



**CALIFORNIA
ENERGY COMMISSION**



California Energy Commission

STAFF REPORT

Natural Gas Research and Development Program

2018 Annual Report

**Edmund G. Brown Jr., Governor
October 2018 | CEC-500-2019-026**

California Energy Commission

James Friedrich

Molly O'Hagan

Primary Authors

Tiffany Solorio, Lead

Nicole Smith Dani

Project Managers

Erik Stokes

Office Manager

ENERGY DEPLOYMENT AND MARKET FACILITATION OFFICE

Laurie ten Hope

Deputy Director

ENERGY RESEARCH AND DEVELOPMENT DIVISION

Drew Bohan

Executive Director

DISCLAIMER

Staff members of the California Energy Commission prepared this report. As such, it does not necessarily represent the views of the Energy Commission, its employees, or the State of California. The Energy Commission, the State of California, its employees, contractors and subcontractors make no warrant, express or implied, and assume no legal liability for the information in this report; nor does any party represent that the uses of this information will not infringe upon privately owned rights. This report has not been approved or disapproved by the Energy Commission nor has the Commission passed upon the accuracy or adequacy of the information in this report.

ACKNOWLEDGEMENTS

The authors appreciate the contributions from these Energy Research and Development Division staff members:

Rizaldo Aldas

Peter Chen

David Erne

Amir Ehyai

Guido Franco

Chuck Gentry

Rey Gonzalez

Yu Hou

Bradley Meister

Kevin Mori

Kevin Uy

Susan Wilhelm

Yahui Yang

PREFACE

The California Energy Commission's 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 RD&D entities, including individuals, businesses, utilities and public and private research institutions. This program promotes greater natural 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.

The *Natural Gas Research and Development Program 2018 Annual Report* is a staff report prepared by the Energy Commission's Energy Research and Development Division.

For more information about the Energy Research and Development Division, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-327-1551.

ABSTRACT

In 2000, Assembly Bill 1002 (Wright, Chapter 932, Statutes of 2000) was enacted, requiring the California Public Utilities Commission (CPUC) to impose a surcharge on natural gas consumed in California. These monies funded various energy efficiency programs and public interest research and development to benefit natural gas ratepayers. AB 1002 also required the CPUC to designate an entity to administer the research component of AB 1002. In 2004, the CPUC issued Decision 04-08-010, designating the California Energy Commission as the research fund administrator.

The *Natural Gas Research and Development Program 2018 Annual Report* highlights project successes and benefits, and covers results of completed projects and the progress of current research from July 1, 2017, through June 30, 2018. In fiscal year 2017-2018, the California Energy Commission administered \$24 million in natural gas research, development, and demonstration projects geared toward improving energy efficiency, renewable energy, advanced generation, and energy infrastructure for natural gas in California.

Keywords: California Energy Commission, California Public Utilities Commission, natural gas, energy efficiency, pipeline safety, climate change, drought, buildings end-use energy efficiency, industrial, agriculture and water efficiency, renewable energy and advanced generation, energy infrastructure, natural gas pipeline integrity, energy-related environmental research, natural gas-related transportation

Please use the following citation for this report:

Friedrich, James, Molly O'Hagan. 2018. Energy Research and Development Division.
2018. Natural Gas Research and Development Program 2018 Annual Report.
California Energy Commission. Publication Number: CEC-500-2019-026.

TABLE OF CONTENTS

	Page
ACKNOWLEDGEMENTS.....	i
PREFACE	ii
ABSTRACT	iii
EXECUTIVE SUMMARY	1
Internet of Things and Data Science.....	1
Solar Thermal	1
Bioenergy	2
Combined Heat and Power.....	2
Medium- and Heavy-Duty Natural Gas Vehicles	3
Advanced Materials and Manufacturing.....	4
CHAPTER 1: Introduction	5
Reduce Vulnerabilities and Fugitive Methane Emissions in the Natural Gas Infrastructure.....	7
Drive Large-Scale Customer Adoption of Energy Efficient and Low-Carbon Technology Solutions for Natural Gas End-Uses	7
Improve the Cost-Competitiveness of Renewable Gas	7
Minimize Air Quality Impacts from Natural Gas Use to Zero or Near-Zero Levels.....	8
Energy Commission Research and Development Strategy for Natural Gas	8
Internet of Things and Data Science.....	9
Solar Thermal	10
Bioenergy	11
Combined Heat and Power	11
Medium- and Heavy-Duty Natural Gas Vehicles	12
Advanced Materials and Manufacturing	12
The Natural Gas Research Program	13
Energy Commission Administration	14
Bringing Different Perspectives Into R&D	15
Advancing Legislative Priority for Clean Energy Equity	15
Expanding Natural Gas Research	16

CHAPTER 2: Project Highlights.....	17
Reduce Vulnerabilities and Fugitive Methane Emissions in the Natural Gas Infrastructure.....	17
Providing a Foundation for Effectively Reducing Methane Emissions	17
Operationalizing Climate Science Into Energy Planning Decisions.....	19
Addressing Vulnerabilities in the Natural Gas Infrastructure.....	20
High Accuracy Mapping for Excavation Damage Prevention and Emergency Response.....	22
Drive Large-Scale Customer Adoption of Energy Efficient and Low-Carbon Technology Solutions for Natural Gas End-Uses	24
Bringing New Clean Energy Technology Solutions to Affordable Housing.....	24
Increasing Energy Efficiency of Manufactured Homes	26
Success in New Homes Provide Insight for Hot Water Piping Improvements in Existing Homes	28
Driving Down Solar Water Heating System Costs.....	29
Developing Scalable Technology Solutions for Food Production	32
Targeting Natural Gas Savings in Food Service	34
Improving the Cost-Competitiveness of Renewable Gas.....	36
Demonstrating New, Economical Applications for Biogas Recovery.....	37
Reducing the Cost of Biogas Clean-up and Upgrading	39
Minimizing Air Quality Impacts From Natural Gas Use to Zero or Near-Zero Levels ...	41
Reducing Installation Costs for Combined Heat and Power in Commercial Buildings	44
LIST OF Acronyms	46
APPENDICES:	A-1

LIST OF FIGURES

	Page
Figure 1: Measurement Setup at a Sample Houses.....	18
Figure 2: Global Positioning System Device on Excavator and Utility Monitoring Dashboard.....	21
Figure 3: High Accuracy Mapping System – Hardware and Software Interface	23

Figure 4: AeroBarrier Sealant for Building Envelopes	25
Figure 5: Manufactured Home Project	28
Figure 6: Schematics of Two Designs for Solar Thermal Collectors: Flat-Plate Round Tube Solar Thermal Collectors and Solar Thermal Collector Designed With Mini-Channels	31
Figure 7: Cooling Towers Above the Absorption Chiller at the Gallo Cattle Company Cheese Production Facility in Atwater, California	34
Figure 8: Combination Oven Testing at the Foodservice Technology Lab	35
Figure 9: Las Gallinas Valley Biogas Energy Recovery System in San Rafael, California	38
Figure 10: Pilot-Scale Landfill Gas Cleanup Subsystems	40

LIST OF TABLES

	Page
Table ES-1: Technology Categories That Support the Strategic Objectives for Natural Gas Investments	1
Table 1: Technology Categories that Support the Strategic Objectives for Natural Gas Investments	9
Table 2: Advanced Absorption Chiller Versus Other Refrigeration Options	33
Table 3: Tecogen System Compared With Higher Cost CHP Options	45

EXECUTIVE SUMMARY

Recent state policies, including Senate Bill 100 (De Leon, 2018) and Governor Edmund G. Brown Jr.'s Executive Order B-55-18, have put California on a path to completely decarbonize its energy sector by 2045. Under Senate Bill 100, the electricity sector is expected to play a major role in achieving the state's greenhouse gas reduction goals by supplying electricity generation that is 100 percent or near 100 percent renewable. Complementing the supply-side strategy, the state has charted a path towards additional deep greenhouse gas reductions by first electrifying end-uses that can most easily and cost-effectively electrify. While the path is well-paved for new residential construction and programs and incentives are in place to electrify single occupancy transportation such as light-duty vehicles, more must be done to electrify the industrial sector. Research and development (R&D) to enable increased electrification is being conducted under the California Energy Commission's Electric Program Investment Charge (EPIC). However, significant built infrastructure currently depends on natural gas and a transition strategy is still forming. In the meantime, meaningful greenhouse gas reductions can be made in natural gas use through energy efficiency. Other strategies to decarbonize traditional uses of natural gas include solar thermal for heating, technologies to capture and use biogas, and reduction of methane leaks from gas infrastructure. Meanwhile, the development of renewable gas use as an alternative to diesel in the medium- and heavy-duty vehicle sectors is an important strategy for lowering emissions and improving air quality.

California's residential and commercial sectors rely on natural gas for three key end uses: cooking, space heating, and water heating. While electric options exist for these end uses, current commercial offerings do not meet most consumers' demands for cost and performance. For California's industrial sectors such as the food processing sector, the high thermal requirements of many industrial processes make them difficult to electrify. For the transportation sector, battery electric vehicles are poised to dominate the light-duty vehicle sector and even segments of the medium-duty vehicle market. However, battery electric vehicles are unlikely to be a viable option for most medium- and heavy-duty vehicle applications for a while until improvements to the energy density and weight of batteries occur.

The natural gas sector can fill important gaps in areas where electrification will be challenging to achieve. However, there are numerous challenges that must be addressed if the natural gas sector is to fulfill this role in California's future energy mix. The California Energy Commission's Natural Gas Research and Development program is designed to accelerate technology advancement and adoption that will better enable the natural gas sector to support California's energy and environmental policy goals. These technology advancements support the following strategic objectives:

- Reduce vulnerabilities and fugitive methane emissions in the natural gas infrastructure.

- Drive large-scale customer adoption of energy efficient and low-carbon technology solutions for natural gas end-uses that will be challenging to electrify.
- Improve the cost-competitiveness of renewable gas.
- Minimize air quality impacts from natural gas end-uses to zero or near-zero levels.

The Energy Commission's strategy for Natural Gas research and development is organized by the six technology categories that are used in concert with one another to support the four strategic objectives. Table ES-1 illustrates how each technology category supports these objectives.

Table ES-1: Technology Categories That Support the Strategic Objectives for Natural Gas Investments

Strategic Objectives	Technology Categories					
	Internet of Things and Data Science	Solar Thermal	Bio-energy	Medium- and Heavy-Duty Natural Gas Vehicles	Combined Heat and Power	Advanced Materials and Manufacturing
Reduce Vulnerabilities and Fugitive Methane Emissions in the Natural Gas Infrastructure	✓	✓	✓			✓
Drive Large-Scale Customer Adoption of Energy Efficient and Low-Carbon Technology Solutions for Natural Gas End-Uses		✓	✓	✓	✓	✓
Improve the Cost-Competitiveness of Renewable Gas			✓	✓	✓	

Strategic Objectives	Technology Categories					
	Internet of Things and Data Science	Solar Thermal	Bio-energy	Medium- and Heavy-Duty Natural Gas Vehicles	Combined Heat and Power	Advanced Materials and Manufacturing
Minimize Air Quality Impacts from Natural Gas Use to Zero or Near-Zero Levels	✓			✓	✓	

Source: California Energy Commission staff, 2018

The following sections provide a high-level overview of each of these technology categories as well as example projects that are helping to advance the natural gas sector.

Internet of Things and Data Science

The Internet of Things – sensors and intelligent devices combined with advances in machine learning and software platforms – has broad applications for the natural gas sector. Internet of Things solutions for detection and monitoring – such as damage to natural gas pipelines caused by digging, grading, trenching, and boring – can be deployed cheaply and quickly compared to current practices that are labor- and capital-intensive.

In 2016, the Energy Commission awarded funding to the Gas Technology Institute to develop a platform solution that provides real-time visibility and notification to utilities and heavy-equipment operators when construction work is being conducted near natural gas pipelines. The Global Positioning System Excavation Encroachment Notification System integrates a small hardware unit installed on the excavation equipment with geospatial tools and custom-developed algorithms and machine learning capabilities that together provide a rich visual display on excavator status and location in relation to the natural gas pipelines. This unit provides excavator operators with better situational awareness regarding the location of underground pipelines so that they can better avoid accidents. It is anticipated that use of this technology by third-party contractors would result in a 43 percent reduction of nonfatal and noninjury excavation incidents that are caused by excavators, backhoes, and trenchers.

