RESEARCH PROJECT SUMMARIES
2018-2019
Utilization Technology Development, NFP

RESEARCH PROJECT SUMMARIES

2018 - 2019
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Letter to Our Stakeholders

Utilization Technology Development, NFP (UTD), continues to advance the intelligent use of economical, plentiful natural gas to benefit ratepayers and society while addressing major environmental and energy-efficiency goals. As a non-profit applied research organization, UTD is creating, developing, and demonstrating economical new gas-fired equipment to save energy by operating at far higher efficiencies than existing equipment (such as new prototype absorption heat pump units for water heating and space conditioning now in field tests), reduce emissions, enhance safety and reliability, and integrate more renewable energy.

Minimizing energy costs for ratepayers while simultaneously achieving deep de-carbonization and other emission reductions continues to be a foundational need for societal well-being, economic growth and environmental protection. The superior reliability of natural gas supply and the immense seasonal energy storage of the natural gas distribution system continues to benefit end users, to meet extreme cold winters or other weather events, accelerate the integration of renewable energy sources, and foster installations of high-efficiency combined heat-and-power systems or back-up generators.

Expanding ratepayers’ options to select practical and economical high-efficiency, low-maintenance, low-emission technologies is key. During 2018-19, UTD’s 20 members selected, directed, and funded more than 70 research projects across residential, commercial, industrial, transportation, and other sectors to serve their 47 million natural gas customers, their communities, and the environment.

UTD continues to leverage its research investments by cofunding research grants from leading governmental agencies such as the U.S. Department of Energy or the California Energy Commission, and collaborating with national laboratories, university researchers, and leading manufacturers. We thank those who support UTD and other applied research efforts to address the profound market, regulatory, regional, and global needs facing ratepayers and society, with innovations such as those summarized in this report.

Dominic Popielcki  
Chairman

Ronald Snedic  
President
UTD IMPACT

UTD creates and advances products, systems, and technologies to save consumers money, save energy, integrate renewable energy with natural gas, and achieve safe, reliable, resilient end-user operation with superior environmental performance. The commercial products and technology developments shown here illustrate some of UTD’s impacts and benefits for ratepayers, utilities, society, and our planet.

UTD’s proven 15-year track record as a non-profit collaboration of utilities has directly impacted key energy and environmental issues. We thank the leading researchers, governmental agencies, and others who have partnered with UTD to make exciting impacts such as these highlights! Please contact us if you have any questions about UTD.

Ron Snedic (1.847.768.0572) Rich Kooy (1.847.768.0512)

COMMERCIALIZED PRODUCTS

Dedicated Outside Air System/Rooftop Unit
Condensing heating versions of Munters Dedicated Outside Air System (DOAS) and other rooftop unit (RTU) products increase heating efficiency from 80%-81% to 90%-93%. Multiple RTU manufacturers are now offering DOAS with 90+% efficiencies, facilitated by the availability of condensing duct furnace modules first developed with UTD support.

Munters Corporation
Larry Klekar
210-249-3883
larry.klekar@munters.com
www.munters.com

Condensing Duct Furnace Modules
High-efficiency condensing heating modules developed with UTD support are now available from Beckett Gas and other OEMs, including Heatco, and are being applied to DOAS and other products including make-up air units available from multiple manufacturers including Aaon, Daikin, and RuppAir.

Beckett Gas, Inc.
Joel Mohar
440-783-7610
jmohar@beckettcorp.com
www.beckettgas.com
**Yanmar 3-Pipe Engine-Driven Gas Pump**
Yanmar’s 3-pipe, 14-ton gas heat pump with variable refrigerant flow offers an important new energy-efficiency option for the North American market by combining heat recovery with simultaneous heating and cooling. In a 2018-19 field test, UTD is validating the quantitative and qualitative performance of an instrumented installation.

**Sierra™ Engine-driven Gas Heat Pump**
Sierra’s (formerly NextAire™) 11-ton packaged gas heat pump (GHP) can efficiently heat and cool commercial buildings (up to 1.4 COP) while reducing peak and total electric demand. Also available are 8- and 15-ton GHPs with variable refrigerant flow multizone capabilities. More than 700 units have been sold in the North America. UTD’s field studies are supporting best practices for siting.

**Heat Sponge Economizer for Industrial/Commercial Boilers**
In either condensing or non-condensing configurations, this heat-recovery system for commercial and industrial boilers (over 140,000-unit market in U.S.) increases boiler efficiency from 80% to a range of 85%-93% (validated by UTD laboratory testing). It also saves customers 5%-15% in annual energy costs. In 2018, UTD completed a field test in Utah to further validate energy savings.

**M-Trigen PowerAire**
M-Trigen’s PowerAire unit provides high-efficiency microCHP with integrated cooling to homeowners, small businesses, and other users. In 2019, UTD is providing technical support for a notable demonstration and also partnering with NYSERDA, NJNG, and PERC to independently validate performance.

**Cannon Boiler Works Ultramizer®**
The Ultramizer is an advanced heat-and-water recovery system for larger commercial and industrial boilers, of which there are more than 140,000 in the U.S. It increases boiler efficiency from 80% to 93%—saving customers 15% in energy while also reducing water demand.

**S.U.N. Equinox Solar-Assisted Heating System**
The Equinox system is a combination solar/natural gas water heating system that uses an efficient evacuated tube design. It can be used in residential, commercial, or industrial locations and is capable of meeting 100% of domestic hot-water and space-heating needs. UTD validated its energy performance in a field demonstration.

