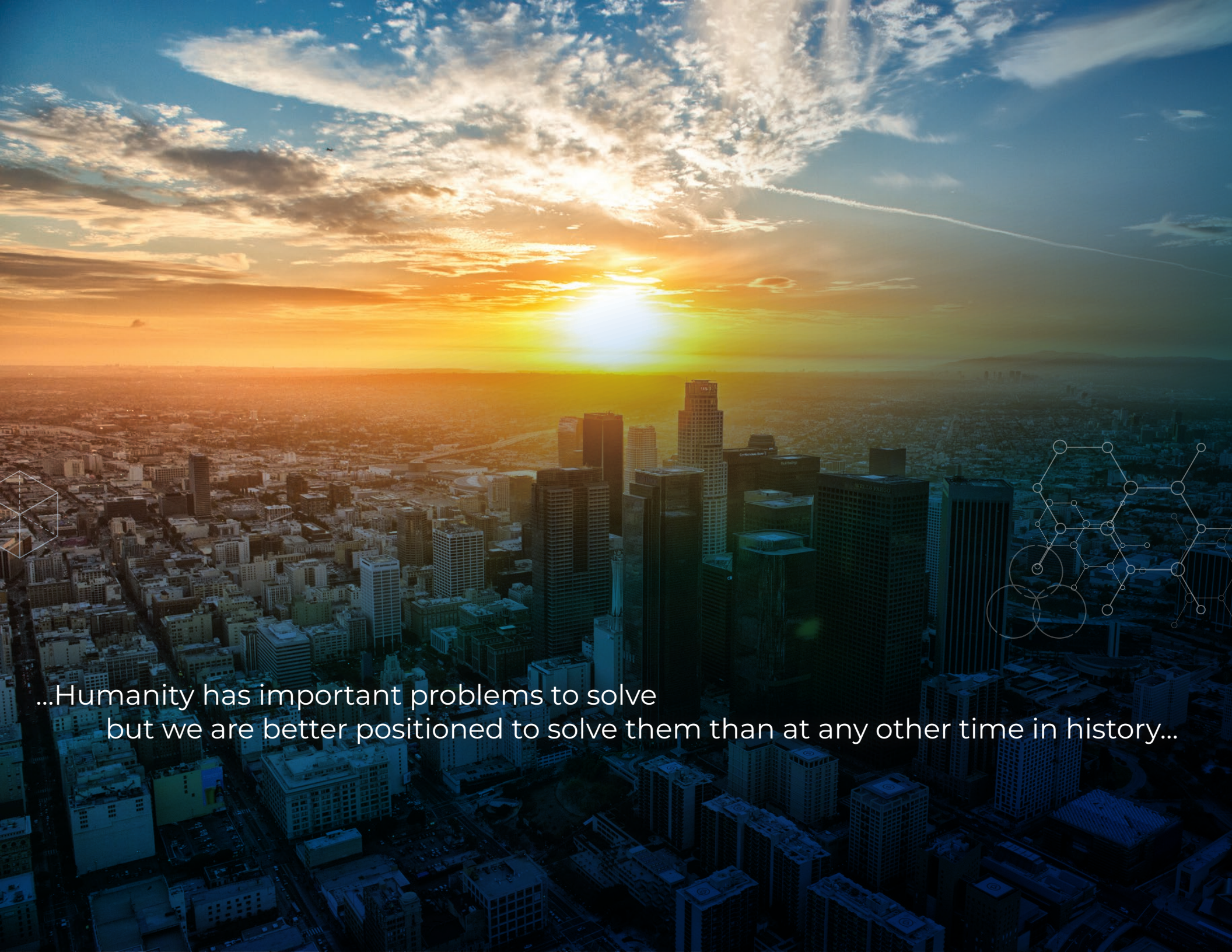
SoCalGas

RESEARCH, DEVELOPMENT, AND DEMONSTRATION PROGRAM

2021 ANNUAL REPORT


“The future
IS VERY BRIGHT...


...Humanity has important problems to solve
but we are better positioned to solve them than at any other time in history...

...To help build a decarbonized energy system for California, SoCalGas is overcoming challenges, implementing solutions, and collaborating with innovative partners so every Californian can have access to clean, reliable, and affordable energy."

—MARYAM BROWN
PRESIDENT
SOCALGAS

Contents

Introduction

2021 was a year of challenges. The pandemic continued to wreak havoc on our healthcare system and on the many individuals and families who suffered illness and loss. Supply chain disruptions plagued the global economy. And an ever-warming planet saw more frequent and intense fires, drought, and heat waves.

But it wasn't all bad news.

2021 was also a time of renewal, with scientific research and exploration leading to incredible discoveries and advancements. Widespread vaccination and the development of promising new antiviral medications began to mitigate the worst impacts of the pandemic. Humanity landed rovers on the Moon and Mars and launched a deep space telescope capable of peering back billions of years to a time when our universe was young.

The energy industry reached significant milestones in its efforts to decarbonize how we produce, store, distribute, and consume energy. Today, more than 90% of newly installed electric capacity comes from onshore wind and solar installations. Over the last decade, the average price of solar installations has dropped by 89%, while onshore wind costs have declined by 70%. And, according to the International Energy Agency's (IEA) Global Hydrogen Review 2021, there are signs that low-carbon hydrogen is on the "cusp of significant cost declines and widespread global growth."

In California and across the nation, investment in clean energy is booming. In 2021, California committed more than $1 billion to clean transportation, long-duration energy storage, green hydrogen production, and other programs and technologies focused on reducing carbon emissions. Nationally, 2021 marked the passage of the Infrastructure Investment and Jobs Act, which allocates more than $20 billion to pilot and demonstration projects that advance carbon capture and removal, hydrogen, and green industrial technologies.

In 2021, California committed more than $1 billion to clean transportation, long-duration energy storage, green hydrogen production, and other programs and technologies focused on reducing carbon emissions.

SoCalGas™ Leads Decarbonization Efforts

With more than 21 million customers and one of the nation's largest networks of gas transmission, storage, and distribution infrastructure, SoCalGas is well-positioned to play a central role in the ongoing decarbonization of the energy industry.

In the short term, the existing gas distribution network can be used to carry drop-in clean fuels, such as renewable natural gas (RNG). California also has access to abundant geological resources that can be repurposed for carbon sequestration.

Sustainable progress, however, will require a diversified portfolio of clean energy sources, technologies, and tools, as well as energy efficiency, to provide resilience and reduce the risks of over-dependence on any one technology.

The SoCalGas Research, Development, & Demonstration (RD&D) Program is tasked with identifying and supporting projects and technologies with the potential to save energy, reduce greenhouse gas (GHG) emissions, improve air quality, and increase the safety, reliability, and affordability of energy. In 2021 alone, RD&D Program staff invested almost $17 million in hundreds of energy technology and clean fuels projects—from those that remove carbon dioxide from ocean water to projects that use hydrogen-fuel-cell-powered drones to inspect gas infrastructure or affordably extract green hydrogen blended into the gas pipeline for use in industry or transportation.

Driven by scientific research and collaboration with subject matter experts from universities, national labs, public agencies, private industry, and research consortia, RD&D Program staff are deeply committed to accelerating the energy transition to clean fuels and educating policy makers, industry, and the general public about the many ways it is seeking to achieve that goal.

"Governments need to take rapid actions to lower the barriers that are holding low-carbon hydrogen back from faster growth, which will be important if the world is to have a chance of reaching net zero emissions by 2050."

—Fatih Birol
Executive Director
International
Energy Agency

Vision, Mission, and Values

The vision, mission, and values of the SoCalGas Research, Development, and Demonstration Program align with SoCalGas' mission to build the cleanest, safest, and most innovative energy company in America.

OUR VISION

Advancing innovative technologies for safer, cleaner, and more reliable energy.

OUR MISSION

Identify transformational energy solutions. Build them. Share them with the world.

OUR VALUES

Science

Our experts in science, engineering, energy systems, and environmental policy seek answers to some of today's most pressing energy questions.

Synergy

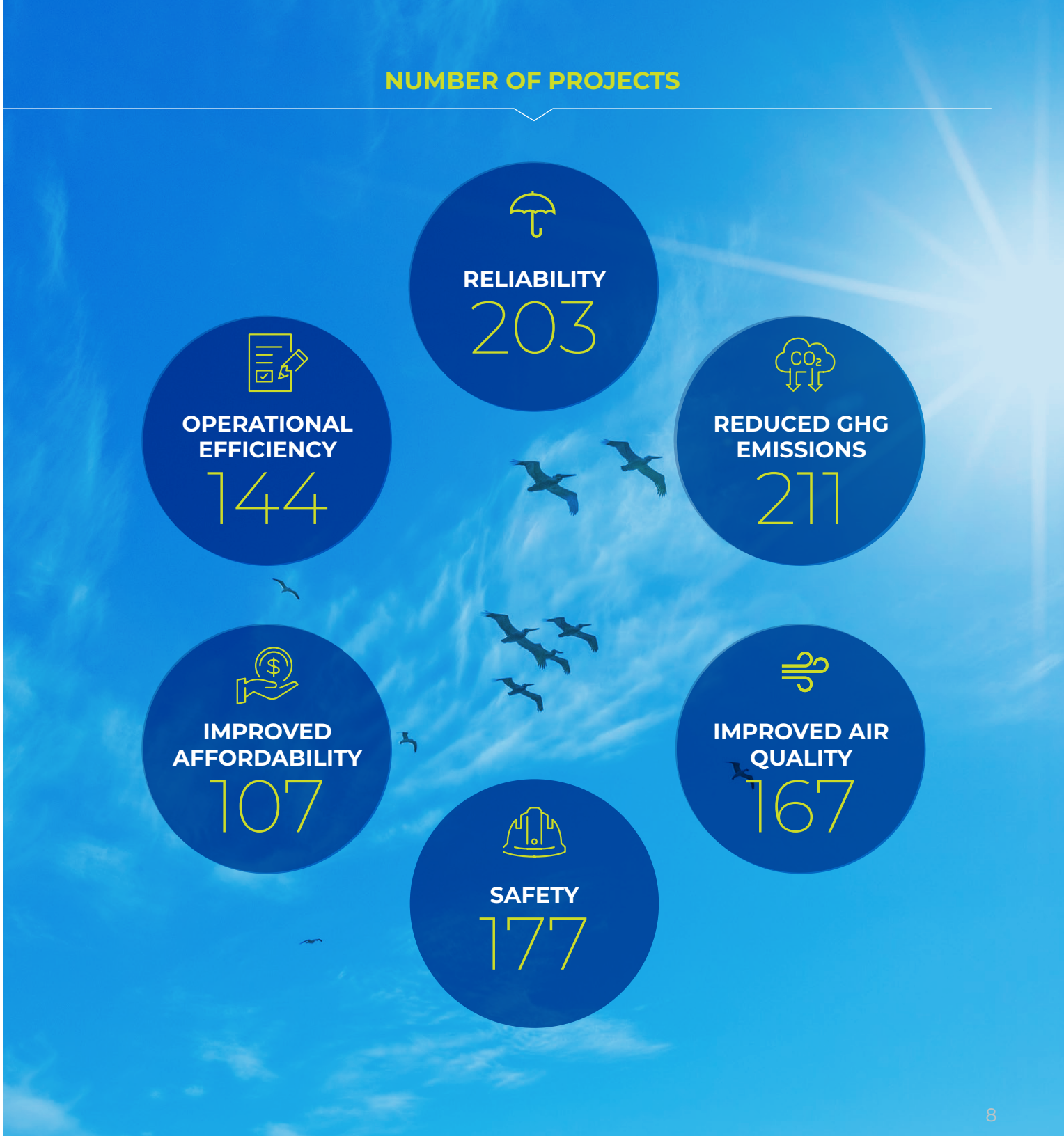
We work with the world's finest researchers in universities, national labs, and industry to develop transformational technologies that support decarbonization, energy security, and economic development.

Equity

We champion technologies that support affordable access to clean, safe, and reliable energy for all Californians.