Solar Thermal

Solar thermal – using the thermal energy of the sun for heating applications - provides a potential low-carbon alternative to natural gas for numerous heating end-uses, particularly for hot water heating and process heating at dairies and industrial and manufacturing customers. However, the market for solar thermal technologies has seen limited growth, due in large part to the capital costs of solar thermal solutions compared to competing natural gas technologies. For example, solar water heaters can be six to eight times more expensive than conventional natural gas-fired water heaters. The solar collector is the biggest cost component of these systems, accounting for nearly 30 percent of the system cost.

The Energy Commission funded a project with University of California, Merced that developed aluminum mini-channel solar thermal collectors that use flat mini-channels or tiny tubes, as opposed to a conventional, copper flat-plate collector. The mini-channel technology increases the surface area exposed to sunlight for heat transfer, which improves the efficiency of the collector. In addition, aluminum is a significantly cheaper metal and easier than copper to extrude and form into mini-channels. The aluminum mini-channel solar thermal technology has the potential to lower the cost of solar

thermal water heating in single-family and multifamily homes by up to 30 percent while improving the efficiency of the solar collectors by 10 to 15 percent. The researchers estimate the cost of the aluminum mini-channel technology at scale could be about \$14 per square foot compared to \$51 per square foot for conventional solar collectors.

Bioenergy

Techniques such as anaerobic digestion and gasification can produce biofuels for generating energy and provide important alternatives to flaring methane. These techniques are most applicable in managing methane from agricultural and waste, such as dairies, wastewater treatment, landfills, forest timber, and municipal solid waste. Where economically feasible, biofuels may provide an option for decarbonizing natural gas supplies. However, biogas is not easily used in a raw or unprocessed state and must be converted into renewable gas to expand the potential for use. The clean-up and upgrading process of the gas costs between \$6-90 per million British thermal units (compared to retail natural gas costs of \$3-\$5 per million British thermal units) which limits the cost-competitiveness of renewable gas compared to the fossil fuel counterpart.

A technology developed by Mosaic Materials could lead to breakthrough cost reductions in the largest step in the cleanup and upgrading process – carbon dioxide removal. Conventional wet scrubbers use liquid solvents to remove pollutants like carbon dioxide, but require pumping and operate under high temperature and pressure regeneration conditions, increasing their energy intensity. The Mosaic Materials technology uses low-cost, solid adsorbent pellets instead of a liquid solvent, which eliminates pumping and can be regenerated under milder operating conditions. This technology reduces the energy costs of removing carbon dioxide from biogas by up to 40 percent.

During the project, the solid adsorbent pellets removed carbon dioxide to the purity required to meet pipeline-quality natural gas standards. Mosaic Materials proved the durability of the sorbent when exposed to raw biogas, and the ability of the material to absorb and desorb carbon dioxide over repeated cycles. Each of these tests validated the commercial viability of the technology. In addition, the team performed a cost analysis of its first-generation system, which showed a capital cost reduction of about 14 percent compared to conventional systems thanks to a simpler process and less equipment.

Combined Heat and Power

Combined heat and power using the waste heat from onsite generation offers several benefits, including a reduction in natural gas consumption and the associated greenhouse gas emissions. The market for combined heat and power has remained relatively flat. New opportunities exist that can further enable the market for combined heat and power, including using the waste heat for high-value chilling and filling market gaps for small and microscale systems. For example, absorption chillers, a system that

uses thermal energy, such as waste heat, as opposed to electricity to produce chilled water, offer a promising and potentially lower-cost alternative for cold storage at dairies and other food processing plants.

In 2016, the Gallo Cattle Company in Atwater (Merced County) was funded to demonstrate a new type of waste heat absorption chiller application for its cheese making factory. For this project, Gallo demonstrated an ammonia-based absorption chiller called the ThermoSorber™ that overcomes some of the key limitations of standard lithium-bromide absorption chillers, including the ability to cool to lower temperatures required by food processing customers. As part of this project, Maas Energy Works, a subcontractor to Gallo, designed an advanced heat recovery system capable of effectively recovering this low-grade waste heat and using it for high-value cooling. The system is capable of refrigeration output as low as -50°F to deliver chilled water, drive an ice maker or freezer, or be used for process cooling.

Medium- and Heavy-Duty Natural Gas Vehicles

The low cost of natural gas relative to diesel fuel is increasing adoption of natural gas medium- and heavy-duty vehicles. A National Petroleum Council study estimates that about 20 percent of Class 7 and Class 8 vehicles will be fueled by natural gas by 2025. However, there are gaps in natural gas engine product offerings that are optimized to the specific application and duty cycles of medium- and heavy-duty vehicle market segments. Transitioning the medium- and heavy-duty vehicle market to natural gas provides an opportunity, through more advanced engine designs, for significant reductions in oxides of nitrogen (NO_x) compared to the more incremental improvements anticipated in diesel engines.

The Energy Commission's natural gas research has been instrumental in spurring the development of medium- and heavy- duty natural gas vehicles. The Energy Commission funded the development of Cummins Westport Inc.'s "Near-Zero" natural gas engines to provide low-emission alternatives to diesel engines for the heavy-duty vehicle market to power transit buses, refuse haulers, vocational trucks, and goods movement trucks. With Public Interest Energy Research Natural Gas funding, Cummins Westport Inc. was able to certify a 9-liter and 12-liter variations of the Near-Zero engines that met the California Air Resources Board's most stringent Optional Low NO_x Standard.

Major fleets such as the United Postal Service and Waste Management demonstrated prototype engines throughout the development process, accumulating more than 1.8 million miles on 28 test units. These tests confirmed durability, reliability, and performance of the Near-Zero engines in real-world commercial fleet applications.

Cummins Westport Inc. produced 3,900 Near-Zero engines as of June 2018. Since the introduction of the Near-Zero engines into the market, several state and local clean transportation incentive programs have provided funding for fleets to accelerate adoption of these engines because of their low NO_x and greenhouse gas emissions compared to diesel engines. Based on analysis of data from Cummins Westport Inc. and

various California incentive programs, an estimated 642 Near-Zero engines have been used in California as of October 2018. This has resulted in nearly 900 tons of NO_x reductions over the lifetimes of the vehicles, as calculated using Argonne National Laboratory's Heavy-Duty Vehicle Emissions Calculator.

Advanced Materials and Manufacturing

Advancements in materials and manufacturing have the potential to provide multiple benefits to natural gas ratepayers. For example, materials advancements can enable more effective and economical approaches for sealing building envelopes and natural gas pipeline leaks.

In 2012, the Energy Commission awarded funding to the University of California, Davis Western Cooling Efficiency Center to further develop a portable automated process for sealing gaps and tightening the envelope of a building. The AeroBarrier system sprays a cloud of waterborne acrylic sealant droplets into a pressurized room. The pressure forces air to escape through leaks, and the sticky particles follow the air flow to the leaks, where the particles are flung from the airstream, coagulating around a leak until it is sealed. In real-world tests, a two-person team reduced the air leakage of a 2,200 square-foot, three-bedroom house by 68 percent in fewer than three hours compared to traditional sealing methods that require more than 20 hours of labor.

AeroBarrier licensed the technology from the University of California, Davis after five years of research and development supported by the Energy Commission's Public Interest Energy Research Program and the Department of Energy's Building America program and hit the commercial market in January 2018. During this period, AeroBarrier was tested in new and retrofit single family and multifamily homes, including homes built by Habitat for Humanity and retrofits to improve multifamily homes in disadvantaged communities. As of 2017, AeroBarrier has sealed more than 125,000 homes and more than 35 million square feet of commercial space. Most recently, AeroBarrier was used in new homes built by Beazer in Sacramento. The National Association of Homebuilders awarded AeroBarrier the 2018 Most Innovative Building Product and Best in Show in January 2018.

CHAPTER 1:

Introduction

Recent state policies, including Senate Bill (SB) 100 (De León, 2018) and Governor Edmund G. Brown Jr.'s Executive Order B-55-18, have put California on a path to completely decarbonize its energy sector by 2045.¹ Under SB 100, the electricity sector is expected to play a major role in achieving the state's greenhouse gas (GHG) reduction goals by supplying electricity generation that is 100 percent or near 100 percent renewable. Complementing the supply-side strategy, the state has charted a path towards additional deep GHG reductions by first electrifying end uses that can most easily and cost-effectively electrify. While the path is well paved for new home construction and programs and incentives are in place to electrify single occupancy vehicles, more must be done to electrify industrial processes. Research and development to enable increased electrification is being conducted under the Electric Program Investment Charge. However, significant built infrastructure now depends on natural gas and a transition strategy is still forming. In the meantime, large GHG reductions can be made in natural gas use through increased efficiency. Other strategies to decarbonize traditional uses of natural gas include solar thermal for heating, technologies to capture and use biogas, and reduction of methane leaks from gas infrastructure. Meanwhile, the development of renewable gas use as an alternative to diesel in the medium- and heavy-duty vehicle sectors is an important strategy for lowering emissions and improving air quality.

California's residential and commercial sectors rely on natural gas for three key end uses: cooking, space heating, and water heating. While electric options exist for these end uses, current commercial offerings do not meet most consumer demands for cost and performance. A recent Energy Commission-funded study by Energy + Environmental Economics (E3) examined the priority, near-term decarbonization strategies to achieve California's 2030 and 2050 GHG reduction goals. Electric heat pumps are a potential technology to electrify space and hot water heating in homes and businesses and a key strategy for meeting the state's 2030 and 2050 GHG reduction targets. Under E3's high electrification scenario, "new heat pump sales must represent no less than approximately 50 percent of new sales of heating, ventilation, and air

¹ For a complete list of recent legislation passed to reduce carbon emissions, see <https://www.gov.ca.gov/2018/09/13/aboard-hybrid-electric-ferry-on-the-san-francisco-bay-governor-brown-signs-bills-to-promote-zero-emission-vehicles-reduce-carbon-emissions/>

conditioning (HVAC) and water heating equipment by 2030.”² However, electric heat pumps have struggled to gain market traction in California, making the ability of these pumps to scale to 50 percent of new HVAC sales by 2030 a heavy lift.

The high thermal requirements of many industrial processes similarly make them difficult to electrify. Substantial material advancements are necessary to increase the conversion efficiency from electric to thermal energy. According to the E3 study, while likely to be “technically feasible for nearly all end uses,” industrial electrification is expected to be high cost because of the “relative inefficiency of using a high-quality final energy carrier such as electricity as a substitute for simple combustion to make heat.” So while emissions from the industrial sector make up a little more than one fifth of California’s GHG emissions, minimizing by electrification is not likely to be cost competitive without major breakthroughs.

For the transportation sector, battery electric vehicles are poised to dominate the light-duty vehicle sector and even segments of the medium-duty vehicle market. However, battery electric vehicles are unlikely to be a viable option for most medium- and heavy-duty vehicle applications without breakthroughs to the energy density and weight of batteries. The low-cost of natural gas relative to diesel fuel is driving adoption of natural gas medium- and heavy-duty vehicles. Yet hydrogen fuel cell trucks are “among the most expensive to purchase and operate,” due to the total fuel storage requirements, according to the E3 study. Even though batteries may be “cheaper than fuel cells per unit of power,” they tend to be more expensive than hydrogen per unit of energy. Therefore, key mitigation scenarios developed by E3 anticipate that by 2050 battery trucks can “displace no more than 50% of truck vehicle miles (those used for shorter-haul distances), while fuel-cell trucks are assumed to serve longer-haul heavy duty trucking. As a result, hydrogen fuel cell heavy-duty trucks are a key *reach technology* in this scenario.”

Even under the high electrification scenario, decarbonization will be needed in the natural gas sector. Deeper GHG reductions will be needed if the technology options to achieve the high electrification scenario do not reach scale. For the natural gas sector to support the state in meeting California’s multiple energy and environmental policy goals, the following challenges must be addressed:

² Mahone, Amber, Zachary Subin, Jenya Kahn-Lang, Douglas Allen, Vivian Li, Gerrit De Moor, Nancy Ryan, Snuller Price. 2018. Deep Decarbonization in a High Renewables Future: Updated Results from the California PATHWAYS Model. California Energy Commission. Publication Number: CEC-500-2018-012.

