ENERGY RESEARCH AND DEVELOPMENT DIVISION

FINAL PROJECT REPORT

High-efficiency and Ultra-low Emissions Linear Generator Demonstration Project in Southern California

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PREPARED BY:

Adam Simpson
Keith Davidson
Mainspring Energy, Inc.
Primary Authors

Baldomero Lasam
Project Manager
California Energy Commission

Agreement Number: PIR-17-006

Kevin Uy
Branch Manager
ENERGY GENERATION RESEARCH BRANCH

Jonah Steinbuck, Ph.D.
Director
ENERGY RESEARCH AND DEVELOPMENT DIVISION

Drew Bohan
Executive Director

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division manages the 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 RD&D entities, including individuals, businesses, utilities, and public and private research institutions. This program promotes greater gas reliability, lower costs and increased 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

This is the final report for the High-efficiency and Ultra-low Emissions Linear Generator Demonstration project (Grant Agreement Number PIR-17-006) conducted by Mainspring Energy. The information from this project contributes to the Energy Research and Development Division's 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 Energy Research and Development Division at ERDD@energy.ca.gov.

ABSTRACT

The changing electricity landscape requires dispatchable generation to firm and support renewables and distributed generation to provide resilience when the grid is down. This dispatchable generation must also be efficient to minimize carbon emissions, ultra-low emission to minimize air criteria pollutants, and fuel-flexible to be able to operate on zero- and net-zero carbon fuels.

Mainspring Energy's new linear generator uses a low-temperature reaction of air and fuel to drive magnets through copper coils to efficiently produce electricity with near-zero NOx emissions. The linear generator offers customers an unmatched combination of high electrical efficiency, ultra-low emissions, operational and fuel flexibility, and low costs.

The linear generator's attributes enhance and support California's energy, environmental, and resiliency goals as grid emissions continue to decrease and more renewables come online. Mainspring's first commercial product is an ideal solution for commercial, industrial, and utility customers seeking local, scalable, fuel-flexible power.

This project demonstrated the installation and operation of Mainspring's linear generator at a grocery store in Colton, California. The project was successful and achieved its desired performance targets. Mainspring has announced follow-on projects with Kroger, the nation's largest grocery chain, Lineage Logistics, the largest global cold-storage logistics company, and American Electric Power, a multi-state utility company focused on low-cost solutions for its customers.

Keywords: linear generator, dispatchable generation, power generation technology, linear generator core, grid resilience, fuel-flexibility, Renewable Portfolio Standard, ultra-low emissions

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Introduction

California Senate Bill 100, The 100 Percent Clean Energy Act of 2018 (De León, Chapter 312, Statutes of 2018), updates the state's Renewables Portfolio Standard to ensure that, by 2030, at least 60 percent of California's electricity is renewable. It also sets a 2045 goal of powering all retail electricity sold in California and state agency electricity needs with renewable and zero-carbon resources. The state recognizes the need for firm yet flexible resources to balance the intermittent nature of solar and wind. Reliability measures to maintain a resilient grid include demand response, nuclear, long-term storage, microgrids, and the use of gaseous fueled dispatchable generation that can be deployed when needed to meet demand and support the grid.

The changing electricity landscape in California requires clean firm capacity to supplement the state's increasing amounts of intermittent renewables and to provide grid resiliency during unplanned outages. Dispatchable generation refers to energy resources that can provide power whenever it is needed for however long it is needed, such as pumped hydro and natural gas power plants. Renewable generation refers to energy resources that produce power only when the input resources are available, such as solar and wind generation. It is essential that new fuel-based dispatchable generation have low-criteria emissions, such as low oxides of nitrogen (NOx) emissions, and be fuel-flexible to operate on zero-carbon fuels, such as hydrogen and ammonia.

Mainspring's linear generator is a new category of power generation that is distinct from turbines, engines, and fuel cells. The linear generator offers the high efficiency and low emissions of fuel cells with the dispatchability and low cost of engines and turbines. The linear generator uses a low-temperature, noncombustion reaction of air and fuel to drive magnets through copper coils to efficiently produce electricity with near-zero NO_x emissions and with fuel-flexibility. The linear generator offers customers an unmatched combination of high electrical efficiency, ultra-low emissions, operational and fuel flexibility, and low capital and maintenance costs.

Project Purpose

The purpose of this project was to design, fabricate, install, and demonstrate a high-efficiency, ultra-low emissions distributed generation technology application in a grocery store in Colton, California.

The key innovation of this project is Mainspring Energy's (Mainspring) new category of power generation technology — the linear generator. Mainspring's unique linear generator provides an affordable, resilient, fuel-flexible, and fully dispatchable distribute generation product, one with inherently low emissions and high efficiency. It's an ideal fit for a broad segment of the commercial, industrial, and multi-family market sectors. This demonstration project installed and operated this pilot generator to validate commercial viability and performance in a real-world setting. In addition, Mainspring intended for the project to familiarize prospective end users, government agencies, utilities, and other stakeholders with the linear generator's unique performance attributes and to stimulate early market adoption and sales.

Project Approach

Mainspring brought together a diverse, talented team of individuals who were driven by a vision of the affordable, reliable, net-zero carbon grid of the future. The executive team has deep expertise from leading clean energy companies and is backed by top-tier venture capitalists, strategic partners, and financial investors.

The bulk of the work for this demonstration project was performed in-house, with subcontractors responsible for the site work and installation, emissions testing, and contract administration. The selected project site was a grocery store in Colton, California, where the linear generator provided dispatchable power 24 hours a day, seven days a week for approximately 80 percent of the building's electricity demand.

The project included factory testing, permitting and interconnection agreements, site preparation, installation, commissioning, operation, monitoring, and reporting. The fundamental technical barriers confronting the linear generator were addressed in Mainspring's early years via design, breadboard testing, and near-commercial scale prototype installations.

This project was the first installation of a pilot commercial unit expected to run continuously at a customer site. The linear generator demonstrated a lower power consumption for ancillary equipment and displayed overall higher efficiency compared to conventional combined-heat-and-power systems. The pilot unit product fabrication and assembly costs were developed based on potential volume purchases in a production facility.

The demonstration project encountered nontechnical barriers with permitting and interconnection, which stemmed from government agencies not being familiar with the new technology, but those barriers were ultimately overcome. Several organizations required education about linear generators, including local air districts, city planning departments, electric utilities, and state and federal energy agencies. State and local education is an ongoing effort as the market for linear generators expands in California and nationally.