**ENERGY STAR Fryers**
In 2019 Royal Range introduced the high-efficiency RHEF-75 fryer — building on the success of the smaller-capacity, high-efficiency RHEF-45 fryer that received the National Restaurant Association’s Kitchen Innovation Award and GFEN’s Blue Flame Product of the Year Award in 2017. Independent testing showed 63% heavy-load cooking energy efficiency.
Low-Oil-Volume Fryers
Marketed by Frymaster as Protector® fryers, this equipment increases energy efficiency while also extending cooking-oil quality and life to provide significant customer savings. Field demonstrations completed by UTD have shown an average savings of $4,800 per year per fryer.

ENERGY STAR Convection Oven
ENERGY STAR rated conveyor ovens from Lincoln include an advanced energy-management system to reduce energy consumption up to 38%.

ENERGY STAR Conveyor Oven
ENERGY STAR Convection Oven
This unit showed improved efficiency and 40% energy savings compared to a standard oven during field testing and achieved an ENERGY STAR rating.

High-Efficiency Broiler
This broiler features infrared burners and an energy-saving hood that showed an average of 23% energy savings during field testing. It offers more efficient cooking as well as reducing heat gain to the kitchen.

ENERGY STAR Countertop Steamer
A compact, gas-fired countertop steamer for commercial foodservice offers enhanced cooking rates while providing energy savings and reduced water consumption. It was the first gas-fired boilerless steamer on the market and received an ENERGY STAR rating.

Gas Quality Sensor
The Gas Quality Sensor uses solid-state infrared light absorption spectroscopy to measure Btu content and composition of natural gas and biomethane fuels. It provides faster response at much lower cost than a gas chromatograph. Developed with UTD support, it was commercially introduced by UTD partner CMR Group in 2019.

Cummins Westport 6.7L Medium-Duty NGV Engine
In December 2016, Cummins-Westport Inc. began full production of this 6.7 liter, 240-HP, medium-duty, factory-built, dedicated natural gas vehicle engine for school bus, shuttle bus, medium-duty truck, and vocational uses. It meets U.S. 2017 EPA GHG requirements and CARB’s optional more stringent low-NOx standard of 0.1 g/bhp-hr.

Cummins Westport 8.9L Near-Zero Emission NGV Engine
This 8.9L 320-HP NGV engine is widely used, with 50,000+ engines sold for transit, refuse-collection, and regional hauling applications since 2007. In 2016, it was advanced to become the first engine certified in North America to meet the 0.02 g/bhp-hr optional Near Zero (NZ) NOx emissions standard (i.e. 90% lower than the current EPA NOx limit of 0.2 g/bhp-hr).
Cummins Westport 11.9L Near-Zero Emission NGV Engine

This 11.9L 400-HP NGV engine is used in large trucks, buses, and refuse vehicles. Engine sales since 2013 are approaching 10,000 units and 25,000+ engines will likely be sold in North America by 2020, yielding emissions reductions and $600+ million in annual fuel sales. In Model Year 18, it became CWI’s second engine certified to meet NZ NOx emissions standard of 0.02 g/bhp-hr.

HyperComp/3M NGV Cylinders

These lightweight Type IV naturl gas vehicle cylinders are manufactured using advanced 3M nanoparticle-enhanced matrix resin technology for high strength and durability. Three tank sizes of 30, 40, and 45 diesel gallon equivalent are now offered in nine unique CNG Fuel System Solutions from Momentum Fuel Technologies, including roof mount, saddle mount, and back-of-cab designs.

Ultimate CNG FuelMule™

The patented FuelMule™ mobile fueling solution dispenses eight diesel gallon equivalent per minute and fuels 35-50 medium-duty vehicles per delivery. It is used as a temporary starter station, station back-up, or for mobile onsite fueling. It logged 250,000+ miles and almost 6,000 compressor hours delivering natural gas fuel to vehicles across the U.S. in its first five years of operation.

External Concentration Parabolic Collector

This patented, non-tracking, extremely-low-profile concentrator can achieve 200°C (392°F) solar thermal energy to economically serve commercial and industrial facilities and reduce greenhouse gas emissions. It can also be integrated with natural gas as a supplemental energy source. UTD provided technical and product development support and experimental validations over a seven-year period.

KEY INFORMATION & ANALYTICAL TOOLS

Reliability, Cost and Environmental Impacts of Standby Generation Systems

In 2017, Generac launched a website supported by UTD research that provides technical information on costs, emissions, and reliability for natural gas generators, including a white paper on natural gas reliability and a Total Cost of Ownership calculator that compares costs and emissions of natural gas vs. diesel-fueled standby generators. In 2018, UTD researchers also published a whitepaper that substantiated the high reliability of natural gas deliverability.


Building America

Under five separate projects from 2011 to 2019, UTD has developed key information and tools to support the U.S. DOE’s Building America research, development, and demonstration program, which helps accelerate use of best practices by residential builders, remodelers, installers, code officials, designers, raters, teachers, and others. Most recently a simplified combustion safety protocol was introduced.


Commercial Foodservice (CFS) Equipment Calculator

Introduced in 2016, with UTD support, this website hosts CFS information and tools for the restaurant industry and others to determine the economic and environmental benefits of using new, more advanced commercial foodservice equipment. The website was showcased at several restaurant trade shows during 2017-19 and improvements are underway in 2019.