Reduce Vulnerabilities and Fugitive Methane Emissions in the Natural Gas Infrastructure

High-profile events such as the San Bruno pipeline explosion (2010)³ and Aliso Canyon gas storage facility leak (2015)⁴ demonstrated the vulnerabilities of the natural gas system, intensifying the need to research and improve its safety and integrity. Moreover, environmental events like the state's recent prolonged drought, extensive tree mortality, climate change related subsidence, and seawater rise have broadened the research necessary for the natural gas sector to be able to adapt to climate change and contribute to the state's GHG reduction goals.

Drive Large-Scale Customer Adoption of Energy Efficient and Low-Carbon Technology Solutions for Natural Gas End-Uses

To reach California's energy and climate change goals, energy efficiency is essential for all sectors. However, current technologies do not always meet acceptable payback periods necessary to drive large-scale market adoption of energy efficiency upgrades without policy changes. In addition, the invasive nature of some energy efficiency upgrades that require occupants to temporarily vacate, combined with high customer acquisition costs and low equipment turnover, create a limited window for when customers are receptive to installing energy efficiency upgrades. New technology advancements and strategies are critical to overcome these market barriers.

Improve the Cost-Competitiveness of Renewable Gas

Under E3's high electrification scenario, the largest remaining source of GHG emissions will be from non-combustion emissions, including methane from agriculture and from waste such as wastewater treatment, landfills, and municipal solid waste. Capturing and converting this methane for energy purposes will become a critical strategy for meeting the 2050 GHG emission reductions targets, both by reducing GHG emissions from non-combustion emissions and decarbonizing natural gas supplies. "[Renewable gas] does not face the same type of customer adoption and building retrofit challenges as a building electrification strategy." [E3 study] However, the cost of renewable gas from agriculture and waste is several times greater than traditional fossil fuel natural gas supplies.⁵

³ The explosion of a PG&E natural gas pipeline occurred on September 9, 2010 in San Bruno, California, a suburb of San Francisco, causing the death of eight people, destroying or damaging dozens of homes, neighborhood roads and infrastructure.

⁴ Natural gas escaping from a Southern California Gas Company's underground storage facility in the Santa Susana Mountains near Los Angeles, California occurred October 23, 2015 causing the relocation of more than 11,000 area residents.

⁵ Jaffe, A.M., Dominguez-Faus, R., Parker, N., Scheitrum, D., Wilcock, J., Miller, M., 2016. The Feasibility of Renewable Natural Gas as a Large-Scale, Low Carbon Substitute. Sacramento, CA.

Minimize Air Quality Impacts from Natural Gas Use to Zero or Near-Zero Levels

Large portions of California, most notably Southern California and the San Joaquin Valley, are in air quality non-attainment zones. These are areas considered to have air quality worse than California ambient air quality standards. Industrial and goods movement is a key economic sector of these regions and major producer of air pollution emissions. As these industries move from diesel to natural gas, opportunities exist to reduce air pollution emissions by ensuring natural gas is combusted using technologies that surpass best available control technology limits.

Energy Commission Research and Development Strategy for Natural Gas

The Energy Commission's strategy for Natural Gas R&D is organized by six technology categories that identify key market sectors. Many of these technology categories are used in concert with one another and address multiple challenges described previously and shown in Table 1.

Table 1: Technology Categories that Support the Strategic Objectives for Natural Gas Investments

	Six Technology Categories					
Strategic Objective	Internet of Things and Data Science	Solar Thermal	Bio-energy	Medium- and Heavy-Duty Natural Gas Vehicles	Combined Heat and Power	Advanced Materials and Manufacturing
Reduce Vulnerabilities and Fugitive Methane Emissions in the Natural Gas Infrastructure	✓	✓	✓			✓
Drive Large-Scale Customer Adoption of Energy Efficient and Low-carbon Technology Solutions for Natural Gas End-Uses		✓	✓	✓	✓	✓
Improve the Cost-Competitiveness of Renewable Gas			✓	✓	✓	
Minimize Air Quality Impacts from Natural Gas Use to Zero or Near-Zero Levels	✓			✓	✓	

Source: California Energy Commission staff, 2018

Internet of Things and Data Science

The Internet of Things (IoT) - sensors and intelligent devices combined with advances in machine learning and software platforms - has broad applications for the natural gas sector. IoT solutions for detection and monitoring can be deployed cheaply and quickly

compared to current practices that are labor- and capital-intensive. In addition, IoT solutions can provide more granular data to better target technology and policy solutions. Furthermore, the machine learning capabilities can optimize and automate end-use natural gas appliances for energy efficiency without sacrificing customer preferences.

Key Challenges and Needs:

- Demonstrating the value proposition of IoT solutions for natural gas sector-specific applications.
- Developing user interfaces and visualization tools capable of more effectively and efficiently operationalizing the data.
- Improving the accuracy, cost and capabilities of sensors.

Applications: Building and appliance controls, detecting thermal losses in buildings, natural gas pipeline detection, fugitive methane emission monitoring.

Sectors: Residential, commercial, industrial, natural gas supply.

Solar Thermal

Solar thermal provides a potential low-carbon alternative to natural gas for numerous heating end-uses, particularly for dairies and industries and manufacturers. Beyond the small carbon footprint, solar thermal can help customers lower operational costs and reduce exposure to price volatility of natural gas.⁶ However, the market for solar thermal technologies has seen limited growth, primarily because solar thermal system costs are high.

Key Challenges and Needs:

- Capital costs of solar thermal solutions compared to competing natural gas technologies.
- Demonstrating that new solar thermal technologies can meet the thermal requirements of specific market segments.
- Physical footprint of solar thermal technologies and competing uses for land and rooftop space.

Applications: Residential and commercial hot water heating, industrial and food processing, desalination.

Sectors: Residential, commercial, industrial.

⁶ Weather, availability of storage, and commodity cycles are all factors that contribute to natural gas price volatility. It is not uncommon to see natural gas prices double or triple during cold winters. For more information, see <https://www.sparklibrary.com/drivers-us-natural-gas-price-volatility/>.

Bioenergy

Techniques such as anaerobic digestion and gasification can produce biofuels for generating energy and provide important alternatives to flaring methane. These techniques are most applicable in managing methane from agricultural and waste, such as dairies, wastewater treatment, landfills, forest timber, and municipal solid waste. In addition, when used onsite, bioenergy can alleviate some of the natural gas supply issues such as methane leakage and natural gas price volatility. However, current commercially-available bioenergy systems are not economically feasible under market conditions without support mechanisms like the Bioenergy Market Adjusting Tariff.

Key Challenges and Needs:

- Energy- and capital-intensive processes required to convert biogas into high-quality biomethane.
- Transport costs for biomass feedstocks if not generated on-site.
- Variations in biogas composition from site-to-site based on feedstock differences.

Applications: Wastewater treatment, landfill and food processing and dairy operations; agricultural and urban residues (agricultural waste and urban wood waste), forest management.

Sectors: Industrial, wastewater treatment, transportation, natural gas supply.

Combined Heat and Power

Using the waste heat from onsite generation offers several benefits, including a reduction in natural gas consumption and the associated GHG emissions. The market for CHP has remained relatively flat. New opportunities exist that can further enable the market for CHP, including using the waste heat for high-value chilling and filling market gaps for small and microscale systems. Technology advancements are necessary to realize these market opportunities.

Key Challenges and Needs:

- Economically converting waste heat into high value thermal energy.
- Advanced control technologies capable of optimizing combustion efficiencies and minimizing NOx emissions to near-zero levels.
- Capital costs required to install and interconnect new CHP equipment.
- Matching thermal and electrical loads.

Applications: Process heating, water heating, thermal chilling.

Sectors: Commercial, industrial.

Medium- and Heavy-Duty Natural Gas Vehicles

The low cost of natural gas relative to diesel fuel is driving adoption of natural gas medium- and heavy-duty vehicles. A National Petroleum Council study estimates that about 20 percent of Class 7 and Class 8 vehicles will be fueled by natural gas by 2025.⁷ However, there are gaps in natural gas engine product offerings that are optimized to the specific application and duty cycles of medium- and heavy-duty vehicle market segments. Transitioning the medium- and heavy-duty vehicle market to natural gas provides an opportunity, through more advanced engine designs, for significant reductions in NOx emissions compared to the more incremental improvements anticipated in diesel engines. Finally, technology advancements in refueling and onboard storage for natural gas vehicles can also be leveraged for hydrogen vehicles as fuel cells and renewable hydrogen production become more economical.

Key Challenges and Needs:

- Filling gaps in natural gas engine product offerings including gas/electric hybrids.
- Advanced control technologies capable of optimizing combustion efficiencies and minimizing NOx emissions to near-zero levels.
- Cost and weight required for onboard storage.

Applications: Drayage, regional haul, refuse, transit.

Sectors: Transportation.

Advanced Materials and Manufacturing

Advancements in materials and manufacturing have the potential to provide important benefits to natural gas ratepayers. Materials advancements can enable more effective and economical approaches for sealing building envelopes and natural gas pipeline leaks. Breakthroughs at the nanoscale level (ultra small particles) can provide new coatings and materials that greatly improve heat transfer capabilities of thermal systems at lower manufacturing costs than current technologies. Furthermore, advancements in manufacturing can help improve the efficiency of buildings while minimizing the cost.

Key Challenges:

- Long development times for new materials.
- Customer concerns about performance, longevity, quality, and market acceptance of the resulting product.

⁷ National Petroleum Council, 2012, Advancing Technology for America's Transportation Future, Part One—Integrated Analyses

- Technology learning needed among downstream actors responsible for installation and operation.

Applications: Building envelope, industrial manufacturing, pipeline safety, heat exchangers, pre-fabricated housing.

Sectors: Residential, commercial, industrial, natural gas supply.

The Natural Gas Research Program

The California Energy Commission's Natural Gas Research and Development (R&D) program is designed to advance science and develop technologies to increase natural gas end-use efficiencies, improve reliability, and reduce environmental impacts that are not adequately addressed by competitive or regulated entities. The Natural Gas R&D program is designed to meet energy policy goals and standards while maintaining safety and reliability. For more information on select energy policy goals for California's future, see Appendix A.

Assembly Bill (AB) 1002 (Wright, Chapter 932, Statutes of 2000) created the program, recognizing natural gas as a vital energy resource for California. AB 1002 directed the California Public Utilities Commission (CPUC) to impose a surcharge on all natural gas consumed in California. This surcharge funds a range of public interest R&D activities in energy efficiency, renewable energy and advanced generation, and energy infrastructure. The California Energy Commission has administered natural gas R&D in the public interest since 2004. SB 1250 (Perata, Chapter 512, Statutes of 2006) updated the program, changing how the natural gas research funds are encumbered and managed.

The CPUC established that the Energy Commission's Natural Gas R&D projects must:

- Focus on energy efficiency, renewable technologies, conservation, and environmental issues.
- Support state energy policy.
- Offer a reasonable probability of providing benefits to the public.
- Consider opportunities for collaboration and co-funding with other entities.

Each year the Energy Commission is required to submit to the CPUC a proposed program plan and funding request for the Natural Gas Research and Development Program. When creating the budget plan and developing the research portfolio, the Energy Commission receives input from experts in energy research, including the state's investor-owned gas utilities, state and federal agencies, industrial experts, academic researchers, and other interested parties. Each year the Energy Commission, in conjunction with the CPUC, holds a workshop to explore research initiatives across all natural gas technical subject areas considered for the next funding cycle. Other workshops are held throughout the year to gather input on various research areas and

topics. These workshops help avoid research duplication; generate new research ideas; create the best research industry practices; and bring together utilities, researchers, manufacturers, end users, and policy makers from state and federal agencies, such as the California Air Resources Board (CARB) and the United States Department of Energy (DOE), respectively.

The CPUC approved the FY 2017-18 plan in September 2017 by Resolution G-3527 and authorized the Energy Commission to administer \$24 million for Natural Gas R&D projects during a two-year funding period. In April 2017, the CPUC also approved the Energy Commission's proposed *Reliability and Climate Focused Natural Gas Supplemental Budget Plan* for the investment of \$5.9 million in previously-allocated unspent funds.

The Energy Commission submitted its most recent funding request in March 2018 and is awaiting CPUC approval. Typically, the CPUC approves the research funding request before, or soon after, the beginning of each fiscal year. The Energy Commission respectfully requests that the *Natural Gas Research and Development Program Proposed Program Plan and Funding Request for Fiscal Year 2018-19* is considered at a CPUC business meeting soon to avoid a hiatus in research projects.