Project Results

This project supported the demonstration of an early pilot of Mainspring's linear generator at a grocery store in Colton, California, for nine months. As of July 2023, the linear generator is still operational. The project achieved its desired performance targets for power output, efficiency, emissions, and run time, which was a significant achievement for this new category of power generation technology. The linear generator, with a nameplate rating of 230 kilowatts (kW), was able to track load and maintain efficiency above 40 percent across the facility's load range (130-370 kW). Low-emissions operation was achieved across the building load range, always less than 0.07 pound per megawatt-hour (2.5 parts per million) NOx at all loads. Third-party emissions testing was performed, and the unit met all requirements to achieve permission to operate from the South Coast Air Quality Management District.

Mainspring learned from the testing and validation of this pilot unit's performance at a customer site. Design improvements have been made based on testing at Mainspring's facilities and will be incorporated in future commercial products. Near-term improvements are aimed at reducing power consumption for auxiliary components, along with ongoing advancements to the linear generator core. These design improvements will lower cost and increase power to 250 kW and efficiency to 45 percent or greater.

Mainspring has seen significant market interest from national and multi-national corporations. During this project, Mainspring announced projects with Kroger, the nation's largest grocery chain, Lineage Logistics, the largest global cold-storage logistics company, and American Electric Power, a multi-state utility company focused on low-cost solutions for its customers.

Sharing the Knowledge and Advancing the Research to Market

These activities are multi-faceted and include market knowledge, competition, intellectual property, government advocacy, utility cooperation, end-user market development, and a production plan that anticipates volume growth.

Market Characterization

Broad market categories for Mainspring's linear generator include commercial and industrial behind-the-meter applications, utility front-of-the-meter applications, and microgrids. According to a *Guidehouse Insights* 2021 white paper study, the market for linear generators is 5.5 gigawatts (GW) per year in the United States and 14.3 GW per year outside of the U.S. (Asmus and Rodriquez, 2021). Mainspring estimates this market share for California to be approximately 20 percent of the U.S. market, or 1.6 GW per year.

Market Adoption

Mainspring has identified several states, including California, and utilities to start installing the linear generator, expanding in the U.S. and globally as more production reduces costs and prices. Early-entry market customers include national and multinational corporations with sustainability practices that include innovative, cutting-edge measures and technologies. Mainspring began shipping pilot units to multiple Fortune 500 customers in 2020 and expects to scale commercial product shipments in 2022 and beyond.

Technology Transfer

In addition to targeted marketing to national accounts and verticals, Mainspring accelerated its public messaging in 2021 with select presentations, news releases, and articles, which are accessible on Mainspring's website (https://www.mainspringenergy.com). Making this information accessible to public agencies is critical to getting the linear generator technology recognized as a new category of power generation. Technology transfer will be an ongoing activity as Mainspring expands its market reach to new regions and customer segments.

Production Readiness

During the commercial introduction period, product assembly will be performed by Mainspring employees at its existing California facility.

Benefits to California

The linear generator's low costs, ultra-low criteria emissions, dispatchability, and fuel flexibility will enhance and support California's energy, economic, environmental, and resiliency goals as grid emissions continue to decrease and more intermittent renewables come online. Specific benefits include:

- Lower Costs: Low-cost electricity provides cost savings to the customer and reduces overall demand on the electric grid, which decreases the need for centralized generation and its associated transmission and distribution costs and losses.
- Environmental Benefits: Ultra-low emissions provide cleaner air for all Californians, especially in the state's non-attainment districts and disadvantaged communities.
- Clean Backup Power: Load tracking, fast on/off, and black start capabilities enable both savings and grid parallel and resilient power when the grid is down.
- Fuel-Flexibility: The technology continuously adjusts operation, allowing it to dynamically switch to zero-carbon fuels such as biogas, green hydrogen, and green ammonia.
- Economic Development: The technology creates jobs for general, electrical, mechanical contractors and engineers, for service, installation, and maintenance technicians, and for possible manufacturing in California.

CHAPTER 1: Introduction

Project Goals and Objectives

The goal of the project was to demonstrate Mainspring Energy's (Mainspring) new category of generation technology — the linear generator — at a customer site in Southern California. This demonstration included the installation, operation, and monitoring of an early product over the course of nine months. Mainspring's linear generator technology offers commercial and industrial customers an unmatched combination of high electrical efficiency, ultra-low emissions, dispatchability, fuel flexibility, and low costs.

Specific project objectives included:

- Designing and building a commercial pilot product.
- Installing, interconnecting, and permitting at a commercial site in Southern California.
- Operating and monitoring performance for nine months.
- Measuring performance data to validate and demonstrate a pathway to achieving mature product performance targets of 250 kilowatts (kW) net alternating current (AC) power output, greater than 45 percent net AC efficiency, and criteria emissions that meet California Air Resources Board (CARB) DG certification requirements.