Program Benefits

Each year, the RD&D Program supports hundreds of projects along the commercialization pathway, with the ultimate goals of saving energy, reducing GHG emissions, improving air quality, and increasing energy safety, reliability, and affordability.



2021 IN REVIEW

"We've got the whole delegation here as a united front on this challenge, which is, how do we make sure that people understand that this clean energy transition is about opportunity and creating jobs instead of fearing it."

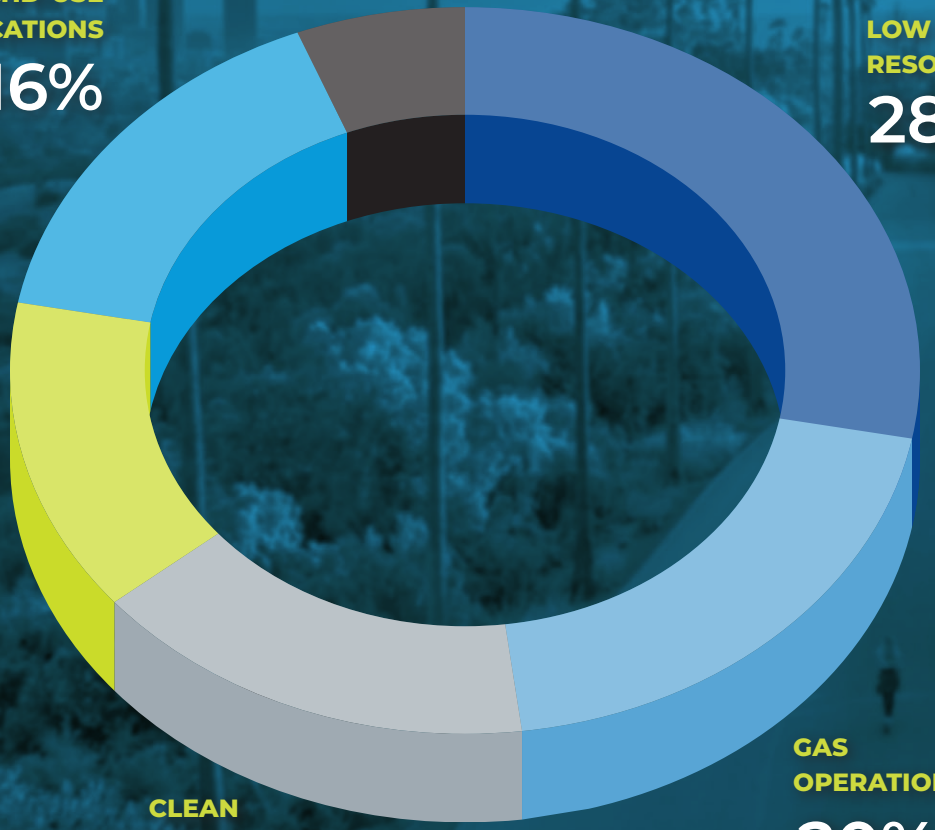
—Jennifer Granholm
U.S. Energy Secretary

Financial Highlights

In 2021, the RD&D Program supported 379 RD&D projects and distributed $16,977,474 to projects across the entire gas value chain. In executing these projects, SoCalGas collaborated with many of the most forward-thinking research consortia, universities, national labs, public agencies, and entrepreneurs across the nation and around the world. Collectively, these organizations provided significant funding, as well as invaluable guidance, review, technical expertise, and access to resources and infrastructure.

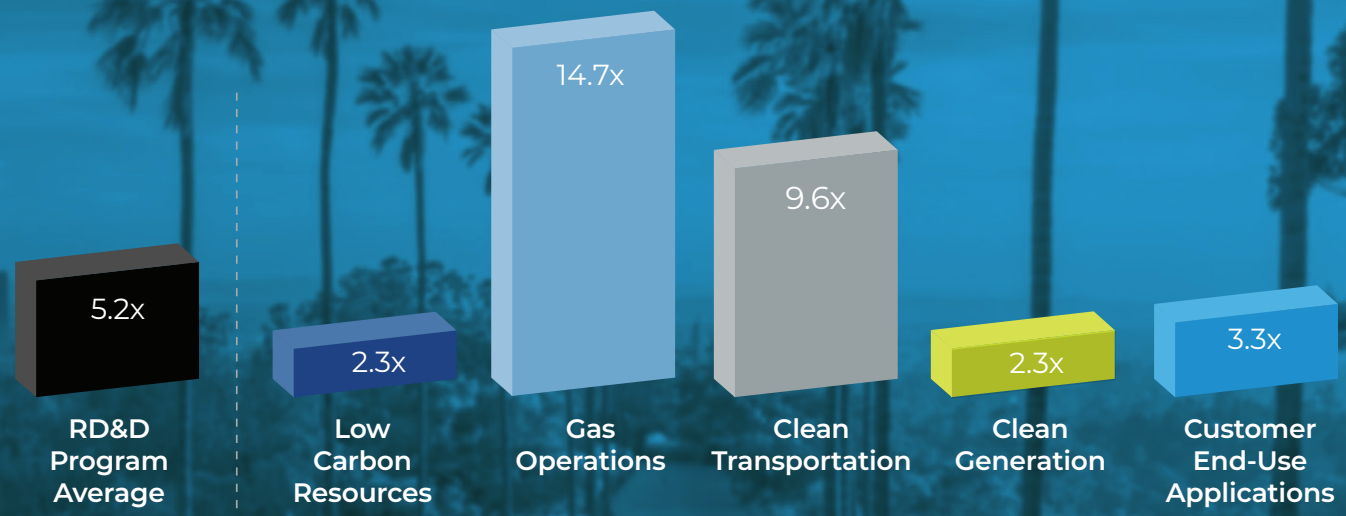
Split across five program areas—Low Carbon Resources, Gas Operations, Clean Transportation, Clean Generation, and Customer End-Use Applications—these projects encompassed everything from fundamental

2021 ACTUAL FUNDING BY PROGRAM AREA AND ADMINISTRATIVE COSTS



research and laboratory testing to real-world demonstrations and pilots. Importantly, they achieved substantial progress toward commercializing new, safe, reliable, and affordable clean energy products and technologies.

RATIO OF OUTSIDE FUNDING TO SOCALGAS FUNDING



2021 Funds Expended

In 2021, the SoCalGas RD&D Program invested $16,977,474 in numerous projects across the entire gas value chain, with an additional $1,057,195 going toward program management and administration. Collectively, these projects leveraged significant co-funding from businesses, research consortia, and other participating organizations. On average, every dollar of SoCalGas RD&D funds expended was matched by $5.20 in funding from other sources in 2021.

PROGRAM	2021 ACTUALS
Low Carbon Resources	$5,018,729
Gas Operations	$3,561,049
Clean Transportation	$2,844,666
Clean Generation	$2,608,167
Customer End-Use Applications	$2,944,863
SUBTOTAL	**$16,977,474**
Management & Administration	$1,057,195
TOTAL	**$18,034,669**

Significant 2021 Milestones

TOTAL **ACTIVE PROJECTS** IN 2021
379

TOTAL **PROJECTS COMPLETED** IN 2021
114

TOTAL **PROJECTS INITIATED** IN 2021
72

2021 ANNUAL STAKEHOLDER WORKSHOP

On April 14, 2021, RD&D Program staff hosted an online workshop attended by 165 individuals from a wide variety of organizations, including GTI, Lawrence Berkeley National Laboratory, Los Angeles Department of Water and Power, National Renewable Energy Laboratory (NREL), Society of Professional Hispanic Engineers, Stanford University, and the University of California. Program staff incorporated input received at the workshop into the 2021 RD&D Program Research Plan.

RESEARCH WEBINARS

In 2021, SoCalGas presented quarterly research webinars discussing three projects supported by the RD&D program.

- **Materials-Based Hydrogen Storage for Heavy Duty Vehicles**
  October 14, 2021: Representatives from Sandia National Laboratories and the DOE Hydrogen Materials–Advanced Research Consortium discussed the development of light-weight materials based on metal hydrides that could enable the use of light-weight alloys to construct storage tanks that operate at relatively low pressure (maximum 100 bar).

- **Biomethanation: Using Natural Organisms to Convert Waste CO2 and Renewable H2 to RNG for Long-Duration Energy Storage and Decarbonization**
  August 24, 2021: In this webinar, Dr. Kevin Harrison, Senior Engineer at NREL, discussed a new technology that uses naturally-occurring micro-organisms to transform renewable hydrogen and carbon dioxide into RNG. This process, known as biomethanation, could aid in decarbonizing the natural gas grid.

- **SoCalGas and C-Zero present: Co-producing Hydrogen and Valuable Solid Carbon from Natural Gas**
  June 23, 2021: Zach Jones and Dr. Fadl Saadi introduced a new process for transforming natural gas into hydrogen and a solid carbon co-product via methane pyrolysis and the role that this process can play in decarbonizing existing natural gas infrastructure.

Significant 2021 Milestones

FOLLOW-ON FUNDING

» **Electrochaea**
With support from the RD&D Program, Electrochaea demonstrated its biomethanation technology at NREL. In 2021, Baker Hughes—a $20-billion industrial services company—purchased a 15% stake in Electrochaea, backing a technology intended to address concerns about GHG emissions.

» **Twelve (formerly Opus 12)**
After early support from the RD&D Program, this electrochemical carbon dioxide reduction startup raised $57 million in Series A funding from lead investors Capricorn Technology Impact Fund and Carbon Direct Capital Management.

» **Stone Mountain Technologies, Inc. (SMTI)**
The RD&D Program provided early support to SMTI, a company focused on providing cost-effective, low-carbon heating and cooling solutions, including gas heat pump technology. In 2021, Enbridge, Inc. invested CAN$4,000,000 in SMTI.

» **High yield Energy Technologies (HyET) Group**
SoCalGas supported a closed-loop field demonstration of HyET's technology by providing access to a demonstration site, funding, and detailed specifications needed to blend hydrogen into the natural gas pipeline. Fortesque Future Industries acquired a 60% stake in HyET in late 2021.

FORTNIGHTLY TOP INNOVATOR 2021

Public Utilities Fortnightly, a forum for stakeholders in utility regulation and policy, recognized the RD&D Program as a Fortnightly Top Innovator in 2021. Fortnightly Magazine interviewed RD&D Program staff members Eric Coene, Ron Kent, and Matt Gregori on October 25, 2021.

EXPANDED OUTREACH

In 2021, the RD&D Program began sharing content about program activities and projects on its new LinkedIn page:

https://www.linkedin.com/showcase/socalgas-research-development-&-demonstration-rd&d-/about/

Leveraged Public Funding

In 2021, program staff supported 11 winning proposals applying for public funding. These projects were awarded $48,429,528 in research funding from the California Energy Commission (CEC), the U.S Department of Energy (DOE), and the DOE's National Energy Technology Laboratory (NETL).

5 PROJECTS WON A TOTAL OF **$12,999,620** FROM THE CEC

Publications

In 2021, projects co-funded or otherwise supported by the RD&D Program were featured in 40 reports, technology briefs, or articles in prestigious academic journals, such as Nature Communications and ACS Energy Letters.