Available online at cfscalc.gastechnology.org.
For more information, contact Frank Johnson; fjohnson@gti.energy
Virtual Test Home

A virtual test home (VTH) in a laboratory is being expanded in 2019 with UTD’s support. Leveraging the VTH, UTD has helped Navien and iFLOW demonstrate that an advanced forced-air condensing tankless water heater combination system can achieve 30%-50% energy savings relative to best-in-class condensing furnaces and water heaters. The VTH is also developing data to help accelerate adoption of advanced gas technologies (such as GHPs, combination units and modulating furnaces) in U.S. DOE’s EnergyPlus™ and other energy software.

For more information, contact Tim Kingston; tkingston@gti.energy

CSA NGV2 CNG Vehicle Fuel Containers Standard Technical Committee Support

The sixth edition of CSA NGV2 issued in 2019 and contains updated information and requirements for the material, design, manufacture, and testing of serially-produced, refillable Type NGV 2 containers intended only for the storage of CNG for vehicle operation. The 2019 revision includes localized fire tests and conformable storage topics. UTD supported participation to lead the Technical Task Force that created the standard.

Available online at www.csagroup.org.
For more information, contact Ted Barnes; tbarnes@gti.energy

CSA NGV4.3 NGV Storage and Delivery Standard Technical Committee Support

CSA NGV4.3 issued in 2018 and specifies the performance requirements for temperature compensation control used to prevent compressed natural gas dispensing systems from exceeding a safe fill level of vehicle fuel storage container(s). It contains safety performance guidelines and field evaluation methods for existing dispensing systems. UTD supported participation to lead the Technical Task Force that created the standard.

Available online at www.csagroup.org.
For more information, contact Ted Barnes; tbarnes@gti.energy

CSA NGV6.1 NGV Storage and Delivery Standard Technical Committee Support

CSA NGV6.1 was introduced in 2016 and defines the requirements for the balance of systems and equipment onboard a natural gas vehicle, which is not otherwise defined by NGV1 for the receptacle or NGV2 for the storage containers. UTD supported GTI’s participation on the Technical Committee.

Available online at www.csagroup.org.
For more information, contact Ted Barnes; tbarnes@gti.energy

CSA NGV5.1 and NGV5.2 Fueling Appliance Standard Technical Committees Support

CSA NGV5.1 was introduced in 2015 and updated in 2016, and provides mechanical, physical, and electrical requirements for residential fueling appliances that dispense natural gas for natural gas vehicles, including indoor and outdoor fueling appliances that connect to residential gas piping. A complimentary standard, NGV5.2 for vehicle fueling appliances in non-residential locations, has been developed and was published in late 2017. UTD supported participation on both of the technical committees.

Available online at www.csagroup.org.
For more information, contact Ted Barnes; tbarnes@gti.energy

Source Energy Technical Data

Researchers are providing unbiased technical data on the benefits of source energy in reducing energy consumption and carbon emissions in buildings and transportation. Source energy is now included in the International Green Construction Code for high-performance commercial buildings, and in various American Society of Heating, Refrigeration and Air-Conditioning Engineers standards (e.g., Standard 100 for existing buildings, Standard 105 method for comparing building energy performance, Standard 189 for high-efficiency green buildings, and Standard 214 for building energy performance rating).

For more information, contact Neil Leslie; nleslie@gti.energy
Source Energy and Emissions Analysis Tool

The Source Energy and Emissions Analysis Tool (SEEAT) allows calculation of the source energy and greenhouse-gas emissions related to point-of-use (site) energy consumption by fuel type for each energy-consuming device. The source-energy and carbon-emission calculation methodology used accounts for primary energy consumption and related emissions for the full fuel cycle for residential and commercial buildings, industrial applications, and light-duty vehicles. SEEAT data is also used in the GTI-developed Energy Planning Analysis Tool.

Available online at www.cmictools.com and www.epat.gastechnology.org. For more information, contact Neil Leslie; nleslie@gti.energy

TECHNOLOGY ADVANCEMENTS

Gas-fired Absorption Heat Pump Residential Water Heater

The latest generation of this efficient residential gas-fired heat pump water Heater, with a projected Uniform Energy Factor (UEF) of 1.20-1.30 and ultra-low-NOx emissions of ≤10 ng/J, is undergoing a five-unit field test with a prospective manufacturing partner in southern California with support from the California Energy Commission, UTD, SoCalGas and others. When commercially available, it will be the only residential water-heating technology with a source-energy-based EF ≥1.0.

Project Manager: Paul Glanville

Gas-fired Absorption Heat Pump for Space Heating or Commercial Water Heating

This gas absorption heat pump (GAHP) for space heating or water heating applications is undergoing a four-unit field test in Wisconsin and Tennessee with prospective UTD manufacturing partner Trane and support from the U.S. Department of Energy, UTD and others. The GAHP has field demonstrated an Annual Fuel Utilization Efficiency of 140%, with 45% gas savings, an estimated financial payback period of as low as three years, and ultra-low-NOx emissions of ≤14 ng/J. The GAHP demonstrated continued operation under extreme cold weather conditions in Wisconsin during the January-February 2019 polar vortex.

Project Manager: Paul Glanville

Ultra-Low NOx Burner

This innovative firetube boiler technology has more than two years of proven successful operation at a Mission Linen Supply facility in California. It improves efficiency and achieves NOx emissions below 9 vppm, while avoiding the significant efficiency, capital cost, and/or operating cost penalties if conventional Selective Catalytic Reduction or burner enhancements such as external Flue Gas Recirculation and/or High Excess Air firing were used. UTD’s partner Power Flame Inc. is helping businesses in 2019 meet NOx emission regulations without sacrificing energy efficiency.