This report highlights project successes and benefits, and covers results of completed projects and the progress of current research from July 1, 2017, through June 30, 2018. For a breakdown of the research area budget expenditures, see Appendix B-1. For a detailed breakdown of Natural Gas R&D project funding of the program history, see Appendix B-3.

Energy Commission Administration

The Energy Commission's administration of the Natural Gas Research Program is in line with best practices for public research programs. The Natural Gas Research Program follows similar practices and procedures to the Electric Program Investment Charge (EPIC), which was recognized in 2017 as part of an independent evaluation of the EPIC program directed by the CPUC. Awarded projects are selected through a transparent process. Each project creates a technical advisory committee composed of diverse professionals to provide guidance in project direction. Research results are widely disseminated and used to guide future policy and research decisions.

In addition to addressing the critical challenges facing the future of natural gas already identified, the Natural Gas R&D program is responding to pressing critical needs that recently elevated the importance of safety and climate adaption. The 2010 explosion at San Bruno highlighted the necessity for improved natural gas infrastructure safety. The large-scale gas leak at Aliso Canyon discovered in October 2015 highlighted the necessity for resilience and improved leak detection. The years of drought and bark-beetle infestation have left 129 million trees dead in California's forests. Over the years, the Natural Gas R&D program has issued specific research solicitations to address these pressing issues. See the following list for specific solicitations that address these urgent

issues. For a complete list of Natural Gas R&D program funding opportunities made available in FY 2017-18, see Appendix B-2.

Pipeline Safety

- PON-14-502: Infrastructure Improvement Research for Natural Gas Fueling Stations
- PON-14-503: Natural Gas Pipeline Safety and Damage Prevention Grant
- GFO-15-507: Natural Gas Solicitation for Energy-Related Environmental Research
- GFO-17-502: Enhancing Safety, Environmental Performance, and Resilience of California's Natural Gas System

Aliso Canyon

- PON-14-507: Regional Climate Impacts and Adaptation Studies for the Natural Gas System and Other Environmental Related Issues
- GFO-15-507: Natural Gas Solicitation for Energy-Related Environmental Research
- GFO-16-502: 2016 Natural Gas Energy Efficiency Research Grants for Residential and Commercial Buildings
- GFO-16-508: Natural Gas Storage Infrastructure Safety and Integrity Risk Modeling Research Grants

Tree Die-Off

- PON-14-505: Advancing Clean Energy from Biogas, Biomethane and Natural Gas

Bringing Different Perspectives Into R&D

Commercializing new energy technologies requires a wide range of stakeholder perspectives and expertise. The Energy Commission plays a vital role in bringing together stakeholders that can collectively enable the commercialization of new energy technologies to meet California's energy and climate change goals. Each research project is advised by a technical advisory committee such as subject matter experts, end- users, equipment manufacturers, national labs, academia, technology developers, governmental agencies, local governments, and private research organizations. In addition, in 2017, the Energy Commission conducted seven public workshops to solicit stakeholder input on how Natural Gas R&D funding opportunities can be most impactful and to provide an opportunity for stakeholders to provide feedback to research priorities and solicitation requirements.

Advancing Legislative Priority for Clean Energy Equity

The California Legislature has made clean energy equity—ensuring that the benefits from our programs are equitably shared, especially by those in the most vulnerable communities—a policy priority. Recognizing this, the Energy Commission has prioritized disadvantaged communities in three of its fiscal year 2017-18 solicitations for the Natural Gas Research Program; setting aside specific amounts for projects in these

areas or providing bonus points for demonstration or pilot test sites in and benefitting disadvantaged communities. These solicitations were:

- Addressing Barriers to Wider Adoption of Near-Zero Emission Natural Gas Vehicles (GFO-17-503).
- Enhancing Safety, Environmental Performance, and Resilience of California's Natural Gas System (GFO-17-502).
- Improving Natural Gas Energy Efficiency, Waste Heat-to-Power, and Near-Zero Emission Distributed Generation Systems (GFO-17-501).

Furthermore, the Energy Commission held multiple workshops, expos, and stakeholder and working group meetings to support community advocacy for diversity around policy research and policy positions, including six workshops to discuss incorporation of community-focused equity in Energy Commission research grant funding opportunities.⁸ The Energy Commission has committed to a 25 percent target of Technology Demonstration and Deployment funding under its EPIC program to be allocated to projects sited in disadvantaged communities, and the Natural Gas program has kept pace. Though the Natural Gas program does not have the same statutory requirements, the Energy Commission is committed to equity across programs.

Out of the 101 California-based Natural Gas program projects that were active during fiscal year 2017-18, 25 have at least one site within a disadvantaged community.⁹

Expanding Natural Gas Research

Despite California's expanding natural gas research needs, program funding has not increased since 2009. To address this limitation, the Energy Commission is preparing to submit a request to the CPUC to expand its Natural Gas R&D program.

CPUC Resolution G-3519 requested the Energy Commission to assess the overall reasonableness of the natural gas research program, and then provide a detailed accounting as part of an annual proposed program plan and funding request. Energy Commission staff is currently assessing the research program. The assessment will span the history of the program and will include the program's drivers, administration, funded projects, and results. In particular, the assessment will highlight the research program benefits to California natural gas investor-owned utility ratepayers. This review will assess whether research led to substantial additional public and private investment, resulted in commercially available products, or informed policy, planning, decision making, codes, and standards.

⁸ One workshop was held in Fresno, CA and another was held in Diamond Bar, CA.

⁹ For more information about these and other Energy Commission diversity commitment activities, please visit: <http://www.energy.ca.gov/commission/diversity/>

CHAPTER 2:

Project Highlights

Reduce Vulnerabilities and Fugitive Methane Emissions in the Natural Gas Infrastructure

An aging infrastructure and a changing climate threaten the safety and resiliency of California's energy systems. Climate change impacts have led to major increases in the frequency, size, and destructiveness of wildfires, while leaks in the natural gas infrastructure have created major safety and environmental concerns. To address these and other challenges, the California Energy Commission is supporting new scientific and technological advancements to equip California's stakeholders with the solutions they need to build a safe and resilient energy system.

Providing a Foundation for Effectively Reducing Methane Emissions

It is estimated that 2 percent of natural gas leaked into the atmosphere during its production, processing, transport, and distribution.¹⁰ The dominant chemical constituent of natural gas is methane – a potent greenhouse gas. Methane is almost 30 times stronger at trapping heat compared to carbon dioxide over a 20-year period. Identifying sources of leakage is critical to reducing greenhouse gas (GHG) emissions.

Home natural gas consumption accounts for nearly 20 percent of total natural gas consumption in California.¹¹ The official GHG inventory prepared by the California Air Resources Board (CARB) assumes that methane emissions from the residential sector are extremely small, and the inventory considers only incomplete combustion of natural gas in furnaces, water heaters, dryers, and stoves to be sources of methane emissions in homes.¹² However, previous Energy Commission-funded research suggests “after

¹⁰ Alvarez, Ramón A., Daniel Zavala-Araiza, David R. Lyon, David T. Allen, Zachary R. Barkley, Adam R. Brandt, Kenneth J. Davis et al. "Assessment of methane emissions from the US oil and gas supply chain." *Science* (2018) 186-188.

¹¹ Calculated using data from https://www.eia.gov/dnav/ng/ng_cons_sum_dcu_SCA_a.htm .

¹² AB 2195 (2018) requires CARB to “Quantify and publish annually, commencing January 1, 2020, and based on the best available science and information, the amount of greenhouse gas emissions, expressed in metric tons of carbon dioxide equivalents, resulting from the loss or release of uncombusted natural gas to the atmosphere and emissions from natural gas flares during all processes associated with the production, processing, and transporting of natural gas that is imported into the state from out-of-state sources.”

meter” natural gas leakage, specifically leaks that occurs within the home, may be a substantial portion of total unaccounted methane emissions.¹³

That project measured natural gas leakage within a handful of homes and found that leaks can be large, meaning that estimates of total methane emissions from the residential sector may be severely underestimated. More data were necessary to properly characterize the extent of this problem.

A recently completed project with Lawrence Berkeley National Laboratory measured in-home methane emissions in 75 sample houses throughout California to collect more data and test whether assumptions about natural gas leakage in the residential sector were accurate. The research team sealed the test homes and used a blower door (Figure 1) to create a constant flow of air. Researchers then determined methane leaks inside the home by measuring the difference in methane concentration from incoming and outgoing air. The project also experimented with how methane leakage varied during operation and non-operation of natural gas appliances in the home.

Figure 1: Measurement Setup at a Sample Houses



Blower door setup to measure methane leakage.

Source: California Energy Commission

¹³ Fischer, Marc L., Wanyu Chan, Seongeun Jeong, and Zhimin Zhu. Lawrence Berkeley National Laboratory. 2018. Natural Gas Methane Emissions From California Homes. California Energy Commission. Publication Number: CEC-500-2018-021.

Most homes exhibited little leakage (less than 1 gram of methane per day), though a few homes had more substantial leaks (greater than 10 grams of methane per day). Methane emissions caused by incomplete combustion from operating appliances were mostly undetectable. On the other hand, storage water heaters and stoves exhibited meaningful methane leakage (roughly 1 to 3 percent of gas consumed) while in standby. Overall, the project team identified whole house leaks (leakage independent of appliance operation), continuous operation of pilot lights, and episodic operation of appliances such as natural gas water heaters and cooking stoves as the most significant contributors to methane emissions. Based on the sample results, they estimated that the residential sector emits 35.7 gigagrams (a gigagram is 1 billion grams) of methane per year, equivalent to about 15 percent of California's overall natural gas sector methane emissions or equivalent to 0.5 percent of home natural gas consumption.

These results provide important information that could be used to update the state's GHG inventory, which is a critical tool used to illuminate appropriate strategies for reducing GHG emissions in California. The Energy Commission shared the results with CARB, which plans to evaluate the results from this project and consider updates to its next annual greenhouse gas inventory reporting. The results from this project were also recently published in the *Journal of Environmental Science & Technology*.¹⁴

The results suggest that repairing leaks, updating combustion appliances (for replacing the pilot light with electronic ignition), and electrifying appliances can greatly reduce methane emissions from the residential sector. Furthermore, eliminating "after meter" natural gas leakage would save ratepayers an estimated \$30 million per year.

Operationalizing Climate Science Into Energy Planning Decisions

California's Fourth Climate Change Assessment (Fourth Assessment), released in August 2018, provided a substantial infusion of new science and data regarding what climate change means for California and how Californians can cope with it. This ambitious effort was led by the California Natural Resources Agency, the Governor's Office of Planning and Research, and the Energy Commission. Results of the Fourth Assessment are all publically available at climateassessment.ca.gov, including 44 peer-reviewed technical reports of which 15 were funded by the Energy Commission to shed light on energy sector vulnerability and resilience.

One Fourth Assessment study supported by the Energy Commission and undertaken by ICF International in collaboration with San Diego Gas & Electric Company (SDG&E) investigated climate-related risks to the natural gas system in SDG&E territory. This study considered multiple hazards, including coastal and inland flooding, wildfire, and extreme heat. The research team used high-resolution projections, data-intensive models, and stakeholder engagement to generate locally specific knowledge of how

¹⁴ Fischer, Marc L., et al. "An Estimate of Natural Gas Methane Emissions from California Homes." *Environmental science & technology* (2018).

weather-related extremes may affect particular assets. This locally resolved information provided a scientific foundation for charting “flexible adaptation pathways” that incorporate evolving knowledge and policy into timing and implementing resilience measures.

Another research project supported by the Energy Commission provided new, high-resolution field measurements of mean subsidence rates of about 0.4 to 0.8 inches per year for some levees in the Sacramento-San Joaquin Delta. This subsidence compounds the risk that sea-level rise and storms could cause overtopping or failure of the levees, exposing natural gas pipelines and other infrastructure to damage or structural failure. At this rate of subsidence, some levees may fail to meet the federal height standard between 2050-2080. This research project involved the local natural gas utility on its technical advisory committee to strengthen and accelerate knowledge transfer to utility technical staff. The research will be used to inform adaptation planning by the utility.