Deployed Technologies

A major goal of the RD&D Program is to bring technology from the lab to market. In 2021, organizations across California and throughout the nation deployed numerous products and technologies for real-world use as a direct result of the support they received from the RD&D Program. Examples from 2021 include:

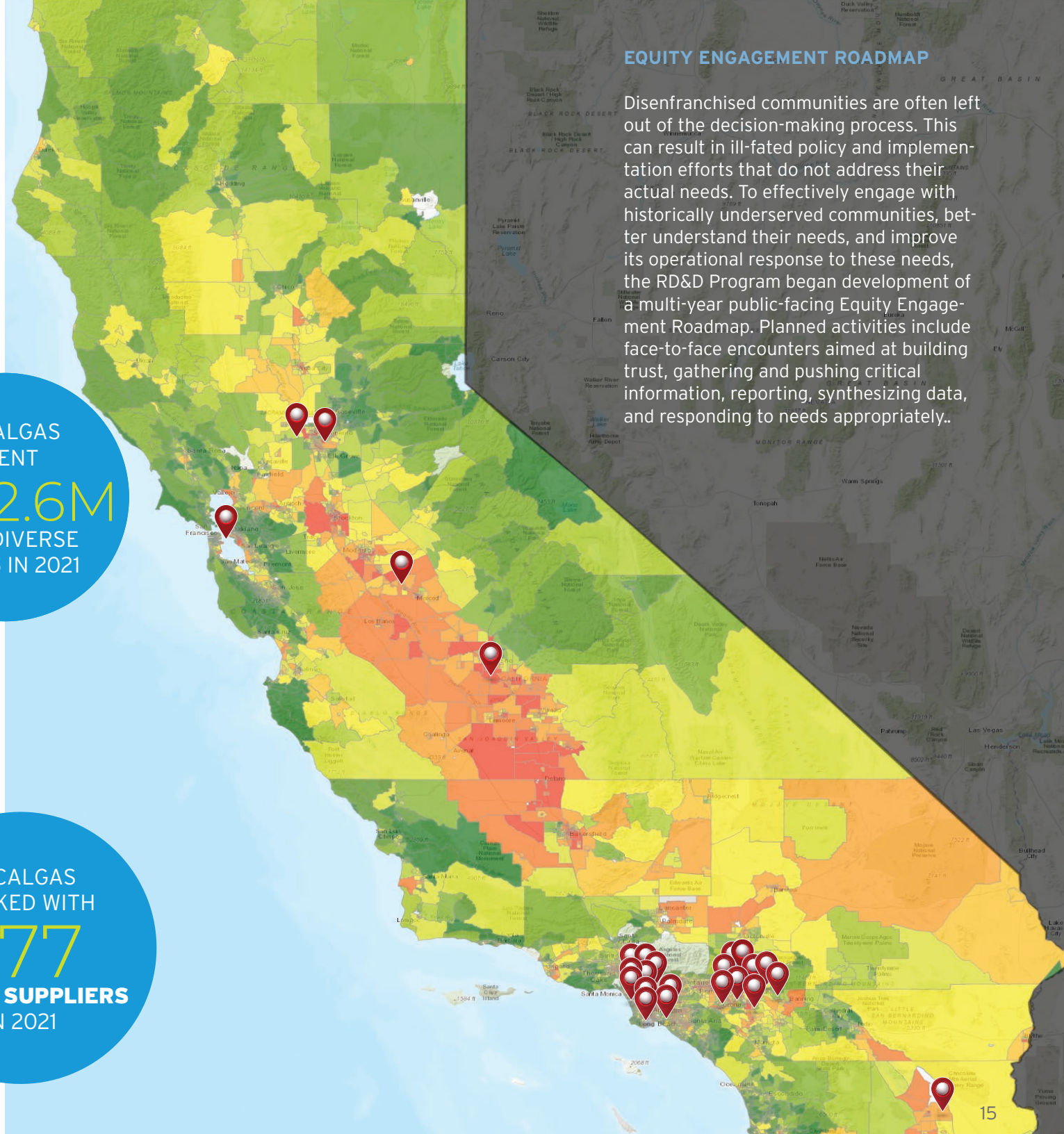
- AC Earth Faults (9.16.d)
- Biomethane Justification Study for Improved/Accepted Gas Quality Standards (7.18.b)
- Fault Displacement Hazard Initiative (UCLA)
- Flow Testing of FS500 Meters (MEAS-6-11A)
- Kiefner Interactive Threats Project (T-768)
- Material - Suppliers Quality Assurance Program (5.17.g)
- Rough Walled Pipe Gas Metering Applications (MEAS-6-5D)
- SMTI Heat Pump Commercialization (Stone Mountain Technologies)
- ThermoLift Combined Heating/Cooling System Technical Support – Phase 2 (1.17.F.2)
- Trace Constituent Database (7.18.h)
- Tracking and Traceability for Transmission, Pipe Materials, Phase 4 (Additional Demos) (5.14.d.4)
- Uniform Frequency Code (5.18.m)
- Unmanned Aerial System RD&D
- Update ASTM Standard on Soil Compaction Control Using the DCP (5.20.o)

2021 Equity Activities

SOCALGAS SPENT
$972.6M
WITH DIVERSE **FIRMS** IN 2021

THE RD&D PROGRAM SUPPORTED
27
PROJECTS LOCATED IN SB 535 DISADVANTAGED **COMMUNITIES** IN 2021

SOCALGAS WORKED WITH
577
DIVERSE **SUPPLIERS** IN 2021



EQUITY ENGAGEMENT ROADMAP

Disenfranchised communities are often left out of the decision-making process. This can result in ill-fated policy and implementation efforts that do not address their actual needs. To effectively engage with historically underserved communities, better understand their needs, and improve its operational response to these needs, the RD&D Program began development of a multi-year public-facing Equity Engagement Roadmap. Planned activities include face-to-face encounters aimed at building trust, gathering and pushing critical information, reporting, synthesizing data, and responding to needs appropriately..

2021 Equity Activities

COMMUNITY OUTREACH CALLS

- **February 24, 2021:** SoCalGas met with representatives from Home Aid Orange County, Proteus Inc., Pomona Chamber of Commerce, Unity Shoppe Santa Barbara, Santa Barbara Zoo, Southeast Community Development Corporation, Family Assistance Ministries, El Concilio Family Services, and Family Service Association. RD&D Program staff presented material about new technologies with the potential to benefit disadvantaged communities and priority populations. Attendees raised concerns about energy reliability and its relation to storing medications or preparing meals. Affordability of both energy and the new technologies was a key concern.

- **March 10, 2021:** Representatives from CSET Community Services Employment Training, Proteus Inc., Orange County Asian and Pacific Islander Community Alliance, Inc., Community Action Partnership of Kern, Asian Youth Center, Endowment for Youth Committee, and the Greater Lakewood Chamber of Commerce. RD&D Program staff presented material about new technologies with the potential to benefit disadvantaged communities and priority populations. Attendees posed numerous questions and raised several concerns, including affordability, which is "the number one concern for our low-income constituents."

- **May 19, 2021:** SoCalGas met with representatives from the University of California Riverside's Center for Renewable Natural Gas, Cal Poly Pomona, California State University (CSU) Long Beach, CSU Fullerton, the University of California-Irvine, and Cal State Los Angeles met with SoCalGas. RD&D Program staff asked the participants how the program could help them meet their goals and solicited input on their key concerns, including energy affordability, safety, air quality, and emissions.

- **August 25, 2021:** SoCalGas hosted representatives from Cypress College, Pasadena City College, Santa Barbara City College, Kern Community College District, East Los Angeles College Engineering & Technologies, Bakersfield College, Cerritos Community College, and Saddleback College. RD&D staff sought to understand how the program could help the participants meet their goals and solicited input on their key concerns, including energy affordability, safety, air quality, and emissions.

- **September 8, 2021:** SoCalGas met with representatives from the University of Southern California, California Greenworks, Delhi Center, and the Municipal Water District of Orange County. RD&D Program staff asked the participants how the program could help them meet their goals and solicited input on their key concerns, including energy affordability, safety, air quality, and emissions.

SPOTLIGHT

2021 Equity Activities

Cal State LA drives upward mobility through senior-year engineering program

The Capstone Senior Design Program helps students learn to solve real-world engineering challenges and gain valuable professional skills.

Located in the heart of Los Angeles, Cal State LA is a public university known for serving numerous Hispanic, Asian American, Pacific Islander, and minority students. Many are from low-income families and are the first in their families to attend college.

The university is ranked number one in the nation for upward mobility, in part due to programs such as its Engineering, Computer Science, & Technology Capstone Senior Design Program. Each year, funded by corporate and university sponsorships, the program gives students open-ended, real-world problems to solve. Working in small groups, the students meet with faculty advisors and project sponsors, work collaboratively, learn new skills, and present their results to faculty and sponsors.

In 2021, Arezoo Khodayari, an Associate Professor in the Department of Civil Engineering, served as faculty advisor on a project sponsored by SoCalGas. Two groups of students sought to optimize the hydrogen production schedule at Cal State LA's Hydrogen Research and Fueling Facility (H2 Station).

With an onsite storage capacity of 60 kilograms (kg), H2 Station is the

Students in Cal State LA's Capstone Senior Design Program sought to optimize the hydrogen production schedule at the university's Hydrogen Research and Fueling Facility.

largest university-located hydrogen fueling facility in the U.S. The station uses grid-sourced electricity to run an electrolyzer to produce hydrogen throughout the day, including during peak demand periods when the cost of electricity—and, therefore, hydrogen—is high. The students sought to minimize the cost of producing hydrogen by developing a smarter production schedule.

The two teams approached the challenge in different ways, with each developing different optimization models. Additionally, each team modeled multiple optimization scenarios, factoring in seasonality, time of day, utility seasonal rates, minimum hydrogen storage levels, and sales demand. One team also explored the impact of incorporating onsite solar into the power supply mix.

The students created an algorithm that used 2019-2020 fuel sales data to estimate fuel production costs for the same period if H2 Station had used the optimized production schedules developed by the students. The students determined that the station could reduce its electricity costs by between 10 and 30%, depending on various factors, such as minimum storage tank capacity and time of hydrogen production.

The students presented their results to SoCalGas, Professor Khodayari, and Professor David Blekhman, the director of H2 Station. "The students showed that the university could significantly reduce electricity costs for H2 Station while continuing to meet demand," said Khodayari. "It was eye-opening."

Sponsorship by SoCalGas has been valuable on many fronts. "The Capstone Program is costly," said Khodayari. "We need funding to reimburse faculty time and purchase supplies and equipment. Our sponsors—including SoCalGas—provide funding and other resources that we use to keep the program running." SoCalGas also helped develop the project concept, advised the students throughout the year, and provided feedback on the end-of-year presentation.

"SoCalGas is a leader in the energy industry, an area that increasingly interests our students," added Khodayari. "Many of them are excited to work for and learn from SoCalGas. In fact, SoCalGas has hired more than one graduate of the program. It has been a great collaboration."

"Without the Capstone experience, many of our students would have no other opportunity to prepare themselves for the job market and gain valuable experience," said Khodayari. "Through the program, they develop valuable skills, grow professionally, and learn how to work on a team and with clients. They become problem solvers—something that is needed on a real job."

"The Capstone Program is costly. We need funding to reimburse faculty time and purchase supplies and equipment. Our sponsors—including SoCalGas—provide funding and other resources that we use to keep the program running."

—Arezoo Khodayari
Associate Professor
Department of Civil Engineering
Cal State LA

Program

Program Goals and Structure

The goals of the RD&D program are to identify, test, and commercialize transformational new energy technologies that will reduce GHG and criteria air pollutant emissions, maintain the energy affordability that natural gas has historically provided, and advance the safety, operational efficiency, and reliability of California's gas delivery networks and systems in an ever-changing operational environment.

Concurrent with the pursuit of these goals, SoCalGas seeks to decarbonize its pipeline by replacing conventionally sourced, fossil-based natural gas with increasingly higher amounts of RNG and hydrogen to benefit its customers and support California in the achievement of its ambitious climate change goals.

Consistent with the framework established in Public Utilities Code Section 740.1, program staff consider multiple factors when selecting projects to support. These factors include regulatory and policy drivers, input from knowledgeable industry stakeholders, equity, and corporate policy and goals.

In 2021, the RD&D Program allocated funding across five research program areas: Low Carbon Resources, Gas Operations, Clean Transportation, Clean Generation, and Customer End-Use Applications.