Project Manager: David Cygan

Low NOx Ribbon Burner System

A new low-NOx combustion system reduces NOx emissions by 50% in food processing, thermoforming, and other industrial applications. The system was evaluated in bench-scale, pilot scale, and full-scale production settings and has demonstrated transparent operation at an industrial bakery in California. In 2019, post-demonstration monitoring will continue at the bakery along with commercialization activities with UTD’s partner Flynn Burner Corp.

Project Manager: Yaroslav Chudnovsky
FlexCHP High-Efficiency Ultra-Clean Power and Steam Package
This innovative combined heat-and-power package allows flexible steam production while meeting stringent California emission levels without a SCR system and across the full range of firing rates — achieving NO\textsubscript{X} levels 50% below CARB limits. A 2014 installation in California operates with 84+% system efficiency and system emissions well below 9 ppm NO\textsubscript{X}. UTD has provided long-term support, including efforts to apply the technology for broader application sizes (e.g. to 400 kW / 400 BHP).

Project Manager: David Cygan

Low NO\textsubscript{X} Advanced 3D-Printed Nozzle Burner
A novel design for next-generation retention nozzles leverages new additive manufacturing capabilities and equipment. In 2019, UTD is evaluating technology licensing applications in boilers and air heating. Laboratory tests to date have demonstrated a robust, high-efficiency (3%-6% increase), ultra-low emissions burner, and >10:1 turndown. It achieved 50%-75% reduction in NO\textsubscript{X} emissions compared to current burners, with the potential to reach < 5 ppm NO\textsubscript{X}.

Project Manager: Sandeep Alavandi

Gas-Fired Warewasher
UTD is funding the laboratory development of a new prototype gas-fired warewasher. UTD project 1.18.B estimated annual savings of $1,100-$9,000 (depending on size and type) for restaurant, cafeteria, and other commercial food service operators – while saving energy and chemicals – and these results supported partnering discussions with warewasher manufacturers at the N.A. Association of Food Equipment Manufacturers in February 2019.

Project Manager: Shawn Scott

Cost-Effective Small-Scale Compressor for Natural Gas Vehicles (NGVs)
A cost-effective small-scale compressor could significantly change the NGV fueling market. With UTD cost share and U.S. Department of Energy funding, GTI and the University of Texas, Austin (using specialty materials from Argonne National Laboratory) developed a novel approach using a linear motor with only one moving piston and operated a prototype successfully in the laboratory. The technology is currently being scaled up to 50 SCFM capacity with UTD funding.

Project Manager: Jason Stair

On-Demand Heat-and-Power System
This unique new technology has received a remarkable three rounds of funding from U.S. Department of Energy, along with UTD and other cofunding support. This technology captures and stores renewable energy (or other resources, including waste heat), augments it with natural gas as needed, and delivers heat and power on-demand to commercial, industrial, and other users. In 2019, the technology is moving to a pilot field scale-up demonstration in California.

Project Manager: David Cygan

CARB-Compliant Engine-Based Micro-CHP System
UTD researchers are collaborating with the California Energy Commission and SoCalGas to advance and commercialize the first-ever engine-based micro-CHP system that complies with California Air Resource Board requirements. A system offered by a major manufacturer in an influential market like California could spark the U.S. micro-CHP market.

Project Manager: Tim Kingston
Low-NO\textsubscript{x} Furnace

Low-NO\textsubscript{x} combustion systems were developed in cooperation with SCAQMD and five residential furnace manufacturers to achieve emissions levels less than 14 ng/J. Innovative burner materials, including metal mesh and metal foam, were used to achieve even heat transfer and uniform flame temperatures. UTD completed durability testing in 2017.

Project Manager: Frank Johnson

ENERGY STAR Residential Gas Dryer

UTD and a major manufacturer developed one of the first commercially-available gas-fired ENERGY STAR clothes dryers (included at energystar.gov/products/appliances/clothes_dryers). UTD is currently investigating next-generation technologies and developing an early-stage prototype residential gas dryer to substantially further increase operating efficiency.

Project Manager: Shawn Scott

iGEN Self-Powered Furnace

The innovative new iGEN furnace generates its own electric power and contains an integrated battery, providing homeowners with continuous heating even during electricity outages. Initial units produce about 45 MBtu/hr and 1kW of power, with reported 95% heating system efficiency. UTD is supporting the technical refinement of this new product in 2019 with laboratory testing, validation, and recommendations.

Project Manager: Tim Kingston

Ultra-High-Efficiency, Combination Heating/Cooling Vuilleumier Cycle Heat Pump

Vuilleumier cycle-based heat pumps could provide a step-change efficiency improvement over vapor absorption- or compression-based cycles, achieving cooling COP > 1 and heating COP > 2. UTD is working with a leading developer to advance key system components using both computational and experimental analysis, to help achieve performance goals in alpha prototype testing funded by the U.S. Department of Energy, UTD and others during 2018. UTD is funding additional research in 2019.

Project Manager: Alex Fridlyand

Next Generation Liquid Desiccant-Based, Heat-Driven HVAC System

Liquid desiccant-based systems can efficiently remove moisture from air and reduce the amount of mechanical energy and water required by conventional HVAC technologies that de-humidify, condition, and re-humidify space air. In cooperation with NYSERDA and others, UTD is testing a novel new non-corrosive, non-toxic desiccant in a gas-driven system that offers a potential 30% increase in COP on a seasonal basis over conventional HVAC technologies.