Addressing Vulnerabilities in the Natural Gas Infrastructure

Damage to natural gas pipelines caused by digging, grading, trenching, and boring is one of the main challenges to safe pipeline operations. The United States Department of Transportation Pipeline and Hazardous Materials Safety Administration reported that excavation damage causes 26 percent of serious incidents to gas transmission and distribution pipeline (involving a fatality or in-patient hospitalization) and nearly 50 percent of these were caused by third-party excavators.¹⁵ Pipeline infrastructure owners and operators have established free call centers (for example 811 Call Before You Dig) to coordinate with third-party excavators to ensure that excavation is performed safely to prevent damage to underground facilities. However, these existing practices do not address all incidents as many accidents result from failure to follow these existing notification practices before digging.

In 2016, the Energy Commission awarded funding to the Gas Technology Institute to develop a platform solution that provides real-time visibility and notification to utilities and heavy-equipment operators when construction work is being conducted near natural gas pipelines. The Global Positioning System (GPS) Excavation Encroachment Notification System integrates a small hardware unit installed on the excavation equipment with geospatial tools, and custom-developed algorithms and machine learning capabilities that together provide a rich visual display on excavator status and location in relation to the natural gas pipelines. This unit provides excavator operators with better situation awareness regarding the location of underground pipelines so they can better avoid accidents.

As part of the Energy Commission funded project, Gas Technology Institute developed, installed, and tested the hardware device on 150 excavation equipment units owned by Pacific Gas and Electric Company, Southern California Gas Company, and third-party

¹⁵ <https://www.phmsa.dot.gov/data-and-statistics/pipeline/national-pipeline-performance-measures>

excavation contractors.¹⁶ The device and dashboard are integrated with the utilities' geographic information system network. Such implementation provided high-accuracy GPS location of excavation equipment, which can overlay the utility's geographic information system map services, call center boundaries, or custom geo-fences around the pipeline right of way (Figure 2).

It also displayed real-time indications of the activities of the geospatially-located excavators and sent instant alerts in the form of sound and light signals in the device, plus graphical and text message alerts to the applicable utility's operators. The system matched actual field observations against the excavators predicted activities of idle, digging, and driving which were about 87 percent, 80 percent, and 85 percent accurate respectively. Accurately predicting excavation activities in real-time then helps predict the risk of encountering a natural gas pipeline. The initial goal is to reduce about 12 percent of the non-fatal and non-injury incidents in California that are caused by first- and second-party excavators and save \$1,564,500 annually in private property and operator damage and emergency response.

Figure 2: Global Positioning System Device on Excavator and Utility Monitoring Dashboard



Source: Gas Technology Institute

¹⁶ Farrag, Khalid; Robert Marros, Jason Sphar; Steven Blitzstein, GTI (Gas Technology Institute). 2018. Global Positioning System Excavation Encroachment Notification System Implementation, Final Report. Publication Number: CEC-500-2018-014.

It is anticipated that use of this technology by third-party contractors would result in a 43 percent reduction of nonfatal and noninjury excavation incidents that are caused by excavators, backhoes, and trenchers. More savings can be achieved if the telecommunication, electrical, water, and agriculture industries adapt the excavation safety technology to their application by identifying their underground networks of equipment, wires, and pipes.

High Accuracy Mapping for Excavation Damage Prevention and Emergency Response

Natural gas operators primarily use manual, paper-based methods to create asset maps and to document asset properties and environmental conditions. These manual methods are time consuming, can lead to human data entry errors, and create delays in making asset and engineering information available to stakeholders. The US Department of Transportation (DOT) Pipeline and Hazardous Materials Safety Administration (PHMSA) regulations for integrity management are incentivizing natural gas operators to implement technology to improve and increase asset data collection. A more automated, mobile technology is needed to create high quality asset maps and records that can serve as the backbone for future asset and integrity management programs, as well as for routine operations and emergency response.

In 2016, the Energy Commission awarded funding to the Gas Technology Institute (GTI) to develop technology that is able to automatically create and display high accuracy maps of underground natural gas distribution assets. The high accuracy mapping (HAM) technology creates spatially accurate maps populated with traceability data for materials, joints, operator qualification status and pressure test. The HAM hardware includes tablets, GPS receivers, GPS antennas, barcode scanners and seven-foot survey poles (Figure 3). The HAM software application captures high accuracy GPS and material traceability data, automates the creation of GIS maps and related records, and synchronizes data to a cloud-hosted database. The data displayed by the application provides real-time information on underground distribution assets and excavation activity. It offers the utility a common operating picture at any point for more functional communications, planning and ultimately more efficient and safe operation.

Figure 3: High Accuracy Mapping System – Hardware and Software Interface



Source: Gas Technology Institute

This automated, high-accuracy mapping technology is able to map over 90 percent of the underground assets with an accuracy within 6 inches. It also allows users to electronically collect information on 17 infrastructure features and 190 feet of pipe per day on average, whereas paper-based data collection and sketch creation typically take one or more hours to complete. Moreover, this technology takes only minutes to collect pipeline information electronically, and it improves the accuracy of data and location information. Pacific Gas & Electric (PG&E) estimated that the technology can reduce excavation damage events by 50 percent, or 300 total damage events annually throughout California, leading to increased reliability and security of natural gas infrastructure and supply. This corresponds to cost savings of \$1.5 million and reductions of natural gas emissions by 11,700 million standard cubic feet annually in California. The technology improves system integrity by reducing excavation damage and improves public safety by promoting situational awareness through the visualization of high accuracy maps and related information during emergencies.

In close collaboration with PG&E, the HAM technology has been demonstrated in field by configuring and deploying 22 units to 10 service locations throughout PG&E service territory, and PG&E crews have mapped a total of 37,951 feet of pipe and 3,475 point features (valves, fittings, etc.). The target market for the HAM technology is natural gas infrastructure operators and mapping service providers and the estimated size of total addressable market is 6,000 field crews. A survey of 16 gas utility companies

demonstrated a 75 percent interest rate in applying the technology. GTI is working with a subcontractor on a commercialization strategy for the technology and plans to roll out HAM product to several gas utilities in 2018. The research team also expected 50 percent of the largest natural gas distribution companies with over 1 million meters to conduct pilot projects by the end of 2019.

Drive Large-Scale Customer Adoption of Energy Efficient and Low-Carbon Technology Solutions for Natural Gas End-Uses

Energy plays a critical role in the affordability, health, and comfort of California's residential customers and the communities in which they live. However, rising energy costs burden low-income communities disproportionately because residents in these communities typically spend a larger share of their income on energy than other households. Furthermore, energy expenses incurred by municipal buildings and facilities – such as wastewater treatment plants – add costs to residential customers. Moreover, the housing shortage in California has shown the necessity for low-cost, rapidly deployable construction methods.¹⁷ Advances in energy efficiency technologies in existing buildings and new construction projects not only save residents money, but can also increase the comfort of homes by more efficiently controlling heating and cooling.¹⁸

California is the fifth largest economy in the world and the energy sector is a vital contributor of the necessary goods, products, and services that have helped achieve that status. California's agricultural, commercial, and industrial sectors are large users of natural gas. To help maintain California's global competitiveness and continue the state's leadership in advancing low carbon opportunities, the Energy Commission supports research to develop the next-generation of clean energy technology solutions that help Californians use gas more efficiently.

Bringing New Clean Energy Technology Solutions to Affordable Housing

Housing affordability is a top concern for residents in California's disadvantaged and low-income communities. Housing and energy costs can account for more than 50 percent and 16 percent of their income, respectively.¹⁹ To lower their living expenses, residents of these communities need affordable housing that does not sacrifice energy efficiency. However, affordable housing developers typically adhere to smaller, tighter budgets that limit their ability to install high-efficiency appliances. Effectively sealing the envelope of the home – including the roofs, walls, and floors – can go a long way towards improving the energy efficiency and comfort of a home. However, sealing the

¹⁷ <https://www.sacbee.com/news/politics-government/capitol-alert/article168107042.html>

¹⁸ https://www.energy.ca.gov/renewables/tracking_progress/documents/energy_efficiency.pdf

¹⁹ https://www.energy.ca.gov/renewables/tracking_progress/documents/energy_innovation.pdf

envelope -a process typically involving caulk, spray foam, weather stripping, or other materials - can be difficult, labor-intensive, and not always effective.

In 2012, the Energy Commission funded the University of California (UC) Davis Western Cooling Efficiency Center to develop a portable automated process for sealing gaps and tightening the envelope of a building.²⁰ The AeroBarrier system sprays a cloud of waterborne acrylic sealant droplets into a pressurized room. The pressure forces air to escape through leaks, and the sticky particles follow the airflow to the leaks, where the particles are flung from the airstream, coagulating around a leak until it is sealed. A computer controls the temperature, pressure, humidity, and distribution of the sealant, and technicians are able to monitor the progress in real time. In fewer than three hours, a two-person team reduced the air leakage of a 2,200 square-foot, three-bedroom house by 68 percent compared to traditional sealing methods that require more than 20 hours of labor. Tests showed that AeroBarrier can seal holes as tiny as a human hair and as large as a half inch across, and can reduce leaks by up to 90 percent in new buildings. This process is GREENGUARD Gold certified,²¹ meaning it meets or exceeds low emissions standards for volatile organic compounds in indoor spaces.

Figure 4: AeroBarrier Sealant for Building Envelopes



Source: <https://aerobarrier.net/article/wcec-research-highlights/>

²⁰ More information available at https://wcec.ucdavis.edu/wp-content/uploads/2013/01/WCEC_Case-StudyAeroseal_2010-10.pdf

²¹ http://greenguard.org/en/manufacturers/manufacturer_childrenSchools.aspx

Successful early demonstrations of AeroBarrier in California homes proved the effectiveness of the technology and drew the attention of home builders and designers. AeroBarrier licensed the technology from the University of California, Davis after five years of research and development supported by the Energy Commission's Public Interest Energy Research Program and the DOE's Building America program and hit the commercial market in January 2018. During this period, AeroBarrier was tested in new and retrofit single family and multifamily housing, including homes built by Habitat for Humanity and retrofits to improve multifamily housing in disadvantaged communities. As of the end of 2017, AeroBarrier has sealed more than 125,000 homes and more than 35 million square feet of commercial space.²² Most recently, AeroBarrier was used in new homes built by Beazer in Sacramento. The National Association of Homebuilders awarded AeroBarrier the 2018 Most Innovative Building Product and Best in Show in January 2018.

Increasing Energy Efficiency of Manufactured Homes

A recent poll conducted by the UC Berkeley Institute of Governmental Studies shows that nearly half of the state's registered voters believe that housing affordability is an "extremely serious" problem in California.²³ The National Low Income Housing Coalition estimates a shortage of 1.5 million affordable low-income housing units.²⁴ One possible solution to improving housing affordability and increasing the availability of low-income housing units is building more manufactured homes. Manufactured homes are built off-site in a factory on a non-removable steel chassis and can be a lower cost alternative to standard home construction. Manufactured homes typically cost an average of \$60 to \$70 per square foot to build at the factory compared to the average price of \$120 to \$150 per square foot to build a site-built home.²⁵

All manufactured homes produced in the nation conform to one set of standards, the Manufactured Housing Construction Safety Standards, enforced and maintained by the United States Department of Housing and Urban Development (HUD). The standards, first established in 1976, contain thermal requirements that were last updated in 1994. The HUD standards preempt California's Energy Code (Title 24) requirements and have

²² <https://aerobarrier.net/about/>

²³ Berkeley IGS Poll, Release #2017-16, September 19, 2017, <http://escholarship.org/uc/item/65s716jf#page-1>

²⁴ California Department of Housing and Community Development, California's Housing Future: Challenges and Opportunities Final Statewide Housing Assessment 2025, February 2018 http://www.hcd.ca.gov/policy-research/plans-reports/docs/SHA_Final_Combined.pdf

²⁵ Average Cost of a Manufactured Home in 2018, <https://www.thehomesdirect.com/blog/average-cost-of-a-manufactured-home>, <https://www.manufacturedhousing.org/wp-content/uploads/2018/05/2016-US-Census-MH-vs-SB.pdf>; and <http://www.usmodularinc.com/pricing/>

far less stringent energy efficiency requirements. Increasing the energy efficiency of these units makes them more affordable and comfortable for homebuyers. However, to keep home prices low, manufactured home builders are very sensitive to increased cost of construction. The manufactured homes market is competitive and builders may not want to add items that will increase cost and affect future sales. Many of California's renters and homeowners face high housing costs and any increase in price might mean not qualifying for a home loan or not being able to afford basic amenities.²⁶

A PIER research project with The Levy Partnership focused on increasing the energy efficiency of manufactured homes by developing and commercializing the next generation of wall and roof envelope designs that are highly energy efficient and add minimally to first costs (Figure 5). The project was successful in developing advanced envelope designs that add minimally, or about \$2,700, to the first cost of a manufactured home. The advanced wall and roof insulation greatly reduces the exchange of heat into and out of the home through the exterior surfaces of the building. This means less warm air escapes during winter and less cool air escapes during the summer, which reduces heating and cooling costs. According to The Levy Partnership's research, these advanced envelope designs can reduce the energy bills of gas-heated manufactured homes by up to 48 percent and the energy bills of electric-heated homes by up to 56 percent.