FIVE RESEARCH PROGRAM AREAS

Low Carbon Resources

- Low Carbon Hydrogen Production
- Low GHG Chemical Processes
- Renewable Gas Production

Gas Operations

- Environmental & Safety
- Operations Technology
- System Design & Materials
- System Inspection & Monitoring

Clean Transportation

- Off-Road
- Onboard Storage
- On-Road
- Refueling Stations

Clean Generation

- Distributed Generation
- Integration & Controls

Customer End-Use Applications

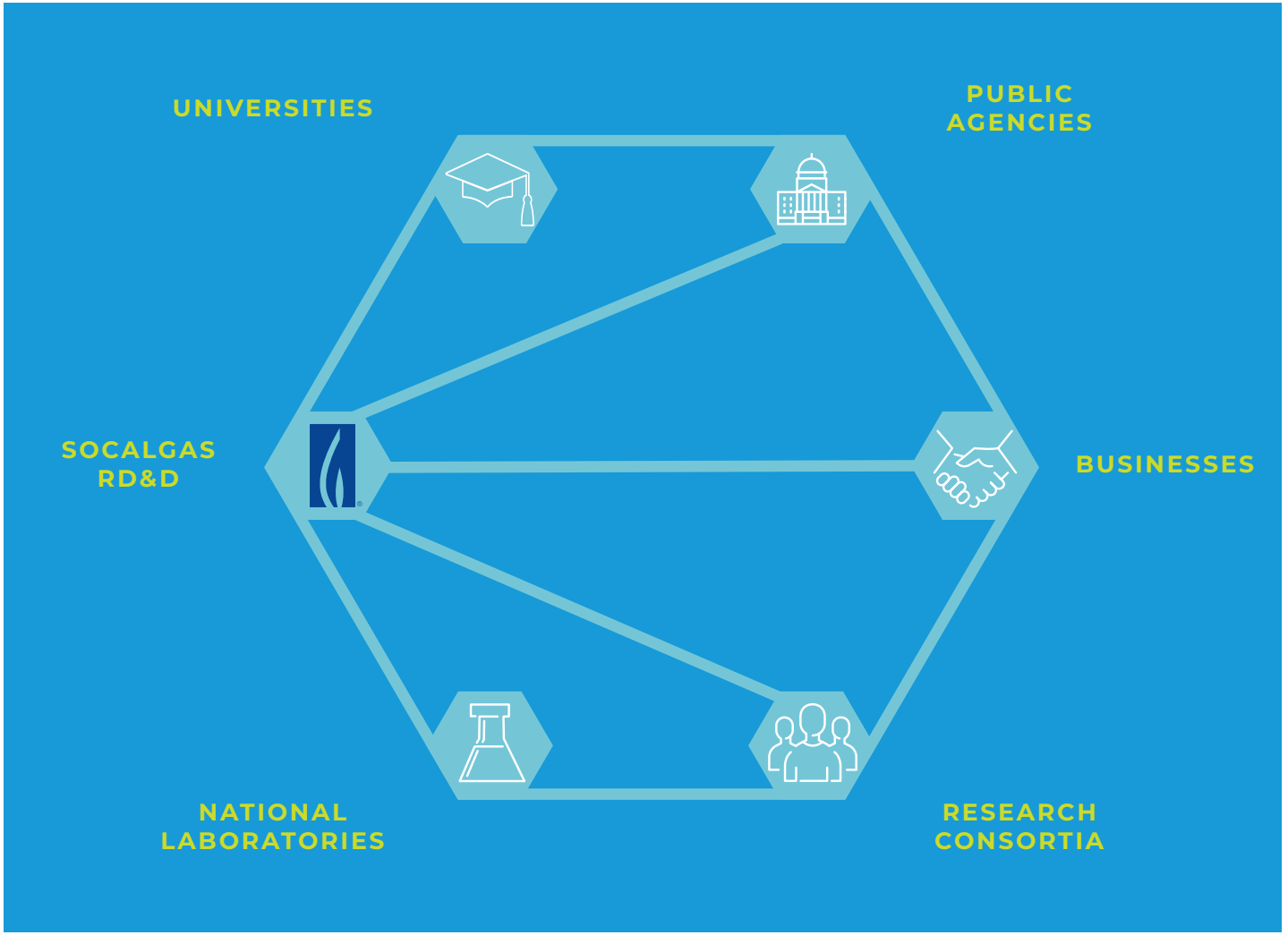
- Advanced Innovation
- Commercial Applications
- Commercial Food Service
- Industrial Process Heat
- Residential Appliances

Research Collaborators

The SoCalGas RD&D Program is a vital element of a much larger technology funding ecosystem that includes gas industry research consortia and numerous federal, state, and regional public agencies. Program staff work with professionals and subject matter experts from these organizations, as well as from universities, national labs, and businesses, to maximize the impact of their investments in promising technologies and products with clear commercialization pathways.

These relationships enable SoCalGas to engage in open dialogues to more effectively identify and close knowledge and research gaps, avoid duplication of previous and ongoing research, and mitigate technical, economic, and commercialization risks. This helps program staff in their quest to develop products and technologies that reduce customer costs, save energy, increase safety and reliability, improve air quality, and reduce GHG emissions.

Together, RD&D staff and research collaborators exchange information and research concepts, collaborate on project development, establish partnerships, and actively seek public and private funding opportunities, with the goals of securing additional co-funding and assembling capable and impactful project teams.



"Our planet's health, economic well-being, and national security are all at risk. It is imperative that we address the climate challenges we face with a fierce sense of urgency — human lives and livelihoods are at stake."

— Colorado Senator John Hickenlooper

PROGRAM: LOW CARBON RESOURCES

The primary goal of the Low Carbon Resources program area is to decarbonize the gas supply while maintaining its affordability and reliability. To accomplish this goal, program staff members develop, promote, and advance new technologies aimed at increasing the production of renewable gas to displace conventionally sourced pipeline gas, while also limiting or recycling GHG emissions.

In 2021, this program included three subprograms:

Low-Carbon Hydrogen Production

This subprogram focuses on the production of low-carbon and GHG-emissions-free hydrogen from various methane feedstocks, including biomethane. Areas of focus include, but are not limited to, advanced steam methane reforming (SMR) and methane pyrolysis technologies.

Low-GHG Chemical Processes

This subprogram focuses on the design, development, and deployment of technologies that can minimize reliance on natural gas combustion, and on carbon capture utilization and sequestration (CCUS) technologies for the capture of GHG emissions and their conversion into valuable chemicals or sequestration.

Renewable Gas Production

This subprogram focuses on the safe, reliable, and cost-effective production of renewable gaseous fuels—specifically, RNG and hydrogen—from various feedstocks and multiple technological pathways. Areas of focus include, but are not limited to, biomass processing and conversion, renewable hydrogen production from direct water splitting, and methanation pathways to produce RNG from captured carbon dioxide.

SPOTLIGHT

Low Carbon Resources

Novel technology extracts hydrogen blended into existing gas pipelines on demand

HyET Hydrogen develops distributed technology with no moving parts that can cost-effectively extract hydrogen from existing gas pipelines.

HyET Hydrogen recently demonstrated a closed-loop pilot system capable of extracting pure streams of hydrogen from blends of methane and hydrogen at the SoCalGas Engineering Analysis Center in Pico Rivera, California.

TOTAL PROJECT COST: $609,500

SOCALGAS:	$609,500
COFUNDING:	$0

Hydrogen is poised to play a key role in the decarbonization of transportation. One of the greatest barriers to its widespread adoption, however, is the cost and difficulty associated with its distribution from the point of generation to its ultimate end users.

Using conventional technologies, this process requires energy-intensive compression and transportation via tanker truck, both of which increase cost and emissions.

To overcome these challenges, gas utilities and technology companies have begun to explore blending hydrogen into existing natural gas infrastructure. One company, HyET Hydrogen, recently demonstrated a closed-loop pilot system capable of extracting pure streams of hydrogen from blends of methane and hydrogen, with hydrogen concentrations ranging from 2.5% to 15% at a variety of flow rates and operating pressures. HyET demonstrated the system at the SoCalGas Engineering Analysis Center in Pico Rivera, California.

"Transporting hydrogen via existing gas pipelines would be a major step forward," said Jonne Konink, Co-CTO of HyET Hydrogen. "You avoid the emissions associated with transporting hydrogen via tanker truck as well as the need to construct a costly, parallel distribution system—something that's virtually impossible in many congested urban areas."

Constructed within a 20-foot shipping container, the pilot system included multiple sample points, storage tanks for methane and hydrogen, a circulation fan, and HyET's innovative compressor and extractor.

At the heart of the extractor is a membrane electrode assembly (MEA), which consists of a proton-conducting membrane coated on both sides with catalysts that can dissociate hydrogen into protons when current is applied. "The membrane allows protons to pass through it and acts as a barrier to other gases in the pipeline," says Konink. On the other side, they recombine with the electrons to form hydrogen gas in a compression stack that gradually builds in pressure as the number of protons increases. "The only moving parts are the molecules."

Initially, the project faced numerous challenges. "We started out trying to build a system in the United States from the Netherlands because we were unable to travel for much of 2020 due to COVID-19," said Konink. When HyET staff finally reached the United States, they faced difficulties sourcing materials and labor. "Hydrogen molecules are quite small and tend to migrate through materials. We had to source specially rated steel for piping as well as welders experienced in working with it."

The team's hard work and perseverance paid off. "The first time we filled up the system and turned on the extractors, we pulled out hydrogen immediately," said Konink. "No tinkering needed. It just worked." HyET experienced similar results with the compressor. "It compressed to 400 bar—as designed—with no issues. We made minor adjustments to sensors and other components, but the actual science worked in one go."

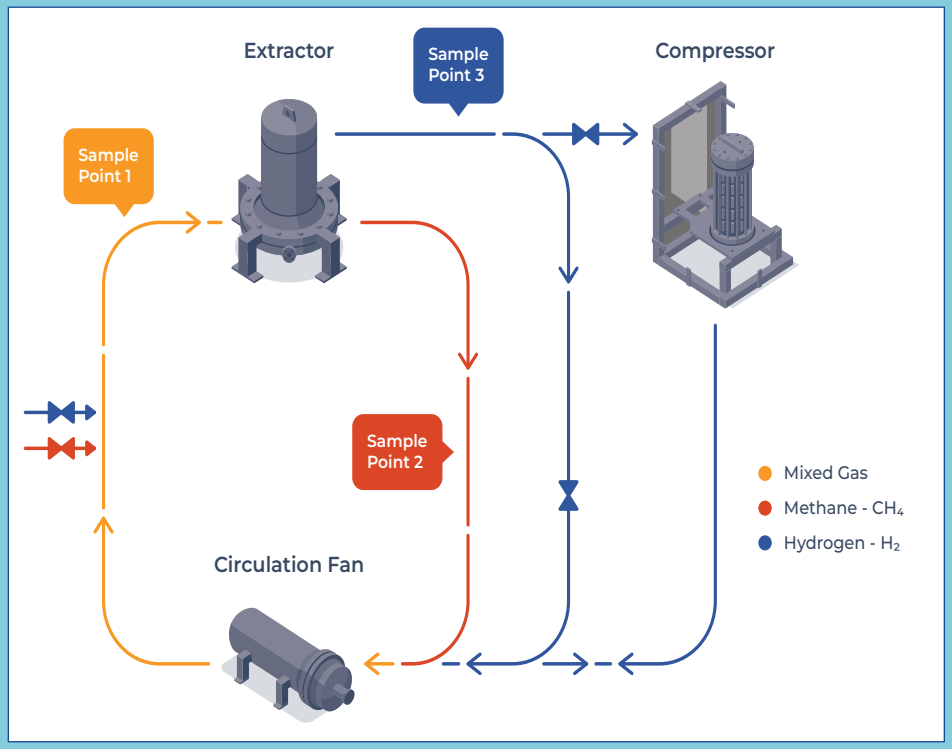
"Our technology does not really have any competitors," said Maria Fennis, CEO of HyET Hydrogen. "You can install it anywhere you have a natural gas line that contains a blend of hydrogen." The system is quiet, turns on and off in seconds, and requires little maintenance. "It literally provides on-demand hydrogen production." Designed to extract 10 kg per day, the pilot can easily scale to 2,000 kg per day simply by increasing vessel size.