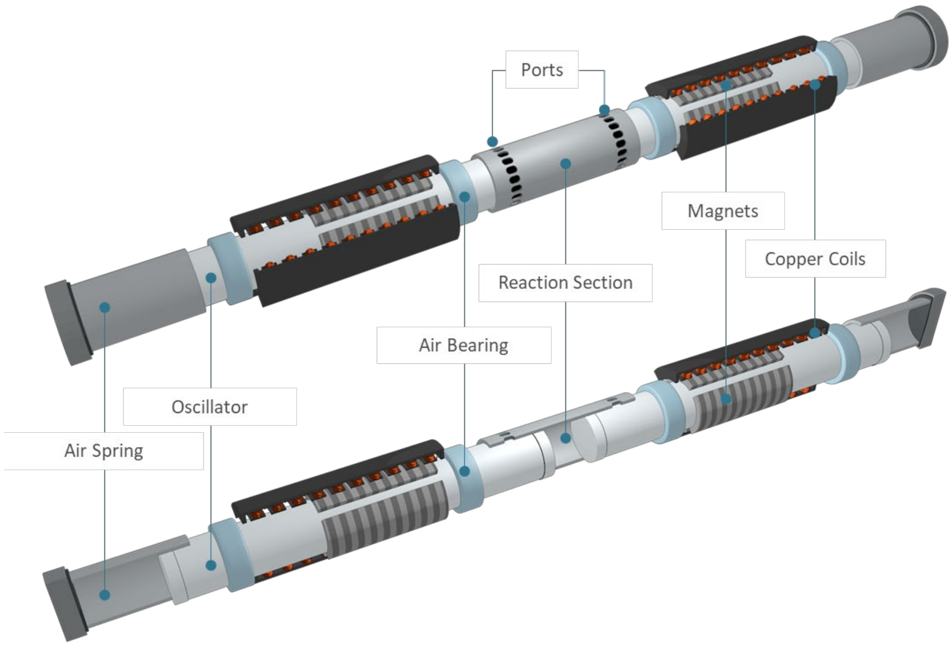
Project Description

An innovative linear generator technology has been designed, built, installed, interconnected, operated, and monitored for electric performance. This demonstration project of an early product linear generator has verified that the performance and cost trajectory of the technology is on track to meet commercial product targets. The addressable market for the linear generator is large and spans the globe. Key market segments include commercial and industrial behind-the-meter (BTM) applications, utility front-of-the-meter (FTM) applications, and microgrids. A market rollout strategy, incremental engineering improvements, and manufacturing cost reduction plans are in-place to transform the market.

Technology Overview

Figure 1 illustrates the components of the linear generator technology developed by Mainspring Energy. The linear generator has a center reaction cylinder with two opposed oscillators and two outer air springs. The reaction section has intake and exhaust ports for gas exchange. Each oscillator has magnets attached to it for electricity production via the surrounding copper coils. The oscillators move linearly back and forth while riding on a cushion of air that is provided by the air bearings located on each side of the copper coils.

Figure 1: Illustration of Free-piston Linear Generator



Source: Mainspring Energy

An operating cycle of the linear generator begins with compression of an air and fuel mixture that is driven by energy stored in the air springs from a previous cycle. Compression continues until a low-temperature, noncombustion reaction occurs uniformly, without burning or a flame. This low-temperature reaction achieves high thermodynamic efficiency and near-zero emissions. The reaction causes the oscillators to move outward, during which a portion of the kinetic energy is directly converted into 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, a gas exchange replaces the reaction products with a fresh air and fuel mixture. The electricity produced is rectified to direct current (DC) through power electronics and the DC power is then converted to three-phase AC power via a UL-listed grid-tie inverter.

High electrical efficiencies are achieved through the high expansion of reacted gases and the direct conversion of linear motion into electricity with near-zero friction. Near-zero nitrogen oxide (NOx) emissions result from the low-temperature, uniform reaction that maintains peak temperatures below those in which NOx formation occurs, which is approximately equal to 2732°F (1,500°C). The linear generator is made from standard materials with only two moving parts and operates without using oil or expensive fuel cell catalysts or complex engine mechanical systems — resulting in low capital and maintenance costs.

Figure 2 shows a linear generator core and Figure 3 shows a packaged product. Mainspring's products are UL-2200 listed and utilize grid-tie inverters (GTIs) that are UL-1741-SA listed, both of which enable streamlined permitting and interconnection.

Figure 2: Mainspring Linear Generator Core

Source: Mainspring Energy

Figure 3: Mainspring Linear Generator Product

Source: Mainspring Energy

Project Team

Mainspring Energy, the prime recipient for this project, is a private company located in Menlo Park, California. It was founded in the summer of 2010 by Shannon Miller, Matt Svrcek, and Adam Simpson. The three co-founders earned their PhDs in mechanical engineering from Stanford University.

This collaborative initiative involved several key team members, all of whom were committed to the project and its ultimate success. Table 1 shows the various team members and their project roles. All team members are California business enterprises.

Table 1: Project Team

Organization	Project Role
Mainspring Energy	Prime recipient, project management, equipment supplier, engineering, maintenance, data acquisition
DE Solutions	Technical advisor, administration and project management support, data analysis, report writing

Organization	Project Role
Southern California Gas Company	Match funder, technical advisor
Core States Group	Construction management
Five Engineering & Plumbing	Mechanical contractor
Braaten Electric	Electrical contractor
Montrose Environmental	Emission monitoring

Source: Mainspring Energy

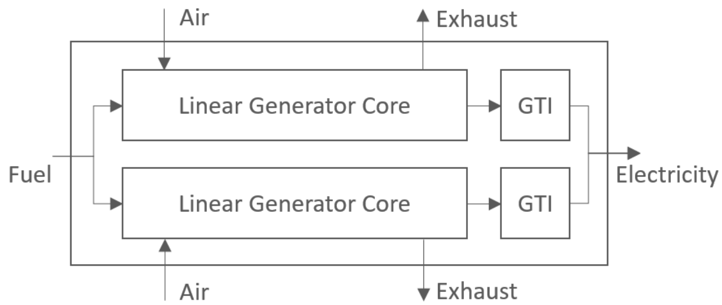
CHAPTER 2: Project Approach

Assembly and Factory Test

Design Overview

The Mainspring linear generator product is comprised of two linear generator "cores," with each core mechanically and electrically independent. The DC electricity produced by each core is converted into AC electricity through GTIs. Figure 4 shows a diagram of the product.

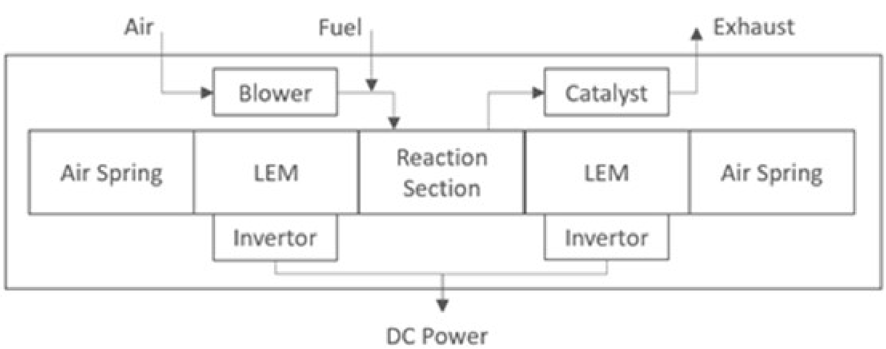
Figure 4: Mainspring's Linear Generator Product



Source: Mainspring Energy

Each core is comprised of a center reaction section, two outer linear electromagnetic machines (LEMs), two outer air springs, a support structure, an air blower, a fuel supply valve, an exhaust system that includes an oxidation catalyst, and inverters to produce DC electricity. Figure 5 shows a diagram of a linear generator core.