The project engaged key industry stakeholders, such as major manufactured home builders in California, and demonstrated the construction methods developed by this project. This advanced envelope design is available as an option to purchasers of manufactured homes and could become standard practice if these designs are directly incorporated at the federal level by HUD or are directly promoted with incentives in California. With nearly 10,000 new manufactured homes constructed each year in California, this project can significantly reduce energy use and result in substantial annual cost savings to purchasers of manufactured homes.

²⁶ <https://calbudgetcenter.org/resources/californians-parts-state-pay-can-afford-housing/>

Figure 5: Manufactured Home Project



Credit: Levy Partnership, Golden West Homes, Perris, California

Success in New Homes Provide Insight for Hot Water Piping Improvements in Existing Homes

More than 10 million California homes heat water with natural gas.²⁷ Water heating accounts for more than 40 percent of all natural gas used in California homes.²⁸ Households using natural gas for water heating consume about 2.5 billion therms per year and emit more than 13 million metric tons²⁹ of carbon dioxide equivalent (CO₂e). Prior Energy Commission research indicated that the efficiency of hot water distribution systems in California homes could be near or less than 50 percent – meaning for every 10 units of energy used to heat the water, only half of that energy reaches the faucet.³⁰

²⁷ Hunt, Marshall, Diane Schwyzer, and Cambell Brown Korbel. Valley Energy Efficiency Corporation. 2005. SuperEfficient Gas Water Heater Appliance Initiative. California Energy Commission, PIER Energy-Related Environmental Research Program. CEC-500-2007-105

²⁸ Magaña, Pilar. 2017. Energy Research and Development Division. 2017. Natural Gas Research and Development Program 2017 Annual Report. California Energy Commission. Publication Number: CEC-500-2017-036

²⁹ A metric ton is 2,205 pounds.

³⁰ Lutz, Jim; Steven Lanzisera; Anna Liao; Christina Fitting; Chris Stiles; Margarita Kloss, (Lawrence Berkeley National Laboratory). 2014. Reducing Waste in Residential Hot Water Distribution Systems. California Energy Commission; Publication number: CEC 500-2015-004.

Improvements in the efficiency of residential water heating distribution could yield huge savings in natural gas and greenhouse gas emissions.

Big Savings Achieved in New Construction Homes

Using a variety of heat transfer tests, conducted under various conditions and on a variety of materials and pipe sizes, research funded by the Energy Commission confirmed that adding insulation to buried and unburied hot water pipes led to significant energy savings in new homes. Laboratory tests indicated that heat loss in uninsulated pipes was seven times greater than insulated pipes.³¹ Adding insulation to hot water pipes dramatically reduces pipe heat loss, which reduces energy costs, water waste, and the wait time to receive hot water to fixtures.

The research was directly responsible for improvements to the residential water heating distribution systems incorporated into the *California Building Energy Efficiency Standards* for new construction.^{32,33} Cumulative savings due to implementing the requirement of pipe insulation in new homes are estimated to be about 8.2 million therms and a reduction of 50,000 metric tons of CO₂e, saving Californians about \$7.9 million and roughly 1.3 billion gallons of water between 2014 and 2020.

Can We Achieve Similar Savings in Existing Homes?

Homes built prior to 2008 have uninsulated hot water pipes. Retrofitting the uninsulated piping system in these homes is challenging because the pipes are often embedded in concrete slabs. In 2017, a research initiative was approved as part of the Energy Commission's *Reliability and Climate Focused Natural Gas Supplemental Budget Plan* to determine the technical and economic potential of increasing the efficiency of existing residential hot water distribution systems, especially uninsulated pipes in slab foundations built prior to 2008.

This research hopes to improve hot water distribution in existing homes and strive for similar savings as those in new construction.

Driving Down Solar Water Heating System Costs

Natural gas-fired water heaters are the norm for home water heating in California, consuming about 2.5 billion therms per year and emitting more than 13 million metric

³¹ Kosar, Douglas, Paul Glanville and Hillary Vadnal. Gas Technology Institute. 2012. Residential Water Heating Program. California Energy Commission. Publication Number: CEC-500-2013-060.

³² http://www.energy.ca.gov/title24/2008standards/prerulemaking/documents/2006-05-18_workshop/2006-05-11_PEX.PDF.

³³ http://www.energy.ca.gov/title24/2013standards/prerulemaking/documents/current/Reports/Residential/Water_Heating/2013_CASE_R_SEMPRA_Single_Family_DHW_%20Sept_2011.pdf.

tons of CO₂e.³⁴ Solar thermal water heating is a viable alternative to natural gas water heating that is more efficient, emits no greenhouse gas, and uses free solar energy as fuel. However, solar water heaters can be six to eight times more expensive than conventional natural gas-fired water heaters because they have additional components and equipment and are costlier to install. Coupled with the low cost of natural gas, these factors make it difficult for solar water heating systems to compete with natural gas water heaters.

Solar thermal water heaters use a solar thermal collector that converts the sun's energy into heat. The solar collector makes up nearly 30 percent of the system cost. Reducing the cost of solar collectors could result in more solar water heating installations.³⁵

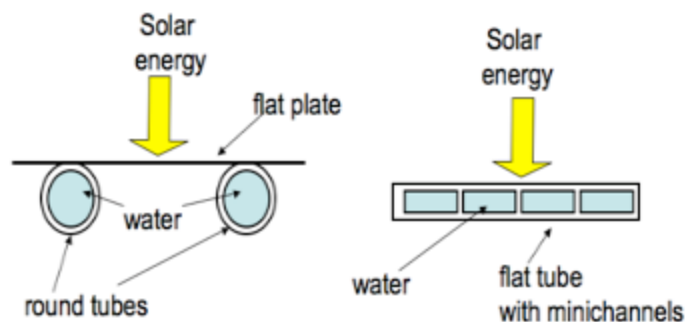
The Energy Commission funded a project with University of California, Merced that developed aluminum mini-channel solar thermal collectors that use flat mini-channels, or tiny tubes, instead of the flat plate design with round tubes attached to a flat copper absorber plate used in conventional solar collectors (Figure 6). The flat-plate round tube design has only a small section of the pipe in contact with the absorber. In contrast, the mini-channel technology increases the surface area exposed to sunlight for heat transfer, which improves the efficiency of the collector. The mini-channel tubes placed next to each other become one big solar collector, drawing the sun's energy directly to the fluid that passes through hundreds of tiny channels. Previous PIER-funded research showed a 10 percent to 15 percent improvement in thermal efficiency compared to conventional copper flat plate collectors.³⁶

³⁴ Seto, Betty; Jarred Metoyer; Rachel Schiff and Jon Taffel. (DNV KEMA Energy & Sustainability). 2013. Natural Gas Energy Efficiency in Buildings. California Energy Commission. Publication Number: CEC-500-2014-036-D.

³⁵ Diaz, Gerardo. (University of California-Merced). 2015. Minichannel Technology to Improve Solar Water Heaters. California Energy Commission.

³⁶ Sharma, Neeraj, and Gerardo Diaz. "Performance Model of a Novel Evacuated-Tube Solar Collector Based on Minichannels." *Solar Energy* 85.5 (2011): 881-890.

Figure 6: Schematics of Two Designs for Solar Thermal Collectors: Flat-Plate Round Tube Solar Thermal Collectors and Solar Thermal Collector Designed With Mini-Channels



The image on the left is the flat-plate round tube design (typically copper). The image on the right is the aluminum mini-channel design.

Source: University of California, Merced.

Another advantage of this technology is the use of aluminum instead of copper. Copper is a better thermal conductor than aluminum, which is why it is typically preferred in heat exchanges. However, aluminum is a substantially cheaper metal and is easier than copper to extrude and form into mini-channels. The researchers estimate that the cost of the aluminum mini-channel technology at scale could be about \$14 per square foot compared to \$51 per square foot for conventional solar collectors.³⁷

Mini-channels have been used in automotive radiators and HVAC condensers, however it was Energy Commission funding that helped create solar thermal collectors that used mini-channel technology for solar water heating. Depending on the operating conditions required, the aluminum mini-channels can heat water to about 130 degrees, well above the typical 120 degree set point of conventional water heaters. Previous laboratory tests did not use the hot water generated for actual hot water loads in real world use, such as for showers or laundry. This project will test how the aluminum mini-channel technology performs in typical hot water use scenarios and will verify the technology cost and energy savings. The project is demonstrating the use of aluminum mini-channel collectors in actual installations in a single-family home and an apartment building in the Los Angeles area.

The aluminum mini-channel solar thermal technology has the potential to lower the cost of solar thermal water heating in single-family and multifamily homes by up to 30 percent while improving the efficiency of the solar collectors by 10 percent to 15 percent. Greatly reducing the upfront cost of solar collectors could lead to an increase

³⁷ https://aceee.org/sites/default/files/pdf/conferences/hwf/2017/Diaz_Session3C_HWF17_2.27.17.pdf.

in market penetration of solar water heating, which would reduce natural gas use and greenhouse gas emissions, improve air quality, and lower ratepayer utility bills.

Developing Scalable Technology Solutions for Food Production

Energy consumption is a large operating expense for California's dairies. Much of this energy consumption is for electrical refrigeration in cold storage facilities that store the dairy products and prevent spoilage. While these systems are effective at maintaining the necessary temperatures, they are expensive to operate and use high global warming refrigerants. Absorption chillers that use thermal energy, such as natural gas or waste heat, as opposed to electricity offer a promising and potentially lower-cost alternative for cold storage at dairy and other food processing plants. However, several technical challenges must be addressed before they can become a viable alternative to electric refrigeration systems. Lithium-bromide-based absorption chillers are the standard but cannot provide sufficient chilling temperatures needed for dairy facilities.

Absorption chillers also have the potential to drive-up natural gas consumption if they are widely used for cold storage facilities. One option to minimize this increase in natural gas consumption is using the waste heat from onsite biogas generators. However, current heat recovery technologies cannot effectively recover this low-grade waste heat and use it for high-value cooling. Instead, dairies exhaust the waste heat into the atmosphere or capture it with economizers for low-value process heating applications.

In 2016, the Gallo Cattle Company in Atwater, California (Merced County) received funding to demonstrate a waste heat absorption chiller application for its cheese making facility. The ThermoSorber™ overcomes two of the key limitations of standard lithium-bromide absorption chillers. For this project, Gallo used an ammonia-based absorption chiller over lithium-bromide because of the ability to cool to lower temperatures. As part of this project, Maas Energy Works, a subcontractor to Gallo, designed an advanced heat recovery system that could effectively replace the electrical chiller and provide a warm water loop for heating processes in the cheese production plant.

Table 2 compares the technical differences between conventional electrical refrigeration and absorption chillers. Advanced absorption chillers have the benefit of reaching temperatures as low as electrical refrigeration but using waste heat as a power source, resulting in lower annual operating costs.

Table 2: Advanced Absorption Chiller Versus Other Refrigeration Options

	Electrical Refrigeration	Absorption Chiller: Lithium-Bromide	ThermoSorber™ Advanced Absorption Chiller
Lowest Reachable Temperature	-80°C	15°C	-70°C
Thermal Efficiency	N/A	Higher	Lower
Energy Intensity	High	Low	Low
Power Source	Electricity	Waste heat or natural gas	Waste heat or natural gas
Operating Costs	High	Low	Low
Uses High Global Warming Potential Refrigerants?	Yes	No	No
Physical Footprint	Small	Large	Large

Source: California Energy Commission staff estimates and conversations with Gallo

The Gallo Energy Efficiency project (Figure 7) is a successful demonstration with average electrical chilling savings of nearly 80 percent observed over a 12 month period (July 2017 to June 2018) and an additional 20 percent in average natural gas savings observed over a six month period (January 2018 to June 2018).