"With this technology, hydrogen distribution is close to being solved," said Konink. Unfortunately, formidable regulatory barriers still remain. "Utilities are not allowed to blend hydrogen into existing pipelines," said Konink. "For the moment, we are confined to testing it on infrastructure isolated from the main gas network."

In the near term, however, HyET's technology shows promise in other applications, such as replacing the costly purification and compression components of conventional SMR systems, today's most common method of hydrogen production. "That would be a tremendous success and would enable us to continue to develop the technology until regulatory conditions are more favorable," said Fennis.

"Ultimately, we are trying to convert consumers to a gas—hydrogen—that doesn't harm the planet, while continuing to earn money with our operations," said Rombout Swanborn, Co-CTO and founder of HyET Hydrogen. "This technology enables us to leverage existing infrastructure while transitioning gradually from natural gas to hydrogen."

"In all of these efforts, SoCalGas staff were absolutely critical," Swanborn continued. "They have been the driving force behind this project, providing access to the demonstration site, funding, and detailed specifications for pressure output, temperature, and blend percentages. They are also helping us plan larger-scale, future applications."



The pilot system included multiple sample points, storage tanks for methane and hydrogen, a circulation fan, and HyET's innovative compressor and extractor.

SPOTLIGHT

Low Carbon Resources

Innovative technology captures carbon dioxide from ocean water

Caltech achieves highest current density ever achieved at lab scale in an electrodialyzer and sets stage for lower-cost carbon capture.

TOTAL PROJECT COST: $1,050,000

SOCALGAS:	$200,000
COFUNDING:	$850,000

In 2021, the average concentration of carbon dioxide (CO_2) in the Earth's atmosphere reached 419 parts per million—the highest level in recorded history—with the total mass of atmospheric carbon surpassing 750 quadrillion kilograms. That number is dwarfed, however, by the vast quantities of carbon found in the oceans, which contain 93% of the carbon stored in the atmosphere, oceans, and land biosphere.

The oceans absorb 30% of the CO_2 released into the atmosphere. As anthropogenic carbon emissions have increased, however, the oceans have been negatively impacted. "When CO_2 diffuses into oceanwater, it combines with water molecules to form carbonic acid, a weak acid that dissociates into hydrogen ions—protons essentially—and bicarbonate ions," says Chengxiang Xiang, Research Professor of Applied Physics and Materials Science at the California Institute of Technology (Caltech). "More CO_2 in the air means more protons in the water, which decreases the pH of the ocean and contributes to acidification."

Many companies have begun capturing carbon from industrial processes or removing it from the atmosphere via Direct Air Capture (DAC). "Unfortunately, DAC alone is not enough," says Xiang. Removing CO_2 from the air changes the gas pressure balance between air and water. When the gas pressure of CO_2 in the air drops below that of CO_2 in the ocean, CO_2 diffuses across the air-ocean boundary into the atmosphere—undoing a significant part of the progress made by DAC.

With support from SoCalGas and the U.S. Department of Energy, Caltech is seeking to reverse that process by developing an innovative and affordable Direct Ocean Capture (DOC) technology. "By capturing CO_2 from oceanwater—and changing the CO_2/bicarbonate equilibrium at the ocean water/air interface—the oceans will actually suck CO_2 from the air," says Xiang. When scaled, the technology could potentially remove carbon from the oceans at the gigaton scale.

The project had an unlikely beginning. "In 2020, SoCalGas helped us develop a techno-economic analysis (TEA) of potential ways to produce renewable methane," says Xiang. That study led the team to consider using CO_2 in the air and oceans as a possible feedstock for processes such as methanation, which converts hydrogen and CO_2 into methane. This TEA helped Caltech determine the key technical goals

required to affordably capture carbon from oceanwater.

The Caltech team envisioned an offshore system that would capture CO2 from oceanwater, remove it for industrial use or sequestration, and increase the pH of the water it returns to the ocean to pre-industrial levels, helping to mitigate ocean acidification.

The system inputs oceanwater at a pH of 8.1 and passes it through a micro-screen filter that removes grit, debris, and suspended solids. A very small fraction of the oceanwater is diverted to an electrodialyzer. Here, the ocean-water is dissociated into a concentrated acid, a concentrated base, and dilute streams through use of an electrodi-alysis system supported by a bipolar membrane (BPM). The concentrated acid is used to acidify a large volume of the oceanwater for the subsequent CO2 stripping step. Before its return to the ocean, the process water is combined with the concentrated base and dilute stream to adjust the water's pH to pre-industrial levels.

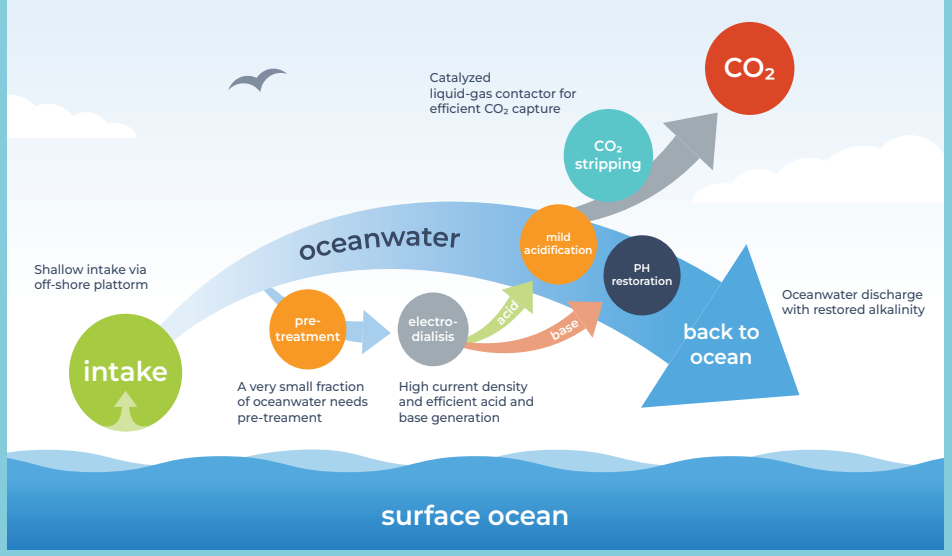
"Early seed funding for the TEA from SoCalGas gave us the time to explore possibilities and attract additional funding," said Xiang. This included an $850,000 award from the DOE's Advanced Research Projects Agency–Energy program for development of an off-shore, electrochemical-driven CO2 capture process. SoCalGas invested an additional $200,000 specifically to advance development of the electrodialyzer.

"The electrodialyzer is the critical cost lever of the entire system," says Xiang. "It is responsible for roughly 80% of overall system energy consumption." To drive down capital costs, Caltech ultimately hopes to achieve a current density of >500 mA/cm2, an order of magnitude higher than traditional sys-tems. "If we can do that, the overall system will be cost-competitive with other carbon capture technologies."

During the lab-scale work on the electrodialyzer, Caltech made signif-icant progress toward that ultimate goal. Caltech staff experimented with a range of materials and configura-tions until identifying a configuration that achieved a current density of 1 A/cm^2. "That's the highest current density ever achieved at lab scale in an electrodialyzer," says Xiang.

Caltech also sought to re-engineer the BPM. "In existing electrodialyzers, the water dissociation reaction is too slow," says Xiang. Additionally, at high current densities, water cannot flow into the BPM interface at a fast enough rate, which limits the maximum allowable cur-rent density. Thus, as voltage increases, there is no corresponding increase in current. "The BPM interface also dries out, which can cause irreversible damage to the membrane. We overcame these limitations by fabricating a custom, asymmetric BPM and using a graphene oxide catalyst at the BPM interface to increase the rate of reaction."

By the end of 2021, Caltech had demon-strated a lab-scale electrodialyzer



The system inputs ocean water and diverts a very small fraction to an elec-trodialyzer, where it is dissociated into a concentrated acid, a concentrated base, and dilute streams. The concentrated acid is used to acidify a large volume of the oceanwater for the subsequent CO2 stripping step. Before its return to the ocean, the process water is combined with the concentrated base and dilute stream to adjust the water's pH to pre-industrial levels.

capable of CO2 extraction from oceanwater at 93% purity with an electrochemical energy of 1 kWh/kg-CO2 at an applied current density of 3.3 mA/cm^2. "We have achieved close to 100% capture efficiency," says Xiang. "Electrodialyzers are not new, but we really pushed the envelope in terms of how they are used in carbon capture."

In 2022, Xiang seeks to scale up the technology to demonstrate the com-mercial viability of a pilot plant capable of capturing CO2 from oceanwater at a rate of 100 metric tons per year. "At that scale, the system will intake 700 to 1,000 gallons a minute," says Xiang.

"SoCalGas has been really support-ive in helping us move from the lab to a much larger scale," says Xiang.

"They not only provided seed and follow-on funding but also specifica-tions for industrial-quality CO2 that could be sequestered to offset the utility's carbon emissions or used to produce renewable methane. SoCal-Gas is also assisting Caltech with an early-stage spinoff, Captura, that is developing a one-ton-per-year pilot system for demonstration in 2022.

"If scaled, this technology could be critical to the fight against climate change," says Xiang. "It would enable industries that are difficult to decarbonize—such as steel, cement, and chemicals—to offset their current carbon emissions. It would also enable them and many other industries to capture histori-cal emissions."

PROGRAM:

GAS OPERATIONS

The Gas Operations RD&D program supports pipeline transportation and storage operations through innovations that enhance pipeline and employee safety, maintain system reliability, increase operational efficiency, and minimize GHG impacts to the environment. The program also supports technology development driven by emerging regulatory requirements. Its primary goals are to develop, test, and introduce new gas operations technologies that are beneficial to ratepayers through improvements in public and pipeline safety, system reliability, operational efficiency, and environmental benefits.

The program invests in technology development projects that are divided into the following subprograms:

Environmental & Safety

This subprogram seeks to advance the environmental integrity of the pipeline network and the safety of those who live and work in proximity to it. Environmental projects focus on developing technologies that also support state goals. Safety projects are concerned with protecting the pipeline from intentional and unintentional damage and with improving the safety of the general public and company employees or contractors working on or around the pipeline. Projects include exploring how blending hydrogen into the pipeline impacts the operation and maintenance of the pipeline system regarding safety, reliability, integrity, and environmental impacts.

Further gas emissions monitoring and reduction research is being supported by the SoCalGas Natural Gas Leakage Abatement R&D Program under the SB 1371 compliance plan, pursuant to the Gas Leak Abatement OIR (R.15-01-008).

Operations Technology

This subprogram supports technologies that improve employee training, efficiency of construction, and the operation/maintenance/rehabilitation of gas pipelines, as well as systems that facilitate continued safe and reliable service. This subprogram also explores how best to prevent gas leaks that result from blending hydrogen into the pipeline.

System Design & Materials

The objectives of this subprogram are to advance materials and materials science, materials tracking and traceability, and technical tools for designing pipeline systems and infrastructure for safety, reliability, efficiency, and maintainability throughout the lifecycle of pipeline assets. Projects include research to advance engineering design standards and models, developing risk analytical tools to comply with pipeline integrity regulations, modeling operational efficiencies of gas storage and compressor station assets, and assessing the effects of incorporating gas from non-traditional sources (biogas and hydrogen-blend) on overall natural gas quality and system integrity.

System Inspection & Monitoring

The objectives of this subprogram include developing technologies and methods for inspection, monitoring, and testing of pipelines and pipeline components to assess the condition and performance of pipeline facilities. The goal is to improve system performance, reliability, safety, and operational efficiencies through data management to identify precursors to failures or incidents. Projects in this subprogram leverage artificial intelligence, machine learning, and preventive and predictive maintenance technologies, including data analytic models and data lakes, and innovative data sources such as Crowd Source and the Internet of Things. This subprogram also seeks to explore tools for managing the potential impacts of blending hydrogen into the gas pipeline.

SPOTLIGHT

Gas Operations

Utility consortium drives policy change through R&D

OTD develops new pipeline integrity methodologies that reduce cost, increase reliability, and improve safety.