Project Manager: Doug Kosar

Self-Powered Tankless Water Heater

Tankless water heaters yield higher levels of efficiency than storage-type water heaters but require the added expense of an electrical connection and are susceptible to power outages unless a separate battery back-up system is installed. UTD researchers have assessed leading thermoelectric generator (TEG) technologies and, in 2019, are analyzing opportunities to economically integrate TEG and other technologies into a prototype water heater design.

Project Manager: Aleks Kozlov

Low NO\textsubscript{x}, High-Efficiency Burners for Commercial Food Service Equipment

UTD is helping manufacturers respond to pending new regulations on NO\textsubscript{x} emissions of commercial foodservice equipment and simultaneously improve energy efficiency by developing and demonstrating prototype equipment that uses advanced burner concepts or components. Both novel new burner configurations as well as state-of-the-art burner technologies are being evaluated.

Project Manager: Frank Johnson
High-Efficiency Gas-Fired Rotary Heat Pump for Food Processing
UTD is partnering with the California Energy Commission, SoCalGas, and others to demonstrate an innovative high-efficiency, thermal-vacuum, gas-fired heat pump technology for food-drying applications at a commercial food-processing company. The new technology has the potential to be about twice as efficient as conventional processes. A prototype system at a field host site will generate performance data during 2019.

*Project Manager: Yaroslav Chudnovsky*

High Efficiency Commercial Clothes Dryer
An advanced natural-gas-fired commercial clothes dryer is being created and demonstrated at laboratory scale that has the potential to save at least 50% of the energy used in the commercial clothes drying sector. It is being developed in partnership with Oak Ridge National Laboratory and others, with financial support from the U.S. Department of Energy and UTD.

*Project Manager: Yaroslav Chudnovsky*

Next Generation Infrared Burner
In partnership with a leading U.S.-based product manufacturer, UTD-funded researchers are testing a variety of unique metal foam materials in a laboratory to evaluate their potential performance as next-generation, high-efficiency, rapid-response, low-emission infrared burners that are directly fired with natural gas.

*Project Manager: Sandeep Alavandi*

Residential Furnace Retrofit for High-Efficiency Heating and Humidification
In December 2017, results of the novel Transport Membrane Humidifier in four homes in Minnesota demonstrated a 14% increase in furnace efficiency while providing humidification without water supply. Discussions with potential licensees are in progress.

*Project Manager: Dexin Wang*

Advanced Combustion System for Next Generation mCHP
An advanced combustion system with thermochemical heat recovery has been created and demonstrated with UTD’s support in a laboratory. Applying the system to a Stirling-based micro-CHP system can increase fuel-to-electric efficiency from 12%-15% to 30%. Testing in 2019 demonstrated low NOₓ and CO emissions at ≤9 ppm (at 3% O2, dry).

*Project Managers: Dave Kalensky and Aleks Kozlov*

**WORKING WITH PARTNERS TO COFUND UTD INITIATIVES**

In 2018, each $1.00 in new UTD funding was leveraged by $5.1 of direct funding from government and industry partners for related end-use R&D. GTI secured $21.9 million from federal and state government partners and $5.2 million in funding from manufacturing partners and other gas industry resources (outside of UTD). Manufacturing partners also provided significant, additional in-kind co-funding. Examples include:

- California Energy Commission (CEC) funding of three new projects totaling $4.4 million. Efforts include new NGV vehicle drivetrain, natural gas/renewable solar systems for industrial applications, and micro-CHP systems.
- California Air Resources Board (CARB) funding of $5.1 million for advanced low-emission vehicle demonstrations.
- U.S. Department of Energy (DOE) funding of $0.8 million for advanced vehicle and power system R&D.
- U.S. Department of Defense (DOD) funding of $11 million to demonstrate new natural gas energy efficiency and resiliency technology at military facilities.
- More than $4.4 million in other gas industry funding for a range of emerging technology efforts aiming to support the evaluation of commercial readiness of new higher-efficiency natural gas technologies.
# UTD RESEARCH PROJECT SUMMARIES
## 2018 - 2019

