- Models have been developed and validated for customer value proposition.

A-1.5Business Development

- EtaGen has met with more than50 prospective customers and have plans for 2019 deployment in several verticals.
- EtaGen recently raised a large amount of private financing to help commercialize its technology and build its sales and business development team.
- Government advocacy and support:
  - EtaGen has been particularly active in California with the Legislature, the Governor's Office, the California Public Utility Commission (CPUC), the California Air Resources Board (CARB), and the Energy Commission.
  - EtaGen is a strong advocate for technology neutral policies and regulations that allow technologies to compete on the~~ir~~ merits rather than picking technology winners and losers.
- EtaGen is members of the following advocacy groups:
  - California Clean DG Coalition (CCDC)
  - Silicon Valley Leadership Group (SVLG).
  - U.S. CHP Association

A-2 -Production Readiness Plan

A-2.1 Product Development

With continued California Energy Commission and SoCal-Gas funding support to augment EtaGen's private investors, a 250-kW commercial product will be commissioned in 2019 at a commercial site in Southern California. Most of the parts and materials will be procured from contract manufacturers and outside vendors, but final assembly and testing will be performed by EtaGen personnel at its facility in Menlo Park.

A-2.2 Manufacturing and Assembly

During the first year of commercial introduction, assembly will be performed by EtaGen personnel at its existing facility. Production will be relocated to a larger facility operated by a contract manufacturing partner following the initial commercial introduction. It's noteworthy that the production facility of EtaGen's products does not require investments in expensive, volume-sensitive manufacturing processes, enabling modest unit production costs, even for low-volume fabrication and assembly. Furthermore, the product itself and the manufacturing process will not include or use any hazardous or non-recyclable materials. Ultimately, production plants will likely be built in multiple locations around the globe to take advantage of select local manufacturing factors and proximity to markets.

Early entry market customers will be national and multi-national corporations with sustainability practices that include innovative, cutting-edge practices and technologies. Most of these customers will require project financing with projects being structured to provide customer savings of 10-20 percent compared to grid prices. EtaGen's installed price target for the 250-kW product will easily be able to provide customers this level of savings.

A-2.3Investment Threshold

EtaGen recently closed a private financing round from 10~~ten~~ investors with deep knowledge in energy generation and distribution. New strategic investors include American Electric Power (AEP), Centrica Innovations, and Statoil Energy Ventures. Along with KCK Group and Louis M. Bacon, they join EtaGen's existing investors Bill Gates and Khosla Ventures. EtaGen will use the funding to scale its manufacturing and operations and augment its sales, marketing, and service teams.

In addition to equity financing, EtaGen will work with its strategic investors and partners to secure project financing for their customers. EtaGen will also continue to monitor any government incentive programs and try to ensure that there is a level-playing field for its technology.

A-2.4 Intellectual Property

EtaGen's intellectual property is well-protected with a strong portfolio of issued U.S. and international patents, along with dozen~~s~~ of pending patent applications. EtaGen has 18 issued U.S. patents and 6 issued international patents.