The U.S. Pipeline and Hazardous Materials Safety Administration (PHMSA) is responsible for developing and enforcing regulations for the safe, reliable, and environmentally sound operation of the nation's 2.6 million miles of pipelines.

In 2020, Congress enacted a law that strengthened PHMSA's authority to advance the safe transportation of energy and other hazardous materials. One consequence of the new law was the sunsetting of a "grandfather" clause that exempted pipeline operators from obtaining critical safety information about pipelines installed prior to 1970. Operators must now provide this information, often at great cost.

"The current gold standard for determining pipeline material properties involves cutting a ring sample from the pipe and subjecting it to destructive testing," says Michael Adamo, Vice President of Operations at Operations Technology Development (OTD), a gas research consortium. This process is costly and can require the temporary shutdown of a pipeline or installation of a bypass.

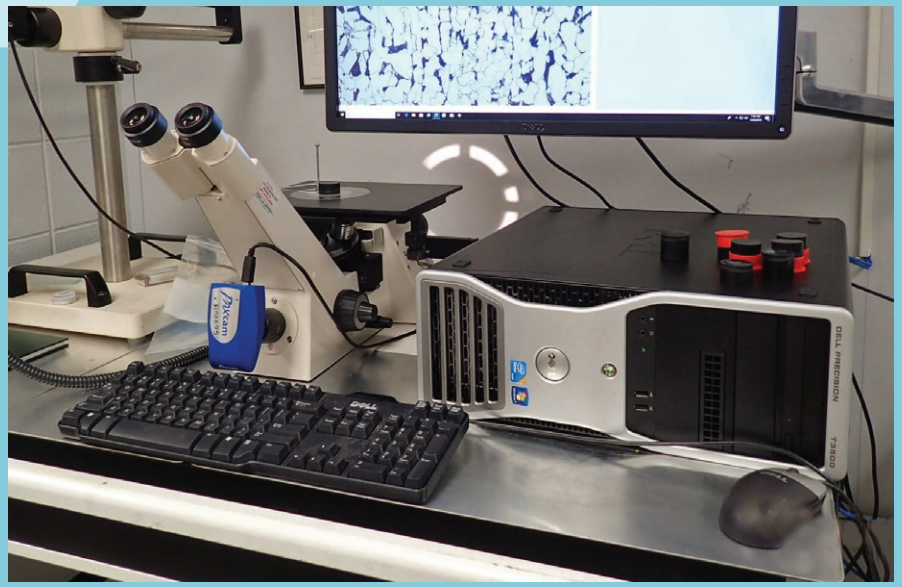
In 2018, PHMSA awarded OTD a $489,515 Safety Research & Development (R&D) grant to develop testing procedures that would enable operators to use nondestructive evaluation (NDE) technologies on a pipe and, through correlation, accurately determine a variety of characteristics about the pipeline properties, including yield and tensile strength, as well as steel chemistry. OTD subcontracted the work of integrating state-of-the-art causal and data modeling to GTI, a non-profit R&D organization focused on new energy technologies.

"Pipeline steel, depending on the manufacturing method and material type, can have varying characteristics on its outside wall compared to its bulk properties throughout the pipe wall," said Adamo. "But

The project sought to develop testing procedures that would enable operators to use nondestructive evaluation technologies on a pipe and, through correlation, accurately determine a variety of pipeline characteristics, including yield and tensile strength, and steel chemistry.

TOTAL PROJECT COST: $1,054,516

SOCALGAS:	$57,874
COFUNDING:	$996,642



Project team members first lab-tested the samples for yield strength, ultimate tensile strength, steel chemistry, grain size, hardness, and in a subset of 30 samples, material fracture and Charpy toughness.

when determining yield strength and setting operating pressure, it's very important to have a consistent and accurate way of modeling these variations. Inaccurate information can lead to unsafe operations."

Daniel Ersoy of Element Resources served as principal investigator. Arizona State University assisted Ersoy with in-depth statistical modeling. Several utilities—including Intermountain Gas Company, Dominion Energy, and Southwest Gas Corporation—provided 70 pipeline samples for use in characterizing pipeline properties, correlating the surface-to-bulk properties, and developing predictive models of bulk properties based solely on surface-obtained pipeline data. More than 60% of the samples were installed prior to 1970.

Project team members first lab-tested the samples for yield strength, ultimate tensile strength, steel chemistry, grain size, hardness, and, in a subset of 30 samples, material fracture and Charpy toughness. Technology providers Frontics, SciAps, and Massachusetts Materials Technology (MMT) then performed NDE testing of the surface of the pipelines using their respective nondestructive testing equipment. The project team compared these data to full wall testing data and used causal and statistical modeling with surface-obtained pipe data to establish yield and tensile strength surface-to-bulk property predictions and chemical variance distributions.

SoCalGas supported this project through its membership in OTD, which includes 28 member utilities from around the country that pool funds to develop advanced technologies for the natural gas industry. "SoCalGas has been a great asset to OTD in helping provide an end user's perspective," said Adamo. "This project is a great example of collaboration between the research community, a regulatory body, and industry to achieve solutions to problems that the entire industry faces. In the end, ratepayers are the real beneficiaries of this research because it reduces operational costs, increases system reliability, and improves safety."

Following successful completion of the project, GTI is working closely with PHMSA to incorporate knowledge gained into its regulation on pipeline safety and testing. Once this happens, utilities across the nation—including SoCalGas—will be able to formally adopt the new methodologies and practices.

SPOTLIGHT

Gas Operations

Design safer, more reliable pipelines

UCLA-led team creates comprehensive database and models to more accurately predict fault displacement hazards that could damage underground pipelines.

California is home to thousands of miles of underground natural gas infrastructure, much of which crosses earthquake fault zones. Moderate to severe earthquakes can rupture the earth's surface along these zones, producing permanent ground displacements. For example, in 2016 an earthquake along the Kekerengu Fault in New Zealand resulted in a displacement of 12 meters. Such displacements can cause significant damage to underground pipeline infrastructure.

Engineers can develop site-specific engineering solutions to quantify the seismic performance of pipelines and other extended infrastructure against fault displacements. To do so effectively, however, they need access to accurate fault displacement data and models.

To address this challenge, the University of California, Los Angeles (UCLA) initiated the Fault Displacement Hazard Initiative (FDHI) Project in 2018. UCLA collaborated with multiple national and international universities, gas and water utilities, and public agencies such as the California Geological Survey.

California is home to thousands of miles of underground natural gas infrastructure, much of which crosses earthquake fault zones. Moderate to severe earthquakes can rupture the earth's surface along these zones, producing permanent ground displacements and damaging pipelines.

TOTAL PROJECT COST: $2,415,000

SOCALGAS:	$150,000
COFUNDING:	$2,265,000

The project seeks to develop a structured relational fault displacement database that will support creation of new, probabilistic models and, ultimately, a probabilistic fault displacement hazard map of the state of California. "Utilities will be able to overlay their pipeline maps on the hazard map and obtain a color-coded risk assessment of their infrastructure that will identify where the risk of catastrophic fault displacement is highest," said Dr. Yousef Bozorgnia, a professor in UCLA's Department of Civil & Environmental Engineering.

For help funding the multiyear project, UCLA first turned to California's largest utilities, SoCalGas and Pacific Gas & Electric Company. "They provided seed funding that enabled us to seek and obtain additional funding from other sponsors," said Bozorgnia. "Their early support was very valuable." The project leveraged this early funding to obtain a grant from the California Energy Commission to further support this fault displacement work as well as research on landslides, liquefaction, and ground shaking.

In 2021, the project team completed the database. "Earthquakes happen around the world but before now there were only databases with limited fault displacement data for various styles of faulting," said Bozorgnia. "Through a literature review and international collaboration, especially with colleagues in Europe, we systematically collected data from 66 global earthquakes of magnitudes 5.0 to 8.0 and then assessed the data for completeness, accuracy, and consistency."

While developing the database, the researchers collaborated extensively with the model developers to ensure that database content addressed the needs of model development. "Several fault displacement models are in use today," said Bozorgnia. "These models differ widely, however, in their input datasets, estimated displacement metrics, modeling techniques, and treatment of uncertainty."

To mitigate these issues, the FDHI modelers are relying on the comprehensive FDHI database and creating four probabilistic fault displacement models, each using different sets of assumptions. It is important to develop multiple models as each model has its own strengths and weaknesses. Model development is on track for completion in summer of 2022. In the final phase of the project—scheduled for completion by early 2023—the team will create the probabilistic hazard map of the state of California for fault displacement.

Once complete, the database, models, and hazard map will be published on the UCLA website and available to everyone. Following publication, the project team will continue to collect data, especially for larger-magnitude earthquakes. "Ultimately, we will update the model every few years to further improve its accuracy," said Bozorgnia.

"Earthquakes happen sooner or later," said Bozorgnia. "With this project, our goal is to reduce the risk that potential hazards will become disasters. What we are doing is not abstract. It is based on real-world numbers and input and will help utilities design safer pipelines and prioritize replacement schedules based on realistic estimates of risk."

PROGRAM:

CLEAN TRANSPORTATION

The Clean Transportation program supports activities that reduce environmental impacts related to the transportation sector. Focusing on utilization of RNG and renewable hydrogen, this program facilitates the development of zero-emissions technology for on-road and off-road applications, fueling infrastructure, and on-board storage technologies.

This program includes four subprograms:

Off-Road

This subprogram focuses on developing zero emission off-road transportation solutions using RNG and renewable hydrogen. Its goal is to achieve emissions reductions from off-road vehicles such as trains, ocean-going vessels, commercial harbor craft, construction equipment, and cargo handling equipment. Subprogram staff have also begun to explore aviation applications, including hydrogen fuel cell aircraft and drones.

Onboard Storage

This subprogram targets the development, demonstration, and deployment of cost-effective technologies and systems that improve onboard storage for gaseous transportation fuels. Areas of focus include advanced materials, low-pressure systems, and conformable tanks for both RNG and hydrogen. Onboard storage, which requires compressed storage and/or the use of advanced adsorption technologies, is a critical element needed for increased utilization of low-carbon, low-emission gaseous fuels.

On-Road

This subprogram targets emissions reductions from medium- and heavy-duty on-road vehicles. The focus is zero-emission, on-road transportation technologies using RNG and renewable hydrogen.