Figure 7: Cooling Towers Above the Absorption Chiller at the Gallo Cattle Company Cheese Production Facility in Atwater, California



Source: Maas Energy Works

Targeting Natural Gas Savings in Food Service

In California, commercial kitchens are five times more energy intensive per square foot than typical commercial spaces.³⁸ High cooking temperatures and always-on control systems are common. Of the 800,000 commercial cooking appliances operating in California, roughly 70 percent are powered by natural gas and a minority have the ENERGY STAR® certification.³⁹ Commercial food service represents a market sector where strategic improvements in appliance design could result in large energy savings and emission reductions.

The Energy Commission funded research by the Gas Technology Institute and the California Food Service Technology Center on technology improvements that would provide energy savings in several key product areas affecting commercial food service. The project evaluated energy and operating patterns using a variety of standard commercial cooking appliances in six types of commercial kitchens, from light batch cooking at a grocery store to heavy use at a 24-hour airline catering business. From this

³⁸ ENERGY STAR® Guide for Cafes, Restaurants and Institutional Kitchens, p3, https://www.energystar.gov/ia/partners/publications/pubdocs/Guide%20for%20Cafes%20Restaurants%20and%20Institutional%20Kitchens_January%202014.pdf.

³⁹ ENERGY STAR® unit shipment dataset, p5: https://www.energystar.gov/ia/partners/downloads/unit_shipment_data/2016_USD_Summary_Report.pdf?cbe5-ee53.

evaluation, the project team identified common technology and operation shortcomings that hinder efficient natural gas use.

What researchers found is commercial food service appliances tend to have low heat use efficiencies, with peak (full-load) efficiencies in the 20 to 30 percent range and actual in-kitchen use efficiencies in the 5 percent to 10 percent range.⁴⁰ Appliances are typically operated under full-load conditions for only a small portion of their daily operating hours. The remaining time the appliances are operated under part-load and idle conditions, and most appliances do not have a setback mode to lower the temperature during non-cooking periods. The necessity for advanced or on-demand controls that sensed when appliances must be used was identified as an important strategy for eliminating wasted energy. Existing equipment also tend to use burners that transfer heat to the food product inefficiently. This finding emphasizes the necessity for advanced heating technologies including power burners, infrared burners, advanced heat exchangers, improved insulation, and combination hot air and steam heating.

The team replaced these food service appliances with more efficient, ENERGY STAR® equipment. The new appliances included more efficient burners and heat exchangers, improved insulation, and more sophisticated controls that allowed operators to optimize using energy in the kitchen without compromising performance. These sites were then monitored for energy use (Figure 8). Monitored sites reduced their gas use by 19 percent to 68 percent after the energy-efficient appliance replacements. One major success was the replacement of steamers and steam kettles to ENERGY STAR® steamers – two case studies showed an 80 to 90 percent reduction in energy consumption and 76 percent reduction in water consumption.

Figure 8: Combination Oven Testing at the Foodservice Technology Lab



Source: Food Service Technology Center in San Ramon, (Contra Costa County), California

⁴⁰ Fisher, D., et al., 2002. Commercial Cooking Appliance Technology Assessment. Food Service Technology Center Report 5011.02.26., <https://fishnick.com/equipment/techassessment/>.

In addition to appliance replacements, the project gathered real-time feedback from food service staff and provided training to help staff increase productivity while dramatically reducing energy consumption. Productivity increased in most of the test sites after equipment replacement while reducing energy consumption. In some cases, productivity increased because smaller, inefficient equipment was replaced by larger and more efficient models but in other cases, the kitchen staff were able to change a recipe or modify food preparation procedures to better use the new equipment. The project team found that training was critical to successfully having the staff integrate using the new equipment with existing operations. Without adequate training, staff either didn't use the equipment or used it incorrectly, thereby hindering the potential productivity benefits of the advanced technologies.

This project included strong links to the food service market and manufacturers with the team showcasing the results to food service operators, engineers, equipment manufacturers, contractors and installers to inform them of the energy efficiency and productivity benefits possible with food service equipment upgrades. Ultimately this project showed industry stakeholders that the initial investment in efficient appliance upgrades results in long-term energy savings that justify the higher purchase price.

Replacing current food service equipment with energy-efficient equipment will reduce energy use and operating cost for food service operators. Assuming a 25 percent market share after five years, equipment improvements and replacements recommended in this research could result in annual savings of 23.2 million therms and reducing 123,000 metric tons of greenhouse gases. Substantial energy cost reductions help California's food service industries stay competitive, and the early adoption of advanced, efficient technologies often confers an additional competitive advantage. Industry stakeholders were interested mostly in long-term potential for energy savings and performance improvements characterized by better cooking uniformity and reduced cook times. Advancements to food service technologies, and the associated adoption by the market, also help drive industry attention and investment in further technological improvements.

Improving the Cost-Competitiveness of Renewable Gas

Biogas represents a source of low-carbon energy to California, that can help minimize the climate change impacts of continued gas use. Renewable gas can be used as a substitute for conventional natural gas in a variety of applications with similar reliability and performance attributes.

Demonstrating New, Economical Applications for Biogas Recovery

There are more than 900 wastewater treatment plants (WWTP) in California that collect and treat roughly 4 billion gallons of wastewater per day.⁴¹ These WWTPs are energy-intensive to operate and produce residuals (such as biosolids) that are costly to manage. They also produce substantial amounts of biogas, about 17 billion cubic feet annually, which could be captured on-site and used to produce renewable energy for heating, electricity, or for transportation fuel. There is a market demand for biogas recovery systems that are designed and optimized for small WWTPs specifically processing fewer than 5 million gallons per day [MGD]) where historically it has not been economical to operate these systems.

The Las Gallinas Valley Biogas Energy Recovery System project with Las Gallinas Valley Sanitary District installed a pre-commercial biogas energy recovery system at a small WWTP in San Rafael, California (Marin County) (Figure 9). Compared to an average WWTP, which processes nearly 18 MGD of wastewater, the Las Gallinas Valley Sanitary District processes about 3 MGD. The system cleans and upgrades biogas produced by the plant into renewable gas, which is used to produce heat for the anaerobic digester of the plant, to produce electricity via two 65 kilowatt (kW) microturbines for plant operations (for example pumping, mixing), and to produce transportation fuel for natural gas vehicles that replace diesel vehicles onsite. Despite being a small WWTP, it is able to economically incorporate a biogas recovery system because the system uses all the available biogas at the plant. Biogas volumes are normally cyclical by season and by time of day. As a result, biogas recovery systems tend to be sized to use a lower volume of biogas with any additional gas being wasted by flaring it into the atmosphere. This system instead captures and uses the gas that would otherwise be flared to power vehicles onsite.

⁴¹ American Society of Civil Engineers. California Infrastructure Report Card: A Citizen's Guide – 2012. 2012. <https://www.watereducation.org/aquapedia/wastewater-treatment-process-california>.

Figure 9: Las Gallinas Valley Biogas Energy Recovery System in San Rafael, California



Microturbines (foreground), hydrogen sulfide removal system, and digester (background) at Las Gallinas Valley Sanitary District WWTP.

Source: Las Gallinas Valley Sanitary District

The biogas recovery system demonstrated by this project will result in important cost and environmental benefits for the WWTP and local community. The project team estimates that converting from diesel to renewable gas to fuel their vehicles will save roughly \$34,000 and 180 tons of CO_{2e} per year. Electricity generation from the microturbines powered by renewable gas displaces electricity purchased from the grid saving nearly \$70,000 per year. In addition, because the microturbines replaced an old reciprocating engine at the site, the system is expected to reduce oxides of nitrogen (NO_x) emissions by more than 8 tons annually.⁴² These results will be validated through one year of data collection which concludes at the end of 2018. Successful

⁴² The 2008 model year single-unit long-haul truck, 3.029 g/mile, 100,000 miles/year. Using emission factors from: Argonne National Laboratory. Updated Emission Factors of Air Pollutants from Vehicle Operations in GREET Using MOVES. 2013. <https://greet.es.anl.gov/publication-vehicles-13>

demonstration of this system will help expand the market for biogas energy systems in small wastewater treatment plants by proving they can operate cost-effectively at a smaller scale.

Reducing the Cost of Biogas Clean-up and Upgrading

California's biogas resources offer an opportunity for renewable energy production with much lower greenhouse gas emissions compared to fossil-derived natural gas. However, biogas is not easily used in a raw or unprocessed state and must be converted into renewable gas to expand the potential for use. Producing renewable gas requires a complex process of cleaning and upgrading biogas to remove contaminants that are not only harmful to human health, but also corrode and damage natural gas pipelines. Though many technologies exist for producing renewable gas they require extensive custom engineering and use large amounts of energy to regenerate the filter media. Some filter materials, such as activated carbon, are not easily regenerated and instead become waste material that is sent to landfills. Current state-of-the-art technologies are costly, complex, and energy intensive, produce waste material, and have a large physical footprint. The clean-up and upgrading process costs between \$6-\$90/mmBTU (compared to retail natural gas costs of \$3-\$5/mmBTU) which limits the cost-competitiveness of renewable gas compared to the fossil fuel counterpart.

The Energy Commission is funding several projects to improve the biogas cleanup and upgrading processes, looking for low-cost, energy-efficient solutions. One such project conducted by the Gas Technology Institute is developing and demonstrating a novel pathway to producing renewable gas from landfill gas, and is aiming for cost and complexity reductions across the entire biogas to renewable gas pathway.

Gas Technology Institute's flexible system is made up of three subsystems that are designed to remove a specific set of contaminants. The first subsystem removes water and carbon dioxide from the biogas, the second removes hydrogen sulfide, siloxanes, and oxygen, and the third removes nitrogen (Figure 10). Typically, each contaminant requires a specific subsystem for removal, while this system can remove multiple contaminants within one subsystem. Plants can identify which contaminants are most prevalent in the respective biogas source, then scale up or down the capacity of each subsystem to optimally reduce this unique mix of contaminants. This technology also uses less toxic and acidic compounds than conventional wet scrubbers and requires substantially less energy to regenerate the solvents for reuse after they have absorbed the contaminants.

Figure 10: Pilot-Scale Landfill Gas Cleanup Subsystems



Pilot-scale landfill gas cleanup subsystems which will sequentially remove water/carbon dioxide (left), nitrogen (middle), and oxygen/hydrogen sulfide/siloxanes (right).

Source: Gas Technology Institute

This system was designed and tested using actual landfill gas and each subsystem has demonstrated the ability to remove their targeted contaminants. To validate long-term operation, the project team is demonstrating a pilot-scale (100 standard cubic feet per minute) version of the system at the Coyote Canyon Landfill in Newport Beach, (Orange County) California. This size is comparable to the small end of commercially available systems that range from 50-500 standard cubic feet per minute.

While the Gas Technology Institute is targeting the entire biogas to renewable gas pathway, Mosaic Materials (PIR-14-021) aims for breakthrough cost reductions in the largest step in the process – carbon dioxide removal. Conventional wet scrubbers use liquid solvents to remove pollutants like carbon dioxide, but require pumping and operate under high temperature and pressure regeneration conditions, increasing their energy intensity. The Mosaic Materials technology uses low-cost, solid adsorbent pellets instead of a liquid solvent, which eliminates pumping and can be regenerated under milder operating conditions. This technology reduces the energy costs of removing carbon dioxide from biogas by up to 40 percent.

During the project, the solid adsorbent pellets removed carbon dioxide to the purity (less than 2 percent) required to meet pipeline-quality natural gas standards. Mosaic Materials proved the durability of the sorbent when exposed to raw biogas, and the ability of the material to absorb and desorb carbon dioxide over repeated cycles. Each of these tests validated the commercial viability of the technology. In addition, the team performed a cost analysis of its first-generation system, which showed a capital cost reduction of around 14 percent compared to conventional systems thanks to a simpler process and less equipment.

Successful demonstration of these systems will help expand the market potential for biogas to renewable gas systems in California. When commercially mature, both systems are expected to reliably and cost-effectively produce high quality renewable gas with a payback period of five years or less for potential customers such as landfills, wastewater treatment plants, organic waste recycling facilities, and dairy farms. In September 2018, Mosaic Materials received \$1.4 million in follow-up funding from the DOE to demonstrate the efficacy of the product at a wastewater treatment plant with the Napa Sanitation District.