Figure 5: Linear Generator Core



Source: Mainspring Energy

System Assembly

A product is assembled by first building a linear generator core. Figure 6 shows two cores at various stages of production, Figure 7 shows a core near the final stage of production, prior to the attachment of auxiliary equipment, and Figure 8 shows two fully built cores. Following the completion of a core build, each core is inspected and tested for build quality, safety, and performance.

Figure 6: Two Cores in Different Stages of Production

Source: Mainspring Energy

Figure 7: A Core Near Completion

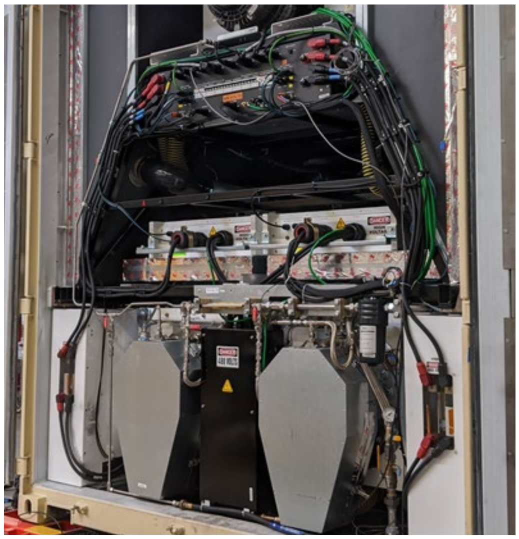
Source: Mainspring Energy

Figure 8: Two Cores with Auxiliaries

Source: Mainspring Energy

In parallel with core builds, the package with auxiliary electrical and cooling equipment is manufactured. Once the cores and the package have been quality and safety tested, the cores are inserted into the package. Figure 9 shows the cores inserted into the package with other electrical auxiliary equipment, and Figure 10 shows a fully packaged unit outside of Mainspring's manufacturing facility.

Figure 9: Package with Cores Inserted into the Package



Source: Mainspring Energy

Figure 10: A Fully Packaged Product

Source: Mainspring Energy

Demonstration Installation and Commissioning

Construction and Installation Process

Prerequisite permits and agreements included a building permit and an electrical interconnection from the City of Colton, a gas interconnection from the Southern California

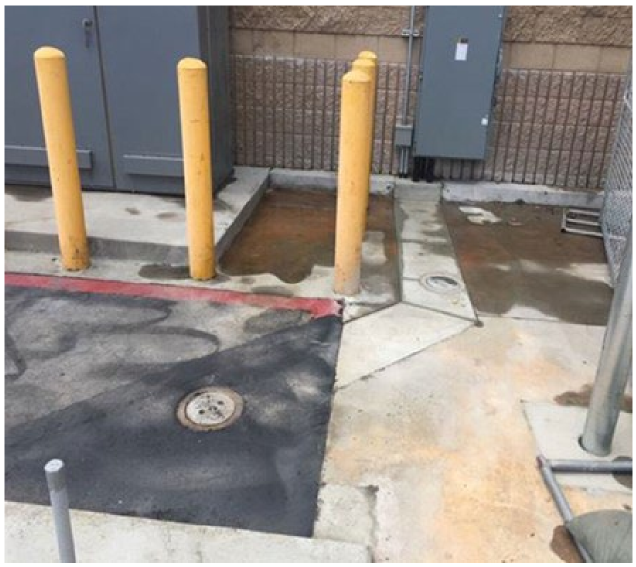
Gas Company, and a permit to construct from the South Coast Air Quality Management District.

The site preparation required three key elements:

1. Trenching and backfilling for electrical conduit and wiring.
2. Trenching and backfilling for gas piping.
3. Pouring a concrete pad for the product.

Figure 11 shows the electrical upgrades, Figure 12 shows the gas service upgrades, and Figure 13 shows the concrete pad with gas and electrical stub-ups.

Figure 11: Site Electrical Upgrades



Source: Mainspring Energy

Figure 12: Site Gas Service Upgrades

Source: Mainspring Energy

Figure 13: Concrete Pad for the Product

Source: Mainspring Energy

The product was shipped from Mainspring's research and development (R&D) and manufacturing facility in Menlo Park, California, and was installed at the customer's site the next day. Figure 14 shows the product on the flatbed truck at Mainspring's facility. Figure 15 shows the product installed at the site without the intake and exhaust acoustic and aesthetic panels, and Figure 16 shows the product installed at the site with all panels.

Figure 14: Loading Product on Truck for Shipment

Source: Mainspring Energy

Figure 15: Product Installed at Customer Site Without All Panels

Source: Mainspring Energy

Figure 16: Product Installed at Customer Site With All Panels

Source: Mainspring Energy

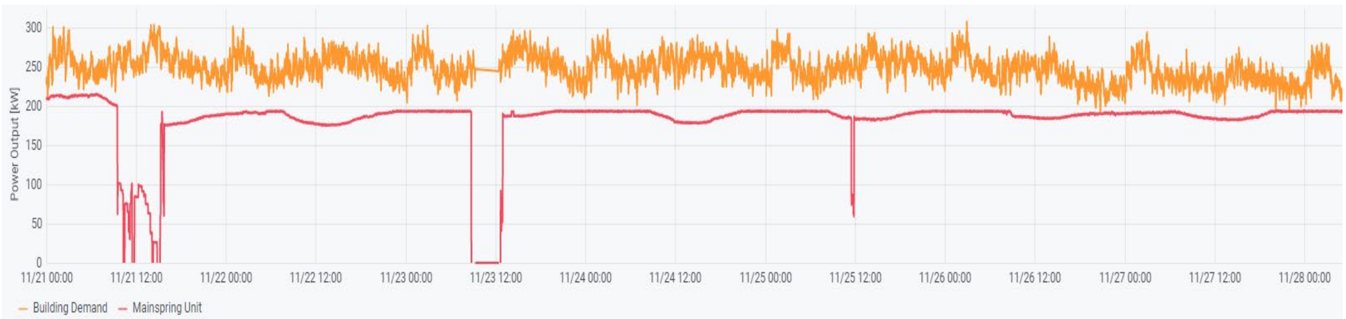
Commissioning

The product was first commissioned on November 21, 2020. Figure 17 shows continuous measurements of the building load (orange) and the linear generator output (red) during the first seven days of commissioning.[1] The commissioning process went smoothly; there were

[1] The building load was calculated by summing the power outputs from the linear generator and power consumption from the grid, both measured using utility-grade power meters.