Refueling Stations

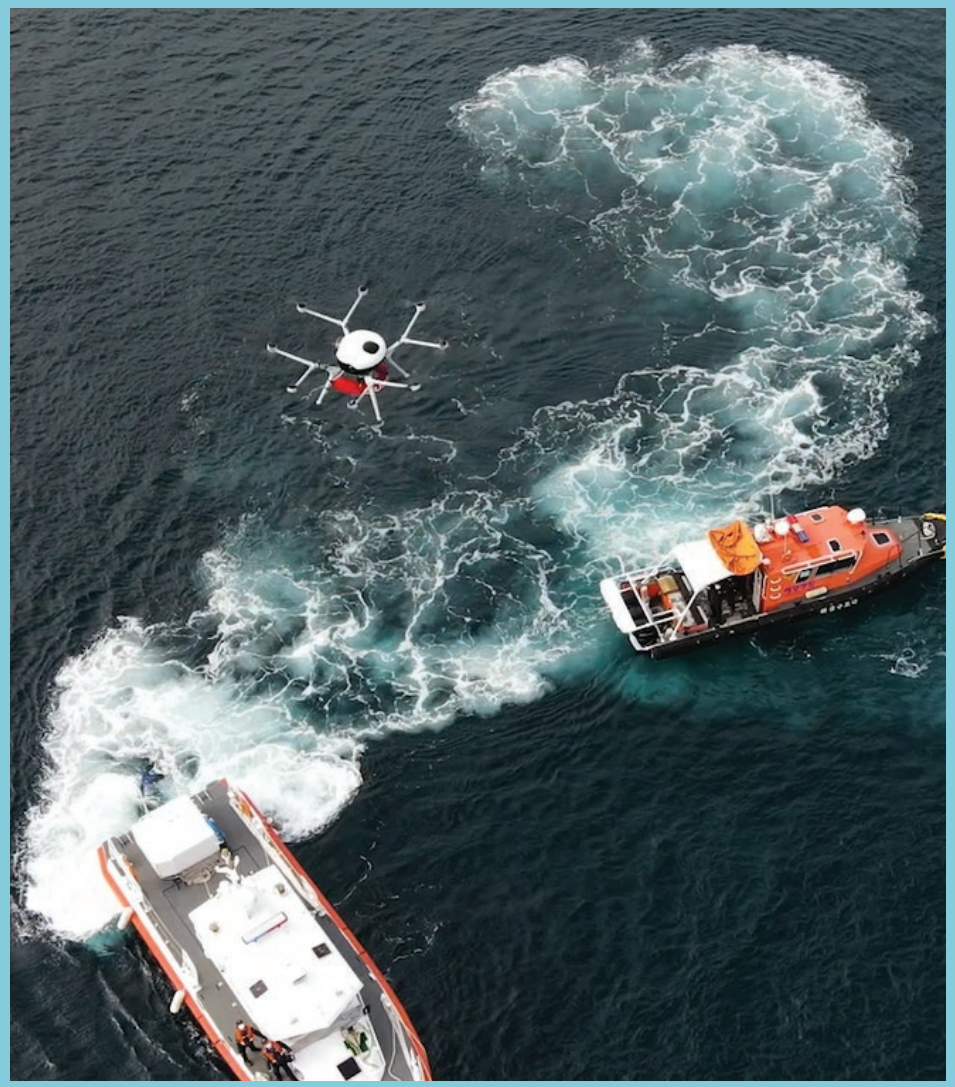
This subprogram targets the development, demonstration, and deployment of technologies and systems that support refueling for alternative fuels, including gaseous and liquid hydrogen and RNG. Subprogram staff also seek to identify and manage concerns and issues related to refueling, from storage to safety and standardization.

SPOTLIGHT

Clean Transportation

Hydrogen-fuel-cell drones enable long-range pipeline inspection

Zero-emission drones lay the groundwork for a companywide transition to hydrogen-fuel-cell-powered aircraft.



SoCalGas operates a fleet of fixed-wing airplanes, rotary aircraft, and battery-electric drones. "We use the drones to inspect difficult-to-access sections of our pipeline network," says Miguel Cara, Aviation and Flight Operations Management Team Leader for the company's Aviation Services Group.

To improve the efficiency of its inspections, SoCalGas has begun exploring the use of zero-emission, hydrogen-fuel-cell-powered drones with Korean firm Doosan Mobility Innovation (DMI) and GTI, an R&D organization that develops and demonstrates new energy technologies.

DMI has developed a suite of drones and fuel cell powerpacks with a wide range of potential applications, including surveillance, search and rescue, product delivery, and aerial inspection. On this project, DMI integrated its DP30 fuel cell powerpack with its DS30 commercial drone. Designed for operation in harsh environments, the integrated drone weighs 21 kg, is equipped with an LTE modem, and can carry a payload of 5 kg. Critically, the DP30 powerpack carries 300 grams of hydrogen and

TOTAL PROJECT COST: $250,000

SOCALGAS:	$250,000
COFUNDING:	$0

DMI's integrated drone weighs 21 kg, is equipped with an LTE modem, and can carry a payload of 5 kg for up to 120 minutes—roughly four times the range of battery-electric drones. Potential applications include surveillance, search and rescue, product delivery, and aerial inspection.

can travel up to 120 minutes—roughly four times the range of battery-electric drones.

"Through a series of demonstrations, our goal is to show SoCalGas that it can replace its battery-electric drones with hydrogen-fuel-cell-powered drones," says Soonsuk Roh, a manager in DMI's Business Execution Team. Although the project experienced significant delays due to COVID-19, it achieved its first significant milestone in September 2021 with a demonstration at SoCalGas' facilities in Downey, California.

Buoyed by this success, DMI began planning extensive field tests for 2022. "Because SoCalGas' battery-electric drones have ranges of only 20 to 30 minutes, the missions they fly are necessarily short," says Roh. DMI carefully evaluated the existing missions and developed new missions that took advantage of its drone's much longer range.

To close out 2021, DMI conducted one additional demonstration at the University of Texas, Austin under a GTI-led project funded by the US Department of Energy's H2@Scale program. "We are building a hydrogen ecosystem that includes generation, storage, and end use on one campus," says Ted Barnes, Director of R&D at GTI. "Integrating hydrogen fuel cell drones enabled us to prove their value and reliability to potential commercial end users."

In 2022, DMI plans to run the real-world missions it developed in the previous year. DMI will also seek to optimize the sensors carried by the drones, including thermal cameras, gas sensors, multi-spectral cameras, and air quality sensors. GTI will provide valuable assistance on hydrogen infrastructure and refueling planning—both for the immediate project and for future mass deployments of hydrogen fuel cell drones. "Our role is to support the integration of hydrogen into a new technology space," says Barnes. "For example, although many standards and codes exist for fueling hydrogen vehicles, there are none for hydrogen drones. That's an area where we can add value."

"SoCalGas has shown great leadership in using hydrogen fuel cell drones for field inspections of its pipeline network," says Roh. By the end of 2022, DMI hopes to see its drones in full commercial deployment at SoCalGas. Ultimately, DMI hopes to replicate the success of this project at other gas utilities around the nation.

Miguel Cara sees even more possibilities. "SoCalGas is evolving into a provider of innovative solutions for alternative fuels. This project—and others funded by the RD&D Program—are laying the groundwork for that transition. If it is successful, it could spur the adoption of hydrogen in all of the company's aircraft and position SoCalGas to be the largest supplier of hydrogen for air transportation in the United States."

PROGRAM: CLEAN GENERATION

This program targets the development and demonstration of high-efficiency products and technologies associated with the generation of power for the residential, commercial, and industrial market segments. Its goals are to reduce emissions, lower customer costs, integrate renewable fuels, and improve energy reliability and resiliency.

Clean Generation is composed of two subprograms:

Distributed Generation

This subprogram develops and enhances distributed generation technologies. Microgrids and the increasing availability of RNG and hydrogen offer new opportunities for the deployment of low-emission and renewably fueled distributed generation technologies.

Integration & Controls

This subprogram develops, enhances, and demonstrates technologies and control systems that integrate diverse distributed generation resources and thermal loads. The focus is on enabling low-emissions, distributed generation, and storage technologies to provide energy resilience and affordability to customers.

SPOTLIGHT

Clean Generation

Residential nanogrids promise a more distributed and equitable energy future

University of California, Irvine team optimizes residential nanogrid configurations for climate, cost, equity, and emissions.

TOTAL PROJECT COST: $881,153

SOCALGAS:	$761,653
COFUNDING:	$120,000

PHASE 1 TOTAL COST: $325,000

SOCALGAS:	$325,000
COFUNDING:	$0

PHASE 2 TOTAL COST: $556,000

SOCALGAS:	$436,653
COFUNDING:	$120,000

California has some of the world's most ambitious climate goals, including decarbonizing its thermal and electricity energy loads. One approach to this challenge that has seen success at larger scales—such as industrial or university campuses—is the microgrid. Microgrids combine power generation and energy storage technologies to reduce consumption of costly grid-sourced electricity or sustain operations during power outages.

To date, however, little progress has occurred in the development of much smaller, residential nanogrids. To address this gap, researchers at the University of California, Irvine (UCI) are working with SoCalGas and two industrial partners—Heila Technologies and InstantOn—to explore ways to achieve zero net energy in providing heat and power to residences.

The ultimate goal of the multi-phase project is to design and analyze a residential nanogrid that integrates a solid oxide fuel cell (SOFC) combined heat and power system, photovoltaic (PV) solar electricity, and battery storage to achieve zero net energy. Work began on phase one in late 2019.

As a first step, UCI conceived four potential residential nanogrid configurations and assessed their effectiveness across California's 16 climate zones. "Homes in different regions have different energy requirements," said Jack Brouwer, PhD, Professor of Mechanical and Aerospace Engineering at UCI. "A nanogrid solution that works well in a hot, dry climate might not be optimal for a house located in a much colder, damp environment."

UCI determined that an entirely electric solution was impractical due to the surface-area requirements of a PV system large enough to meet a residence's typical electrical demand. Instead, the research indicated that a more practical approach to achieving zero net energy could be found in

two mixed-fuel scenarios modeled by the team, where natural gas is used for heating. Mixed-Fuel #2 scenario resulted in the least reliance on the electrical grid while still achieving zero net energy. This scenario was particularly effective because the SOFC produced electricity and co-generated heat.

Configurations	PV	Heat	SOFC Fuel	Battery
All-Electric #1	Yes	Electric	N/A	Yes
All-Electric #2	Yes	Electric	Natural Gas	Yes
Mixed-Fuel #2	Yes	Natural Gas	N/A	Yes
Mixed-Fuel #2	Yes	Natural Gas	Natural Gas	Yes

In early 2021, UCI began assembling hardware for a lab-scale system that it would use to model how a nanogrid would respond to a variety of environmental conditions, energy costs, and electrical loads. The system—which UCI energized in December 2021—includes solar panels, an inverter, battery energy storage, an SOFC, and a residential simulator to simulate residential power demand dynamics. "Using the simulator, we will be able to replicate the power demand dynamics of any residence and connect it to the residential nanogrid hardware in the lab," said Brouwer.

During phase two of the project, UCI plans to use residential dynamic load profiles from earlier research and relevant literature to demonstrate the system at lab scale. "We will work with Heila and InstantOn to modify their control software based upon the results we obtain working with the physical hardware," said Pegah Mottaghizadeh, a PhD candidate in UCI's Advanced Power and Energy Program (APEP). The system will be capable of responding to static price signals from the grid. "But we will also develop new software and algorithms that enable it to accept more dynamic, real-time rates—something that could help homeowners pay significantly less for heat or electricity in the future."

That ties in with another key driver of the project: equity. "To date, most adoption of renewable and energy storage technologies has occurred in relatively affluent neighborhoods," said Brouwer. "We believe that this technology opens up new possibilities for bringing affordable renewable energy to all residents in California."

One of the key goals of the research is to understand the role of renewable gas in a sustainable energy future. "Many think total electrification of residential neighborhoods is the answer, with full reliance on wind and solar," said Robert Flores, PhD, a Senior Scientist at APEP. "Fundamentally, we agree with that approach but think that delivering some of that sun and wind energy as renewable gas might make the most sense."

For example, groups of houses with solar power could share energy storage or fuel cells. "If they are trying to achieve net zero energy, then they would all have to export electricity to the grid in the middle of the day—when the grid needs it least," said Flores. "With a network of residential nanogrids and shared resources, the houses could store that electricity for use when demand for electricity—and its cost—rises." The residences could also use the surplus renewable electricity to produce renewable gases, such as green hydrogen.

UCI will evaluate the cost, equity, and GHG and criteria pollutant emissions implications of the different strategies. "Depending on whether cost, environmental, or utility infrastructure impacts are prioritized, we anticipate quantifying very different cost savings and emissions reductions that can be achieved with residential nanogrids," said Brouwer.

At project's end, UCI anticipates being able to determine with a high level of certainty which nanogrid technologies should be considered in any given climate zone. UCI also hopes to provide valuable feedback to Heila and InstantOn so that they can adapt their control systems and improve their products. "That will not only help improve the efficiency of the nanogrids but also make the products more consumer friendly," said Brouwer.

Finally, Brouwer hopes the project will contribute to the understanding of how to optimally decarbonize both the gas and the electric systems. "We want everyone to have access to clean energy and clean air," said Brouwer. "That's not necessarily possible today because many cannot afford solar PV and battery systems or they don't own their residences. But in the future, clean renewable energy is going to cost less and be much more distributed, reliable, and equitable, particularly if both the gas and electric systems are decarbonized."