### Table of Contents

#### RESIDENTIAL APPLICATIONS

<table>
<thead>
<tr>
<th>Project</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.11.H</td>
<td>Next-Generation Residential Gas Heat-Pump Water Heater</td>
<td>3</td>
</tr>
<tr>
<td>1.11.M</td>
<td>Evaluation of Whole-House Residential Retrofit Technologies (Building America)</td>
<td>5</td>
</tr>
<tr>
<td>1.13.D</td>
<td>Codes and Standards for Advanced Gas Technologies</td>
<td>7</td>
</tr>
<tr>
<td>1.15.C</td>
<td>Next-Generation Advanced Residential Gas Clothes Dryer Development</td>
<td>15</td>
</tr>
<tr>
<td>1.15.G</td>
<td>Residential Kitchen Cooking Ventilation Effectiveness</td>
<td>17</td>
</tr>
<tr>
<td>1.15.H</td>
<td>Maintenance-Free Approaches for Tankless Water Heaters</td>
<td>19</td>
</tr>
<tr>
<td>1.16.C</td>
<td>High-Performance Building Initiative</td>
<td>21</td>
</tr>
<tr>
<td>1.16.E</td>
<td>Low-Capacity Heating Systems Portfolio</td>
<td>23</td>
</tr>
<tr>
<td>1.16.L</td>
<td>SuperPerm Burner for Water Heaters</td>
<td>29</td>
</tr>
<tr>
<td>1.16.Q</td>
<td>Elevated-Gas-Pressure Water-Heater Market and Technical Evaluation</td>
<td>31</td>
</tr>
<tr>
<td>1.17.B</td>
<td>Thermoelectric Generator for Self-Powered Water Heater</td>
<td>33</td>
</tr>
<tr>
<td>1.17.C</td>
<td>Gas Heat Pump Combination Space/Water-Heating Design</td>
<td>35</td>
</tr>
<tr>
<td>1.17.E</td>
<td>Emerging Combination Air-Handling Units</td>
<td>37</td>
</tr>
<tr>
<td>1.17.F</td>
<td>Combination Heating/Cooling Vuilleumier Cycle Heat Pump</td>
<td>39</td>
</tr>
<tr>
<td>1.17.H</td>
<td>Residential Cooking Pollutants and Indoor Air Quality</td>
<td>41</td>
</tr>
<tr>
<td>1.18.D</td>
<td>Integrating Thermal Energy Storage in Advanced Gas/Renewable Homes</td>
<td>43</td>
</tr>
<tr>
<td>1.18.E</td>
<td>Field Evaluation of Central Condensing Tankless Water Heaters for Energy Savings</td>
<td>45</td>
</tr>
<tr>
<td>1.18.F</td>
<td>Quantifying Methane Emissions from Tankless Water Heaters</td>
<td>47</td>
</tr>
<tr>
<td>1.18.G</td>
<td>Integrating Gas Heating and Cooling in Advanced Gas/Renewable Homes</td>
<td>49</td>
</tr>
<tr>
<td>1.18.H</td>
<td>Economical High-Efficiency Residential Gas Absorption Heat Pump with Integrated Cooling</td>
<td>51</td>
</tr>
<tr>
<td>2.17.D</td>
<td>iGEN Self-Powered Furnace Laboratory Testing</td>
<td>53</td>
</tr>
</tbody>
</table>

#### COMMERCIAL APPLICATIONS

<table>
<thead>
<tr>
<th>Project</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.12.U</td>
<td>Gas Engine Heat Pump Modeling for Different Climates</td>
<td>57</td>
</tr>
<tr>
<td>1.13.B</td>
<td>Commercial Foodservice Tools and Calculators</td>
<td>59</td>
</tr>
<tr>
<td>1.13.L</td>
<td>SPC204 mCHP Test Method Standard Support</td>
<td>61</td>
</tr>
<tr>
<td>1.14.B</td>
<td>Commercial Foodservice Equipment Demonstrations</td>
<td>65</td>
</tr>
<tr>
<td>1.14.C</td>
<td>Demonstration of High-Production Fryers</td>
<td>67</td>
</tr>
<tr>
<td>1.15.B</td>
<td>Demonstration of Demand-Control Kitchen Ventilation System</td>
<td>69</td>
</tr>
<tr>
<td>1.15.E</td>
<td>Gas-Fired High-Efficiency Liquid Desiccant Air Conditioning and Humidity Control</td>
<td>71</td>
</tr>
<tr>
<td>1.16.A</td>
<td>Chain Restaurant Equipment Usage Survey</td>
<td>73</td>
</tr>
<tr>
<td>1.16.B</td>
<td>Commercial Foodservice Codes and Standards</td>
<td>75</td>
</tr>
<tr>
<td>1.16.I</td>
<td>Commercial Gas-Fired Heat Pump Water Heater</td>
<td>77</td>
</tr>
<tr>
<td>1.17.G</td>
<td>Yanmar Three-Pipe Gas Engine Heat Pump Field Study</td>
<td>79</td>
</tr>
<tr>
<td>1.18.C</td>
<td>Advanced Nozzle Burner for Commercial Water Heaters</td>
<td>83</td>
</tr>
<tr>
<td>1.18.I</td>
<td>Gas Heat Pump RTU Cold-Climate Performance Assessment</td>
<td>85</td>
</tr>
<tr>
<td>2.17.C</td>
<td>High-Efficiency Thermo-Vacuum Commercial Clothes Dryer</td>
<td>87</td>
</tr>
<tr>
<td>2.18.C</td>
<td>Sheet Metal Surface Burner Evaluation</td>
<td>89</td>
</tr>
</tbody>
</table>
## DISTRIBUTED GENERATION

- **2.12.F** Reliability Assessment of Natural Gas for Standby Power Generation ........................................ 93
- **2.16.H** Test and Demonstrate M-Trigen Micro-CHP System ................................................................. 95
- **2.17.E** Long-Term Performance and Reliability Assessment of CHP and DG Systems ............................ 97
- **2.17.F** CHP System with Integrated Innovative Particle Thermal Energy Storage ....................................... 99
- **2.18.A** Cost Optimization of 3D Printing of Advanced Burners for CHP and Distributed Generation ........ 101
- **2.18.E** Capstone C200S Microturbine Laboratory Evaluation ............................................................... 103
- **2.18.F** Ultra-High-Efficiency Natural-Gas-Fired Combustion Systems for mCHP ...................................... 105
- **2.18.G** Integrating Micro-CHP and PV in Advanced Gas/Renewable Homes ........................................... 107
- **2.18.H** Micro-CHP Characterization and Demonstration ........................................................................ 109

## INDUSTRIAL APPLICATIONS

- **2.12.M** Ribbon Burner Improvements ........................................................................................................ 113
- **2.14.O** Field Validation of Gas-Quality Sensor .......................................................................................... 117
- **2.15.A** On-Site Electrical Generation ........................................................................................................ 119
- **2.16.A** Next-Generation Infrared Burner ..................................................................................................... 121
- **2.16.B** On-Demand Heat-and-Power System ............................................................................................ 123
- **2.16.G** Energy-Recovery Heat Exchanger .................................................................................................. 125
- **2.17.A** Recovery of Water from Humid Exhaust Gas to Save Water and Energy ..................................... 127
- **2.17.I** High-Efficiency Ultra-Low-NO<sub>x</sub> Commercial Boiler Burner .................................................. 129
- **2.18.B** Advanced Immersion Tube Burner .................................................................................................. 131