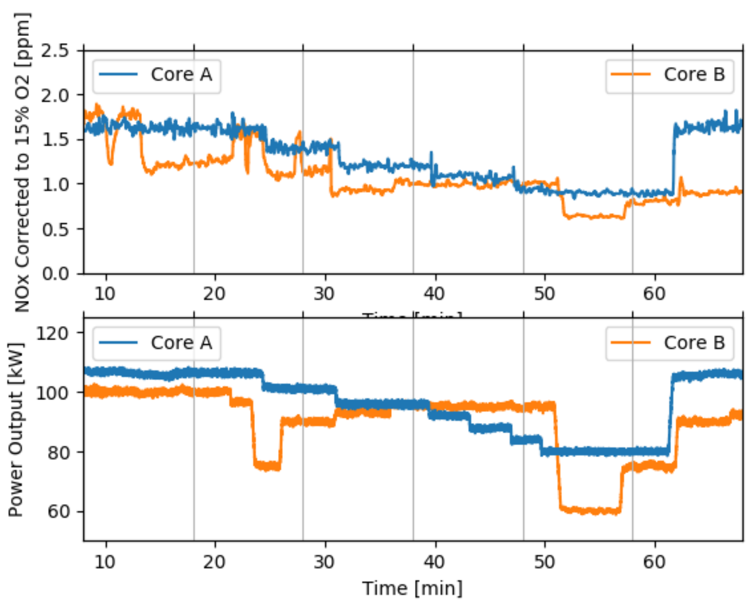
only a few minor software issues, and these were resolved by Mainspring. Following commissioning, Mainspring performed emissions tests using portable continuous emissions monitoring equipment to validate low-NOx performance, and the positive results are shown in Figure 18.

Figure 17: Building Load (Orange) and Power Output (Red) During Seven Days of Commissioning



Source: Mainspring Energy

Figure 18: NOx and Power Output During Emissions Testing

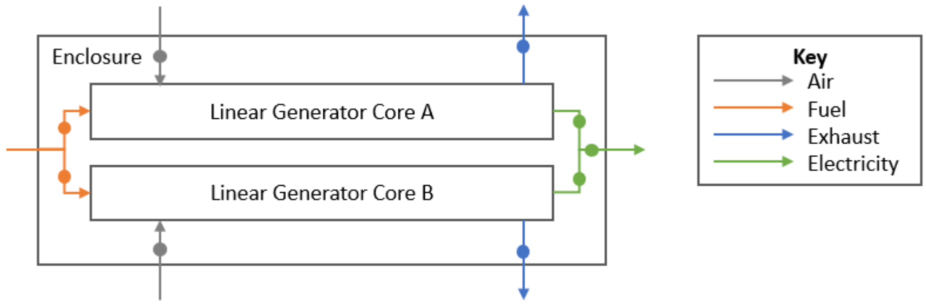


Source: Mainspring Energy

Performance Monitoring

The linear generator product is comprised of two linear generator cores, which are electrically and mechanically independent. A simplified schematic of the product delineating the cores is shown in Figure 19, with all measurement points being denoted by dots in the diagram. The intake air and fuel for each core are measured using equipment developed in-house and the power output is measured using a third-party, utility-grade output meter. The exhaust composition and flow are measured for each core during emissions testing.

Figure 19: Instrumentation Schematic



Source: Mainspring Energy

The data acquisition system was designed by Mainspring and embedded in the control module for the two cores; it communicates via the cloud to Mainspring headquarters. All data is averaged, summed, or calculated for each 15-minute interval. The data is downloadable from the cloud for monitoring and reporting. An operational log is maintained to track scheduled and unscheduled outages.

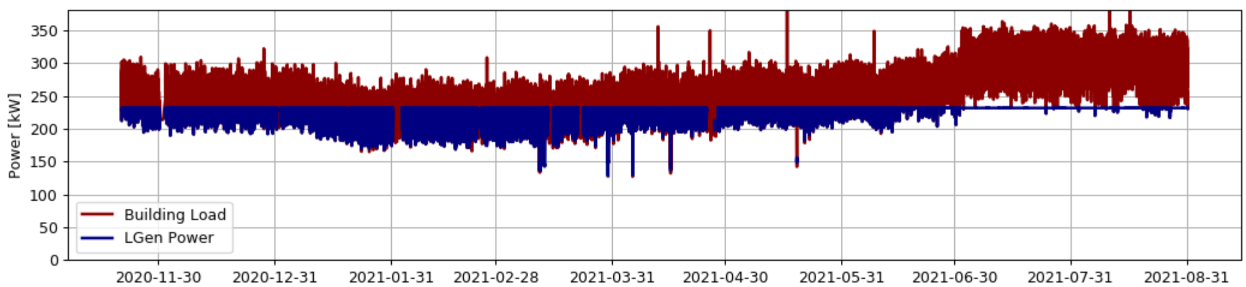
The performance of the unit was continuously monitored for more than nine months, from the commercial operation date in late November 2020 through August 2021. Down-time for system upgrades, grid events, and maintenance was minimal during the monitoring period. Power output, efficiency, and emissions levels met targets and are on path to reaching mature product targets. Performance monitoring results are provided in Chapter 3.

CHAPTER 3: Project Results

Performance Summary

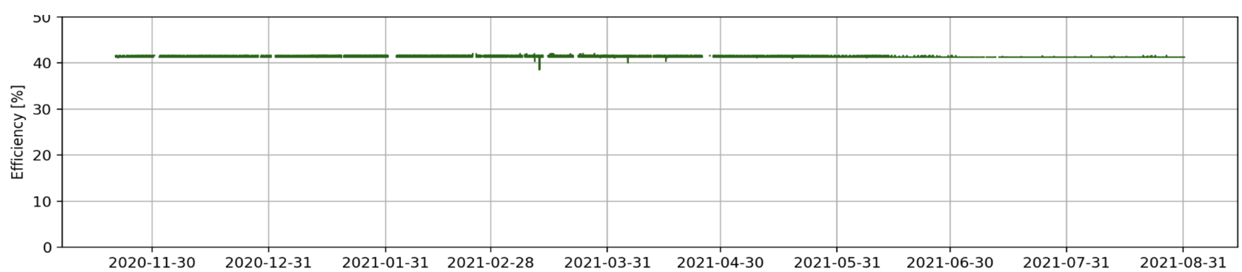
The project was installed on November 21, 2020, and, as part of the project, the performance of the unit was monitored for more than nine months, through August 2021. Figure 20 shows the unit's net-AC power output and the building's load, in kW, over the course of the project. As shown, the building's load varies from 130 kW up to 370 kW and the unit varies its output to track building load when the load is below 230 kW (the maximum output of the unit), as the interconnect agreement prohibits export back to the grid. Figure 21 shows the unit's net-AC efficiency during the project. The efficiency of the unit is relatively constant, slightly above 41 percent, and reduces slightly when power is below 150 kW. Blank spaces in the data correspond to downtime for system upgrades, grid events, or maintenance.