PROGRAM:

CUSTOMER END-USE APPLICATIONS

This program focuses on developing, demonstrating, and commercializing technologies that cost-effectively improve the efficiency and reduce the environmental impacts of gas equipment used in residential, commercial, and industrial settings.

This program includes five subprograms:

Advanced Innovation

This subprogram seeks to develop new, non-traditional technologies to improve energy efficiency and decrease emissions. Relevant applications include smart thermostats, sensors, advanced construction technologies, and machine learning.

Commercial Applications

This subprogram develops and enhances technologies and advancements related to gas consumption and end uses in the commercial sector. Relevant applications include commercial HVAC, hot water service, and commercial laundry.

Commercial Food Service

This subprogram develops and enhances technologies and advancements related to commercial food service. This includes restaurants, catering services, and institutional kitchens that primarily rely on fuel supplied by SoCalGas for cooking and water heating.

Industrial Process Heat

This subprogram develops advanced heating technologies and systems for use in the industrial sector. Relevant applications include food processing, textile drying, chemical processing, and other process heat needs.

Residential Appliances

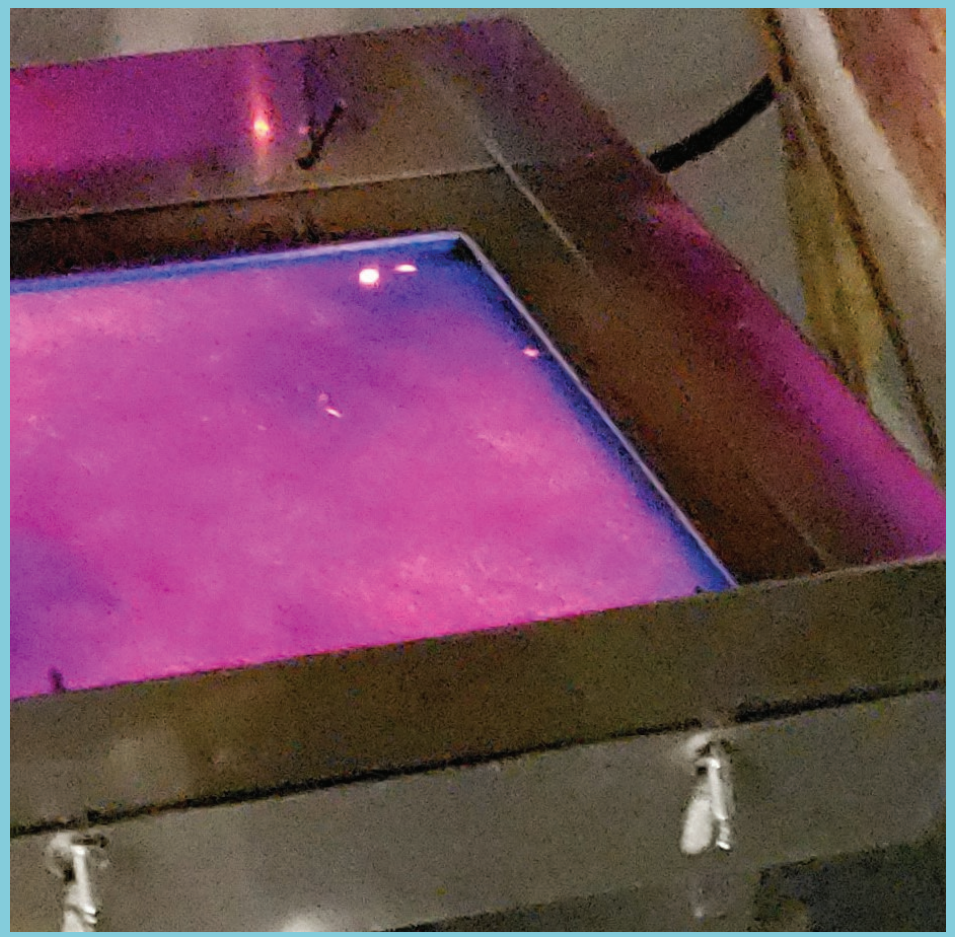
This subprogram develops, demonstrates, and enhances technologies and advancements related to gas-consuming appliances in residences. Relevant appliances include furnaces, hot water heaters, stoves, ovens, and dryers.

SPOTLIGHT

Customer End-Use Applications

Fuel-flexible, flameless appliance consumes blends of natural gas and hydrogen

Oak Ridge National Laboratory develops cooking appliance that delivers immediate emissions and efficiency benefits while enabling future blends of hydrogen.



To support the transition to zero-carbon hydrogen, ORNL began developing a clean, safe, fuel-flexible cooking appliance that can combust any blend percentage of hydrogen in natural gas—from zero to 100%—while delivering immediate efficiency and emissions reduction benefits.

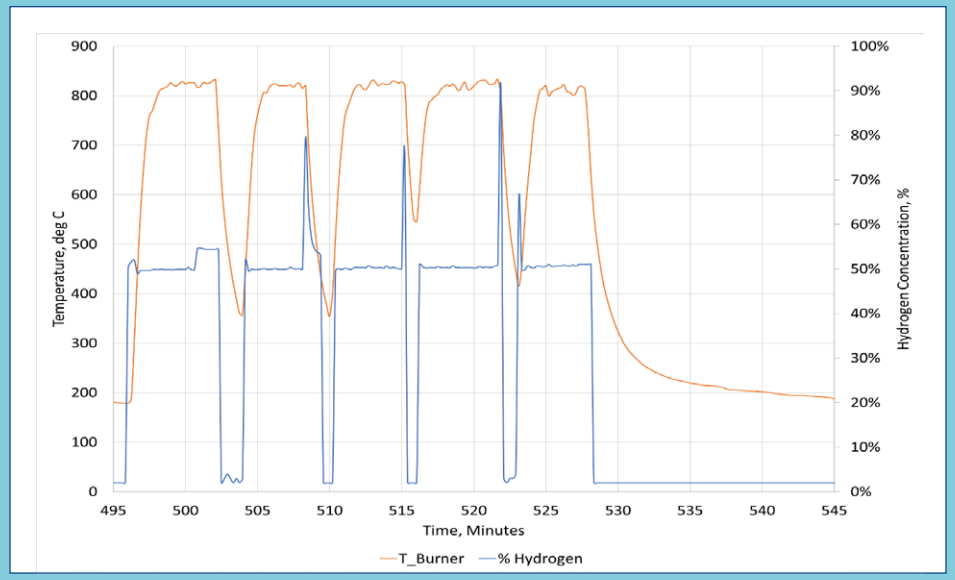
Across the United States, more than 33% of residential and commercial buildings use natural gas for cooking, representing 97 million metric tons (MT) of annual direct and indirect carbon emissions.

By blending zero-carbon hydrogen into the natural gas pipeline, it is possible to reduce those emissions. "Many of today's gas cooking appliances can accept blends of up to 20% hydrogen before they pose operational challenges," says Praveen Cheekatamarla, Senior Researcher at Oak Ridge National Laboratory (ORNL). "Blending at that percentage could eliminate more than 19 million MT of carbon emissions without any new equipment."

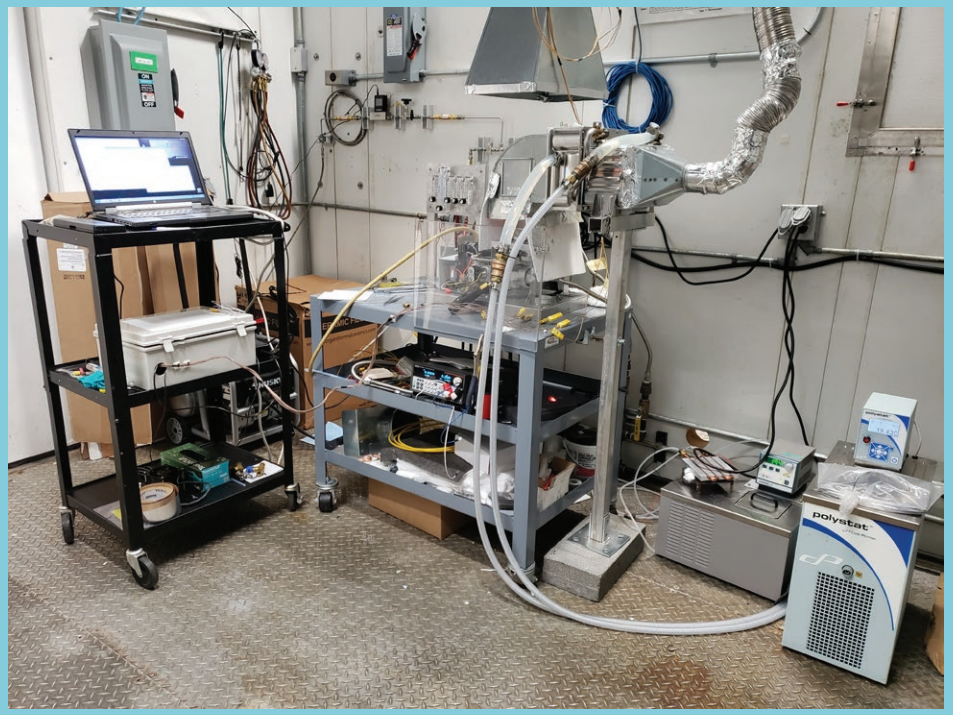
Ultimately, however, decarbonizing commercial and residential cooking will require higher blends of zero-carbon hydrogen. To support this transition, ORNL began developing a clean, safe, fuel-flexible cooking appliance that can combust any blend percentage of hydrogen in natural gas—from zero to 100%—while delivering immediate efficiency benefits and eliminating emissions of nitrogen oxides (NOx).

TOTAL PROJECT COST: $1,000,000

SOCALGAS:	$470,000
U.S. DOE:	$500,000
CO-FUNDING:	$30,000



Thermal cycling test of the heterogeneous burner in the presence of 50% hydrogen. Also shown is the cold and hot restart of the burner.



"Safety and emissions are the key challenges associated with adding hydrogen to the fuel mix in a cooking range," says Cheekatamarla. Hydrogen causes flame temperature to rise, which increases the risk of thermally induced NOx creation. "It also increases flame velocity, which can cause flame propagation to the fuel source and auto-ignition of the feed mixture. That will destroy the burner and create a safety hazard."

To overcome these challenges, ORNL designed a flameless burner that relies on heterogeneous catalytic oxidation. A hybrid combustion module integrating a novel heterogeneous combustion surface with tailored thermal and fluid transfer characteristics enables operation of the burner at moderate temperatures in a safe and clean manner.

Using this approach, the energy of combustion is distributed via infrared radiation (IR) over a much larger surface—and, therefore, at a lower temperature—than in conventional burners, which rely on convection. "Cooking applications require an operating range between 400°C and 800°C," says Cheekatamarla. Flame-based technologies, however, operate at roughly 1,500°C—a temperature that favors NOx formation. "With our technology, NOx cannot form because the burner never reaches the threshold temperature."

In 2021, ORNL drew up multiple design options, fabricated prototypes, and evaluated them with blends of up to 50% hydrogen with natural gas. "By year's end, we demonstrated that the prototype can safely produce IR heat without risk of flashback," says Cheekatamarla. Preliminary testing also confirmed complete elimination of NOx emissions and compliance with carbon monoxide regulations.

In 2022, ORNL will integrate the prototype into commercial appliances supplied by a major appliance manufacturer. "We will evaluate a variety of blend compositions in a realistic cooking environment, with multiple burners operating simultaneously at different energy intensities," says Cheekatamarla. "Our goal is to demonstrate that IR-based heat transfer is 20% more efficient than convection." The OEM will provide engineering resources, product knowledge, and assistance ensuring compliance with industry standards.

"Because the prototype can run on natural gas, you can install it today and it will provide immediate efficiency and emissions benefits," says Cheekatamarla. When hydrogen becomes available, the burner will be able to run on a mixture of the two gases. "Our goal in 2022 is to demonstrate an appliance that can run at both extremes—100% hydrogen or natural gas—as well as anywhere in between."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