## TRANSPORTATION

- **2.14.F** Free-Piston Linear-Motor CNG Compressor Scale-Up ................................................................. 135
- **2.14.K** CNG Composition Impacts on Engines and Fuel-Delivery Systems .............................................. 139
- **2.15.H** Modular CNG Storage System Investigation .................................................................................. 141
- **2.16.M** CNG Dispenser Full Fills .............................................................................................................. 143
- **2.16.N** NGV Codes and Standards Monitoring, Development, and Support ............................................. 145
- **2.16.O** NGVAmerica Technology Committee Participation & Representation ............................................ 147
- **2.16.P** Test and Validate Small-Scale CNG Compressor Fill Devices ...................................................... 149
- **2.17.G** US Hybrid ISL8.9 Charge-Sustaining Hybrid Truck Retrofit and Demonstration .......................... 151
- **2.17.H** CNG Station Measurement Investigations .................................................................................... 153
- **2.18.I** Cost-Effective CNG Pre-Cooling Technologies .............................................................................. 155
- **2.18.J** Virtual Pipeline Market Study and Technical Assessment .............................................................. 157
RESIDENTIAL APPLICATIONS
Next-Generation Residential Gas Heat-Pump Water Heater

In this project, a research team designed and demonstrated the first gas-fired heat-pump water heater to provide end users with a storage water heater with an efficiency factor of 1.3 of greater. Field demonstrations are under way in California.

Project Description

The industry’s first residential gas heat-pump water heater (GHPWH) is near commercialization, with two OEM partners and a series of successful field trials advancing the design of each generation of prototypes. In partnership with other funding agencies, UTD co-founded a team of researchers to develop the residential/small-commercial GHPWH and continue to reduce projected costs and improve reliability by refining a number of system components.

The initial GHPWH development initiative was funded by the U.S. Department of Energy (DOE). This project is a continuation of that development, led by Stone Mountain Technologies, Inc. (SMTI) with commercial OEM partners and Gas Technology Institute.

The first-generation GHPWH units were designed and demonstrated through laboratory testing from 2009 to 2013. Subsequently, six GHPWH units were installed and monitored in the field. Through these initial field tests, critical information was used to improve the GHPWH control strategies and future design improvements (including system sizing).

The current phase of this UTD project is focused on supporting an additional five field demonstrations in a program sponsored by the California Energy Commission (CEC) with support from Southern California Gas Company (SoCalGas).

Benefits / Market Implications

The motivation for developing a GHPWH is efficiency-driven. When delivered to the market, the GHPWH will be the only technology of its kind with a primary energy efficiency of greater than 100%. The efficiency gains are significant, with efficiency factors (EFs) of 1.3 or greater, 76% to 120% greater than condensing and non-condensing water heaters, respectively. Results from this project have the potential to reduce the cost, increase the reliability, and enhance the performance of the next generation of gas heat-pump water heaters.

Technical Concept & Approach

The GHPWH units are driven by an air-source single-effect absorption heat pump, itself driven by a gas burner, capable of Coefficients of Performance (COP) of 1.5 or above. This yields an EF of 1.3, more than twice the efficiency of standard gas storage water heaters, which are in 74% of California homes.
Based upon prior laboratory testing, the units are projected to be low-NO\textsubscript{x} compliant. The packaged GHPWH heats the 60 to 80 gallons of stored water with a nominal 10,000 Btu/hr output ammonia-water absorption heat pump, driven by a small 6,300 Btu/hr low-NO\textsubscript{x} gas burner. With such a small combustion system, the GHPWH offers retrofit installation advantages over other high-efficiency gas products.

Through the broader project funded by the CEC and SoCalGas, the project team is currently focused on the testing of GHPWH units and the development, use, and refinement of advanced fault detection and diagnosis.

The goal is to demonstrate that the projected delivered efficiencies of 130% or greater are valid, robust, and are not achieved through a loss of user comfort. Researchers will estimate annual energy, operating cost, and emissions savings and solicit feedback from host end users and installation contractors through pre/post surveying.

**Results**

Following a laboratory prototype development program, the performance of a gas heat-pump water heater installed in a Tennessee residence over a 10-month period was investigated. The laboratory-validated performance and preliminary field test data suggest that the 1.3 Uniform Energy Factor target is feasible and if achieved during commercialization it can be competitive with other available high-efficiency gas water-heating options. Cycle COPs of the GHPWH are on par with prior laboratory results (1.4-1.8) and, as is expected for this type of technology, are relatively insensitive to ambient temperatures.

The performance of the GHPWH is shown to be robust over a range of operating conditions, including usage patterns, ambient temperatures, and water mains temperatures, by both laboratory testing and field evaluation of the GHPWH in a U.S. residence. The GHPWH is projected to have a reduced retrofit cost with a small input capacity, requiring no upsizing of gas piping and minimal accommodation of small-diameter plastic venting. Thus, if competitively priced, the GHPWH is an important introduction to the high-efficiency water-heating market.

In 2015, project efforts focused on transitioning the purpose-built prototype from field testing to reliability testing. Reliability testing was completed in September 2016.

A report on the initial phases of the project was issued in 2017. In these phases, six GHPWH prototypes were subjected to extended reliability testing. More than 2,500 operating hours were accumulated by these GHPWH units.