Figure 20: Linear Generator Net-AC Power Output and Building Load



Source: Mainspring Energy

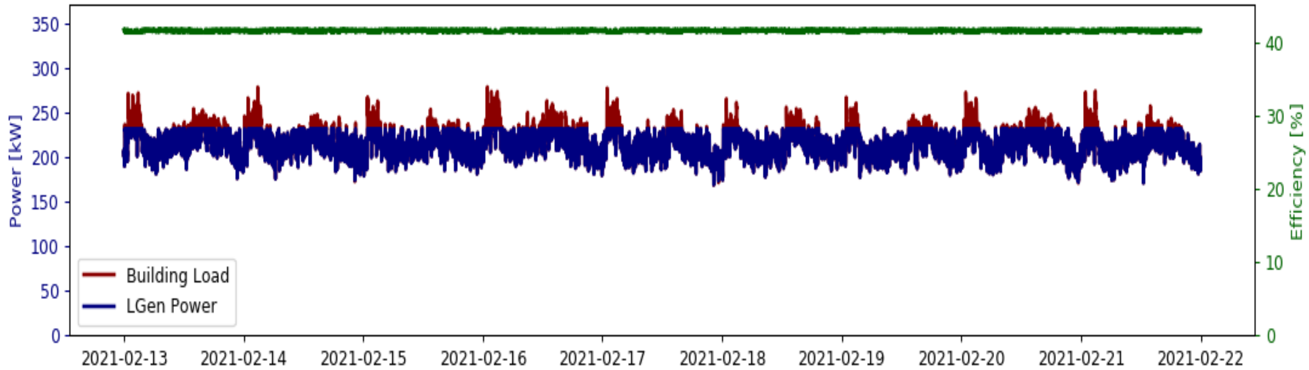
Figure 21: Linear Generator Net-AC Efficiency



Source: Mainspring Energy

Figure 22 shows the unit's net-AC power and efficiency, along with building load, over a 10-day period in February 2021. The unit varies its power output to match building load, and the efficiency is relatively constant over this 10-day period. The net-AC power and efficiency results shown in Figures 20–22 is corrected to the product's rated ambient conditions of 15°C (59°F) and 1 atmosphere of pressure.

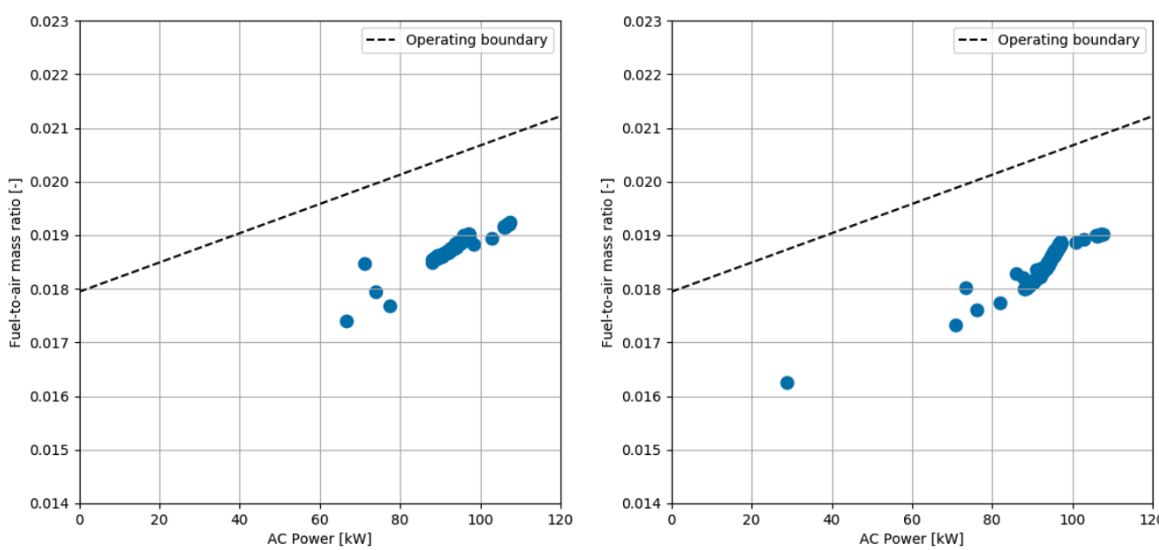
Figure 22: Linear Generator Net-AC Power, Efficiency, and Building Load



Source: Mainspring Energy

As part of the air permit agreement with the South Coast Air Quality Management District, Mainspring parametrically monitored the unit and provided monthly reports to the district to demonstrate compliance with its stringent NOx emissions permit limit. The parametric map is based on net-AC power and fuel-to-air ratio, both per linear generator core. For a given net-AC power and fuel-to-air ratio, Mainspring estimates, based on in-house parametric mapping, the expected NOx emissions. Figure 23 shows the output of this parametric monitoring sent to the district for a given month. Each dot in the plots represents an hour-averaged NOx emissions estimate, and the dashed line represents the operating boundary defined based on the NOx emissions permit limit.[2] The left and right plots correspond to linear generator cores A and B, respectively, within the unit, since each core is permitted separately. As shown in the plots, both linear generator cores operated below the operating boundary for the month.

Figure 23: NOx Emissions Estimates Over a Month



Source: Mainspring Energy

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[2] Equivalent to the CARB DG Certification Standard.

In addition to the monthly parametric monitoring, Mainspring was required to perform a third-party source test for NOx, carbon monoxide (CO), and volatile organic compounds (VOC) within 60 days of installation. Table 2 summarizes the permit limits and results of the source test, both reported as parts per million volumetric dry (ppmvd) corrected to 15 percent O2. As shown, the unit's emissions results were below the permit limits.