Minimizing Air Quality Impacts From Natural Gas Use to Zero or Near-Zero Levels

The transportation sector accounts for about 39 percent of the state's greenhouse gas emissions and about 50 percent when including refinery emissions. Heavy-duty vehicles are the second largest contributor in the transportation sector.⁴³ In addition to carbon emissions, motor vehicles are the largest source of air pollution that harms human health, accounting for nearly 80 percent of NOx emissions and 90 percent of diesel particulate emissions. The Energy Commission is supporting development of advanced near-zero emission natural gas engines that use renewable gas and hybrid gas/electric fuels.

Similarly, combined heat and power (CHP) technologies can provide air quality benefits and reduce greenhouse gas emissions from industrial and commercial plants. CHP systems require less fuel to produce energy because they capture and use heat that would otherwise be wasted. The Energy Commission supports innovations in CHP technologies to lower the air quality impact of natural gas use.

Advancing Low-Carbon Transportation Technologies

Medium- and heavy-duty vehicles (MHDVs) such as trucks and buses account for more than 40 percent of NOx emissions.^{44,45} MHDVs are also responsible for nearly 20 percent of the GHG emissions from the transportation sector despite representing only 3 percent of registered vehicles in California.⁴⁶

⁴³ California Air Resources Board. California Greenhouse Gas Emissions for 2000 to 2016. June 2018. https://www.arb.ca.gov/cc/inventory/pubs/reports/2000_2016/ghg_inventory_trends_00-16.pdf.

⁴⁴ South Coast Air Quality Management District. *2016 Air Quality Management Plan. Appendix III: Base and Future Year Emission Inventory*. <http://www.aqmd.gov/docs/default-source/clean-air-plans/air-quality-management-plans/2016-air-quality-management-plan/final-2016-aqmp/appendix-iii.pdf?sfvrsn=6>.

⁴⁵ San Joaquin Valley Air Pollution Control District. *2016 Ozone Plan for 2008 8-hour Standard*. http://valleyair.org/Air_Quality_Plans/Ozone-Plan-2016/b.pdf.

⁴⁶ California Energy Commission. *Transportation Energy Demand Forecast, 2018-2030*. December 2017.

On-road vehicles with gross vehicle weights of 26,000 to 80,000 pounds are categorized as heavy-duty vehicles (HDV) with the majority powered by diesel engines. Producing and consuming diesel fuel results in high amounts of carbon dioxide (CO₂) emissions from upstream crude oil recovery and refinery processes and the high carbon content of the fuel. Diesel engines also emit high levels of NO_x, especially when operated at low speeds when diesel after-treatment systems are inactive because of low exhaust temperatures.

According to CARB, even a highly aggressive scenario with full-fleet penetration of engines that meet the United States Environmental Protection Agency's 2010 emission standards for heavy-duty on-road engines (0.20 grams per brake horsepower-hour [g/bhp-hr] NO_x) would not provide sufficient NO_x reductions to attain the federal ambient ozone standard.⁴⁷ NO_x emissions from heavy-duty on-road engines must be reduced beyond the 2010 emission standards to meet California's air quality goals.

The Energy Commission funded the development of Cummins Westport Inc.'s (CWI) "Near-Zero" natural gas engines to provide low-emission alternatives to diesel engines for the HDV market to power transit buses, refuse haulers, vocational trucks, and goods movement trucks. CWI built on its previous natural gas engine platform with three primary innovations to achieve low NO_x emissions:

1. An improved passive three-way catalyst after-treatment system that simultaneously reduces carbon monoxide, hydrocarbon, and NO_x emissions. The catalyst coating, volume, and sensor locations were optimized to meet the NO_x reduction target and provide on-board diagnostic capabilities.
2. Optimized engine software maintains tight control over the air-fuel ratio to ensure stoichiometric combustion occurs across the full range of engine operation. Stoichiometric combustion, where the air and fuel is burned completely, is necessary for the catalyst to effectively reduce emissions.
3. A closed crankcase ventilation (CCV) system reduces engine emissions by capturing and redirecting crankcase methane emissions back into the combustion chamber. Previous natural gas engines did not have a CCV system, which meant unburned methane leaked from the crankcase into the atmosphere. The CCV system uses a filter to separate oil from the captured crankcase gases, which helps maintain combustion, reduces NO_x emissions, and increases the engine's durability by preventing excessive oil consumption.

Since 2007, the Energy Commission has funded developing natural gas engines for on-road vehicles to reduce petroleum consumption, criteria pollutant emissions, and GHG emissions from the transportation sector. Past awards supported these natural gas

⁴⁷ California Air Resources Board. *Mobile Source Strategy*. May 2016. <https://www.arb.ca.gov/planning/sip/2016sip/2016mobsrc.pdf>.

engines that were designed to meet the 2010 emissions standard. In 2013, the Energy Commission, South Coast Air Quality Management District, and Southern California Gas Company supported research with CWI (500-12-002) to drive an additional 90 percent reduction in NOx emissions from the 2010 standard on a 9-liter natural gas engine. The success of this work led to continued efforts (500-16-002) to expand the market by developing a larger 12-liter low NOx natural gas engine that can support the performance demands of Class 8 trucks.

CWI certified the 9-liter and 12-liter variations of the Near-Zero engines to meet CARB's most stringent Optional Low NOx Standard (0.02 g/bhp-hr NOx) and began commercial production in 2016 and 2018, respectively.

Compared to a modern 2010 standard-compliant diesel engine, the Near-Zero engines emit 90 percent fewer NOx emissions and 10 percent fewer CO₂ emissions. The 9-liter and 12-liter Near-Zero engines underwent in-use emissions testing at the UC Riverside's chassis dynamometer center. The results validated the ability of the engines to consistently maintain low NOx emissions, even during low speed operation where diesel engines have been shown to emit much higher NOx emissions.⁴⁸

Major fleets such as the United States Postal Service and Waste Management demonstrated prototype engines throughout the development process, accumulating more than 1.8 million miles on 28 test units. These tests confirmed the durability, reliability, and performance of the Near-Zero engine's in real-world commercial fleet applications.

CWI produced 3,900 Near-Zero engines as of June 2018. Since the introduction of the Near-Zero engines into the market, several state and local clean transportation incentive programs have provided funding for fleets to accelerate adopting these engines because of the associated low NOx and GHG emissions compared to diesel engines. For example, 774 trucks equipped with the Near-Zero engines have received funding assistance through the Proposition 1B Goods Movement Emission Reduction Program managed by the San Joaquin Valley Air Pollution Control District and South Coast Air Quality Management District, which will result in 2,400 tons of NOx reductions over the vehicle lifetimes.⁴⁹ With funding assistance through the CARB's Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project and Low NOx Engine Incentives, 644 Near-Zero engines have been distributed. These vouchers require the vehicles to be fueled with renewable gas, which has a 50 percent lower average carbon

⁴⁸ Johnson, Kent, Yu. Jiang and Jiacheng Yang. November 2016. Ultra-Low NOx Natural Gas Vehicle Evaluation ISL G NZ.
http://www.cert.ucr.edu/research/efr/2016%20CWI%20LowNOx%20NG_Finalv06.pdf.

⁴⁹ Data acquired from South Coast Air Quality Management District and San Joaquin Valley Air Pollution Control District in May 2018.

intensity than diesel.⁵⁰ This translates to a reduction of nearly 900 tons of NOx and 1.1 million tons of CO₂ equivalent emissions over the vehicle lifetimes.⁵¹

Reducing Installation Costs for Combined Heat and Power in Commercial Buildings

Interconnection is a major cost component for installing new CHP systems. In 2003, California's Electric Rule 21 (a standardized interconnection process to the electricity grid) opened up the opportunity for distributed generation products to follow a simplified interconnection process if they were tested to be compliant or certified by a national laboratory such as Underwriters Laboratory (UL), and if the host facility met certain guidelines. However, at the time only higher-cost CHP options such as microturbines and fuel-cell combined CHP modules were able to meet the certification requirements.

In 2004, the Energy Commission funded Tecogen to begin developing an engine-driven CHP product that would meet the certification requirements of Rule 21, have ultra-low air emissions on par with fuel cells, and a small footprint with easy plug and play and operational compatibility to lower installation costs.⁵²

Tecogen's engine-based CHP module uses a water-cooled "permanent magnet" generator that produces electricity at much higher efficiency than conventional generators but without voltage and frequency regulation. The inverter power electronics of the module meet the interconnection and safety criteria required for UL 1741 certification. In addition, the module is equipped with sophisticated control algorithms that allows the unit to be operated as part of a microgrid because of the ability to blackstart (restore the system to operation without relying on external electric power grid). The simple interface of the module makes it easy to install in multiple unit applications and is internationally adaptable (50/60 Hertz) via a software change.

In addition, through a proprietary process developed by Tecogen with funding from the California Energy Commission and Southern California Gas Company, Tecogen's ultra-low emissions technology substantially reduces criteria pollutants by using a two-stage exhaust after-treatment catalyst. Emissions measurements from Tecogen systems

⁵⁰ California Air Resources Board. LCFS Pathway Certified Carbon Intensities. July 2018.
<https://www.arb.ca.gov/fuels/lcfs/fuelpathways/pathwaytable.htm>.

⁵¹ Calculation using Argonne National Laboratory's Heavy-Duty Vehicle Emissions Calculator: <https://afleet-web.es.anl.gov/hdv-emissions-calculator/>. Assumes clean truck replacement of 644 refuse trucks with low NOx natural gas trucks with 10 year lifetimes, 25,000 annual miles, and renewable gas derived from landfill gas.

⁵² The Energy Commission funded the development of the Tecogen system under agreement 500-03-039 followed by another agreement PNG-06-002. The Final Report for the first agreement is found here: <https://www.energy.ca.gov/2010publications/CEC-500-2010-006/CEC-500-2010-006.PDF>

equipped with the ultra-low emissions technology conform to the current CARB 2007 carbon monoxide (CO) and NOx standards for distributed power generation (Table 3). Tecogen's CHP module is now commercially available with 315 units sold in the United States and Europe and 13 units installed in California as of October 2018.

Table 3: Tecogen System Compared With Higher Cost CHP Options

	Fuel Cells	Microturbines	Typical Engines-Genset	Tecogen
Capital Costs	High	High	Low	Low
Operation and Maintenance Costs	High	High	Low	Low
Meets Rule 21 Certification	Yes	Yes	No	Yes
Air Pollution Emissions	Low	Low	High	Low*
Physical Footprint	Large	Large	Small	Small
Response Time	Slow	Fast	Fast	Fast

***Post-treatment with ultra-low emissions technology**

Source: California Energy Commission staff, 2018, based on communication with Tecogen

LIST OF ACRONYMS

Term	Definition
AB	Assembly Bill
BTU	British thermal unit
CARB	California Air Resources Board
CCV	Closed crankcase ventilation
CHP	Combined heat and power
CO ₂	Carbon dioxide
CO ₂ e	Carbon dioxide equivalent
CPUC	California Public Utilities Commission
CWI	Cummins Westport, Inc.
E3	Energy + Environmental Economics
EPIC	Electric Program Investment Charge
g/bhp-hr	Grams per brake horsepower-hour
GHG	Greenhouse gas
GFO	Grant Funding Opportunity
GPS	Global Positioning System
HDV	Heavy-duty vehicle
HUD	United States Department of Housing and Urban Development
HVAC	Heating, ventilation, and air-conditioning
IoT	Internet of Things
MGD	Million gallons per day
MHDVs	Medium- and heavy-duty vehicles

Term	Definition
mm/Btu	Million British Thermal Units
NO _x	Oxides of nitrogen
PIER	Public Interest Energy Research
PON	Program Opportunity Notice
R&D	Research and Development
SB	Senate Bill
UC	University of California
UL	Underwriters Laboratory
WWTP	Wastewater treatment plant

APPENDICES:

The following appendices are available under separate cover (Publication Number CEC-500-2019-026-APA-D) upon request by contacting Tiffany Solorio at Tiffany.Solorio@energy.ca.gov:

- Appendix A: Select Policy Goals for California's Energy Future
- Appendix B-1: FY 2017-18 Natural Gas Approved Funding
- Appendix B-2: FY 2017-18 Natural Gas Funding Opportunities
- Appendix B-3: Natural Gas Project Funding 2004 – Present
- Appendix C: FY 2017-18 Natural Gas Active and Completed Agreements List
- Appendix D: FY 2017-18 Natural Gas Active and Completed Project Write-Ups