Table 2: Source Test Results Summary

Emissions	Permit Limit (ppmvd)	Source Test Result (ppmvd)	Result
NOx	2.5	1.6	Pass
CO	12	0.8	Pass
VOC	25	8.4	Pass

Source: Mainspring Energy

CHAPTER 4: Technology/Knowledge/Market Transfer Activities

Knowledge Transfer

The linear generator technology and its performance attributes have been communicated to a host of participants in the energy sector, including investors, government, utilities, developers, and end users (see Chapter 4 for details). A listing of recent (2021) publicly available publications is shown in Table 3. Links to the publications and other background information are on the Mainspring Energy website ("News and Perspectives," n.d.)

Table 3: 2021 Publications

Publication	Publication Status	Title	Author(s)
Power Engineering Trade Journal Article	Published June 21, 2021	Greening the Microgrid: Moving beyond backup with cleaner sources of firm energy	Arne Olson and Adam Simpson
Bloomberg Green Trade Journal Article	Published March 9, 2021	NextEra Bets on New Power Generator that Runs Without Combustion	David Baker
Energy & Environmental Economics Case Study	Published March 2021	The Role of Firming Generation in Microgrids	Zach Ming, Sumin Wang and Chen Zhang
Guidehouse Insights White Paper	Published 2021	Introducing Linear Generators to the Rapidly Evolving DER Landscape	Peter Asmus and Ricardo Rodriquez
Mainspring Energy White Paper	Published March 2021	Reaction Terminology and the Challenges for Energy and Environmental Policy	Mainspring Energy, Inc.

Source: Mainspring Energy

Competitive Landscape

Mainspring's linear generator is a new category of DG that is distinct from fuel cells, engines, and turbines. Table 4 illustrates how Mainspring's linear generator compares to other types of distributed generation technologies. As shown in the table, Mainspring's linear generator combines the high efficiency and low emissions of fuel cells with the dispatchability of engines and turbines, while also having the lowest cost of electricity.

Table 4: Comparison of Linear Generator with Competing DG Options[3]

	Engines	Microturbines	Fuel Cells	Linear Generators
Low Cost				✓
High Efficiency			✓	✓
Low Emissions			✓	✓
Dispatchable	✓	✓		✓
Fuel-Flexible				✓

Source: Mainspring Energy

The linear generator is made from standard materials with only two moving parts and operates without using oil or expensive fuel cell catalysts or complex engine mechanical systems — resulting in low capital and maintenance costs. Based on costs for low-scale manufacturing, equipment costs are expected to be less than $2,500 per kW, based on planned improvements for medium-scale production. Early operational results also indicate the ability to achieve maintenance costs of less than $0.007 per kWh with a scaled installation base. Lower costs are possible with higher-volume production and a larger installation base. Furthermore, early modeling indicates that units configured for combined-heat-and-power applications can achieve greater than 80 percent overall thermal efficiency.

Planned Design Improvements

The demonstration unit is one of Mainspring's initial commercial units. Ongoing product enhancements are underway for future generation products. Key performance metrics for this CEC project (a first "beta" shipment) relative to product targets are shown in Table 5.

Table 5: Linear Generator Performance Metrics

Metric	Beta Units	Scaled Product
Electric Output (net AC)	230 kW	250 kW
Electric Efficiency (net AC)	41.5%	> 45%
NOx Emissions	< 0.07 lb/MWh	< 0.07 lb/MWh
Power Output Range	0-100%	0-100%

Source: Mainspring Energy

Mainspring has developed and launched a flexible linear generator product. Several product options and configurations are planned, such as a combined heat-and-power product and a larger product targeted for industrial and utility applications.

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[3] A 'low cost of electricity' is defined as a levelized cost of electricity of less than 10 cents/kWh using a fuel cost of $5.50/MMBTU (metric million British thermal unit). 'High efficiency' is defined as electric-only efficiency of greater than 40 percent. 'Low emissions' is defined as electric-only emissions of nitrous oxides of less than 0.07 lb/MWh. 'Dispatchable' is defined as fast on/off and full load tracking. 'Fuel-flexible' is defined as the ability to operate on natural gas, biogas, or hydrogen without hardware or performance changes.

Addressable Market

The serviceable addressable market (SAM) for linear generators, according to a recent *Guidehouse Insights* white paper, is 5.5 GW per year in the U.S. and 14.3 GW per year non-U.S. (Asmus and Rodriquez, 2021). This SAM is divided into three market segments: commercial and industrial BTM, grid side, and microgrids. Table 6 shows the SAM breakdown across these segments. The California addressable market is estimated at 16 percent of the U.S. market.

Table 6: Linear Generator Serviceable Addressable Market

Market	U.S./non-U.S.
Commercial & Industrial BTM	1.4 / 7.0 GW per year
Grid Side	3.4 / 6.4 GW per year
Microgrids	0.7 / 0.9 GW per year
Total	**5.5 / 14.3 GW per year**

Source: Mainspring Energy

Product Deployment Strategy

The product will be deployed via direct sales and developers using a phased approached across the U.S. and internationally. Mainspring has identified a handful of states and utilities to start deployment (California included), with a plan for expansion as costs and prices reduce with production capacity. Early-entry market customers are national and multinational corporations with sustainability practices that include innovative, cutting-edge approaches and technologies. Mainspring began shipping pilot units to multiple Fortune 500 customers in the second half of 2020 and planned to launch commercial product shipments in 2022.

Mainspring recently announced a partnership with NextEra Energy Resources for project financing and direct purchases (Shieber, 2021). This partnership will enable Mainspring to offer financing to customers and accelerate market adoption.

Technology/Knowledge Transfer Activities

Mainspring has devoted a lot of time to educating various legislators and State agencies — including the California Public Utilities Commission (CPUC), CARB, and the CEC — about its new category of distributed generation technology.

Government Advocacy

- Mainspring has received ongoing support from the CEC to test, demonstrate, and report on early versions of the linear generator at Mainspring’s factory and at a commercial site.
- Mainspring has been actively interacting in California with the legislature, the Governor’s office, the CPUC, CARB, the CEC, and select air districts.

- Mainspring has been a member of several leading California associations to help drive clean fuels and technology neutral policies. Such associations include the Silicon Valley Leadership Group, the California Manufacturers and Technology Association, the Bioenergy Association of California, and the California Hydrogen Business Council.
- Mainspring has also been active at the federal level with Congress, the Environmental Protection Agency (EPA), and the Department of Energy (DOE).

Utility Cooperation

Mainspring has received support from the Southern California Gas Company to test and demonstrate early versions of the linear generator at Mainspring's factory and at one of its commercial sites. Mainspring has also gained eligibility for the CPUC's self-generation incentive program (SGIP) for onsite and directed biogas projects.

Publications and Presentations

A list of recent public presentations and publications is provided on Mainspring Energy's website: https://www.mainspringenergy.com/news/.

Intellectual Property

Mainspring's intellectual property is well-protected, with a strong portfolio of issued and pending U.S. and international patents, along with dozens of pending patent applications. To date, Mainspring has more than 45 issued U.S. patents and 20 issued international patents, with more than 75 pending patents globally.

Production Readiness

During the commercial introduction phase, assembly will be performed by Mainspring employees at its existing California facility. Mainspring is currently evaluating future production options with global Tier I manufacturing partners. Production does not require investments in expensive, volume-sensitive manufacturing processes, and this enables modest unit production costs, even for low-volume fabrication and assembly lots. 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.

CHAPTER 5: Conclusions and Recommendations

Conclusions

There currently exists a market potential for linear generators of 5.5 GW/year in the U.S., with approximately 20 percent of that potential (1.1 GW/year) in California. With its high efficiency, ultra-low emissions, dispatchability, fuel flexibility, and low costs, Mainspring's linear generator technology offers commercial and light-industrial businesses an onsite electricity solution that delivers cost savings compared to the grid, adds resiliency, and lowers emissions.

With funding from the CEC and the Southern California Gas Company, Mainspring successfully installed, interconnected, operated, and monitored the world's first linear generator for onsite electricity at a commercial site. With the success of this project and the performance knowledge gained, Mainspring has a commercialization road map.

The company has put in place a business plan that includes technology improvements, private capital commitments, manufacturing and assembly expansion plans, and ongoing sales efforts with multi-installation companies throughout the U.S. Efforts will include ongoing government advocacy and outreach to commercial and industrial associations. California has been a prime market target from the beginning and will continue to be a focus for the foreseeable future.

Recommendations

It is difficult to bring a new technology to market, and it is even more difficult to bring a technology to market that does not fit into existing regulatory categories. It is important for federal and state policies to be technology neutral and outcome-based rather than technology specific. Setting clear objectives and letting the market develop solutions that meet those objectives is the best way to spur innovation. Mainspring's multi-year development and testing process has highlighted and remedied many near-term improvements and has identified technology paths for longer-term upgrades.

CHAPTER 6: Benefits to Ratepayers

Business Growth

Based on the *Guidehouse Insights* white paper, "Introducing Linear Generators to the Rapidly Evolving DER Landscape," the compelling advantages of linear generators over competing DG technologies position linear generators, along with energy storage, to complement the vast solar photovoltaic and wind future market share (Asmus and Rodriquez, 2021). According to *Guidehouse Insights*, the SAM for linear generators is 5.5 GW/year in the U.S. and 15 GW/year globally. Mainspring estimates the California SAM at 20 percent of the U.S. market SAM and projects rapid business growth through 2030 toward its share of the SAM.

Jobs

Jobs related to the development, scaling, and installation of linear generators will be substantial and will entail sales and marketing, financing, manufacturing and assembly, distribution and installation, service and product support, and business administration. Many of these jobs will be filled by Mainspring employees and others will be outsourced to partners and suppliers. The projected full-time equivalent of in-house and outsourced employees in 2030 is 2,500 or greater, of which approximately 30 percent or more will reside in California.

Cost of Energy

The cost of electricity from a linear generator includes capital, fuel, and operations and maintenance Offsetting value-added elements include resiliency, flexibility, and incentives. The cost can vary depending on several parameters, including fuel cost, annual operating hours, installation, and available incentives. Typically, the cost of generated electricity from a linear generator will vary from $0.09/kWh to $0.12/kWh. This compares favorably with a California average price of $0.18/kWh (EIA, 2021). Low-cost electricity provides cost savings to the customer and reduces overall demand on the electric grid, which decreases the need for centralized generation and its associated transmission and distribution costs and losses.

Environmental

The linear generator uses a low-temperature reaction of air and fuel that results in ultra-low NOx formation with negligible degradation over time. Demonstrated NOx levels through this project of 1.6 ppm are well below CARB DG certification requirements and the South Coast Air Quality Management District requirement of 0.07 lb/MWh (2.5 ppm), which are the most stringent in the country. Emissions performance was verified by third-party source test measurements.

Reliability and Resilience

Mainspring's linear generator technology improves the reliability of both individual buildings and the grid. For commercial buildings, Mainspring's product offers black start capability with fast on/off and load tracking — eliminating the need for onsite standby generation such as diesel gensets. For grid-side applications, Mainspring's products can displace diesel generators during public safety power shutoff events — as recently piloted with Pacific Gas and Electric Company (Business Wire, 2021). In addition, by adjusting operations to be fuel-flexible, Mainspring's linear generator can dynamically switch to zero-carbon fuels such as biogas, green hydrogen, and green ammonia. Being fuel-flexible can be helpful for resiliency, as this ensures a more reliable energy supply.

Disadvantaged Communities

Linear generators are well-suited for disadvantaged communities, many of which are in grid congested or fire prone areas, where the economic, flexibility, and resilience attributes will be recognized and valued. This technology has ultra-low emissions, which can provide cleaner air.

GLOSSARY AND LIST OF ACRONYMS

Term	Definition
AC	Alternating current
BTM	Behind-the-meter
CARB	California Air Resources Board
CEC	California Energy Commission
CO	Carbon monoxide
CPUC	California Public Utility Commission
DC	Direct current
DER	Distributed energy resources
DG	Distributed generation
DOE	Department of Energy
EPA	Environmental Protection Agency
FTM	Front-of-the-meter
GTI	Grid-tie inverter
GW	Gigawatt
kW	Kilowatt
kWh	Kilowatt-hour
lb	Pound
LEM	Linear electromagnetic machine
LG	Linear generator
MWh	Megawatt-hour
NOx	Nitrogen oxides
ppm	Parts per million
ppmvd	Parts per million by volume dry
R&D	Research and development
SA	Supplemental amendment
SAM	Serviceable addressable market
SGIP	Self-generation incentive program
UL	Underwriters Laboratories
US	United States
VOC	Volatile organic compounds

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