Researchers also performed an analysis of how the GHPWH is impacted by relevant codes and standards in the U.S., Canada, Mexico, and Europe.

In 2017, seven new GHPWH units were built: five units for residential field demonstration, one for evaluation at SoCalGas’ Engineering Analysis Center, and one for proprietary testing by a manufacturing partner.

In 2018, the project team monitored the performance of the five gas GHPWHs installed at the test sites, which continued through June 2019.

Data continue to confirm that ~50% therm savings are achieved on a site-by-site basis and are expected to improve as the ambient temperatures rise.

Preliminary data analyses were performed on a weekly basis and shared with the candidate manufacturing partners to provide early feedback.

Baseline monitoring was completed for the initial equipment at all five test sites. The project team also finalized the Baseline Field Monitoring Report for the project prime project sponsor, CEC.

**Status**

Monitoring of fourth-generation GHPWH prototypes is ongoing at five residential sites.

A survey of hosts/installers post-GHPWH installation is under way.

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Evaluation of Whole-House Residential Retrofit Technologies (Building America)

For this project, researchers are conducting laboratory tests, field studies, and energy analyses to support the option for gas technologies designed to reduce energy costs in existing residential buildings.

Project Description

Through this project, UTD provides support for the Partnership for Advanced Residential Retrofit (PARR), a U.S. Department of Energy Building America team led by Gas Technology Institute (GTI). PARR focuses on retrofit issues in cold climates with high space-heating energy consumption. Building America provides opportunities to present UTD findings promoting intelligent use of gas appliances to reduce source-energy consumption in existing homes.

The project is divided into phases. Phases 1-4 provided cost share for the first five years of the PARR activities, and Phase 5 provides cost share for the 2015-2020 scope, which focuses on managing infiltration, ventilation, and duct system airflows to obtain the best indoor air quality with the lowest energy consumption.

Benefits / Market Implications

This project is providing data and analysis to support natural gas technology assessment and installation best practices in existing residential buildings. It is anticipated that project results will support the continued use of gas equipment and systems in retrofit situations as the most cost-effective potential single measure or as a part of an energy-efficiency package.

Technical Concept & Approach

In cooperation with the Building America program, researchers are verifying the performance of measure packages that provide cost and energy savings, addressing code concerns, and investigating new opportunities in existing single and multifamily buildings.

Investigations were completed for several key areas of research: 1) optimizing gas furnace performance in the field, 2) testing the laboratory performance of furnaces, 3) improving the performance of multifamily buildings that use gas for steam and hydronic heat, 4) measuring the performance of combination heating and water-heating systems, 5) determining the optimum energy upgrade packages for typical midwestern single-family building types, 6) combustion safety for gas appliances using indoor or outdoor air for combustion, and 7) low-cost methods for mitigating radon.

For the 2015-2020 program, key research areas are:

1. A systems approach to air flow in houses (ventilation, air tightness, ducted distribution systems, and combustion air requirements). This scope includes the adoption of outdoor-temperature-based ventilation strategies, air tightness credits for ventilation, and the interaction between ducted air distribution systems and depressurization in the space. Activities include extrapolation of field data collection to a larger population of houses by archetype. This research is a collaborative effort between GTI, the University of Illinois, and the Midwest Energy Efficiency Alliance. Standard and enhanced measures packages will be evaluated in up to 40 homes.

2. Continued support and advocacy through the Building America program for simplified combustion safety test procedures so that fewer homes are rejected by weatherization teams.

3. Continued focus on approaches for determining zero net energy for mixed fuel house using solar photo-voltaics as the renewable resource.

Preliminary airflow data show drastic improvements in uncontrolled air flow.
Results

- **Optimizing Gas Furnace Field Performance**

A study of 48 Iowa HVAC SAVE program evaluations showed that homes were losing 9% of potential performance from their furnaces, usually due to restrictive returns and/or filters. In 10 homes that received more in-depth evaluation, diagnostic data showed that 23% improvement in delivered heating energy could be achieved through system tune-ups.

- **Laboratory Performance of Furnaces Removed from the Field**

Laboratory testing of 12 vintage furnaces removed from the field showed that there was no degradation in performance with time, and the efficiency of the furnaces in the field could be increased an average of 6% through tune-ups.

- **Multifamily Steam Distribution Systems**

A 10-building retrofit study showed 10% savings in natural gas use, with a five-year payback.

- **Combination Heating & Water-Heating Systems**

A two-year study of commercialized combination units in the field found up to 20% savings compared to separate space- and water-heating systems.

- **Energy Upgrade Packages for Midwestern Single-Family Homes**

PARR analyzed cost-optimal energy packages from the Illinois Home Performance program with the ENERGY STAR program as compared to the packages selected by the Building Energy optimization tool for 15 single-family archetypes.

- **Combustion Safety for Gas Appliances Using Indoor or Outdoor Air for Combustion**

PARR developed a Combustion Safety Measure Guideline published by Building America and developed a simplified test procedure for appliances using indoor air.

- **Radon Mitigation Through Air Sealing**

PARR studied the impact of air sealing between first-floor and foundation space on the radon levels in the home. Results show, in many cases, surprising links between hourly measured radon and hourly outdoor temperature. Colder temperatures correlate strongly with lower radon levels. When windows are open, radon is reduced in vented crawl spaces, as expected, as well as in living spaces.

Additional results from the overall PARR program are provided at www.gti.energy/BuildingAmerica.

In the most recent phase of the project, the PARR team conducted an Expert Meeting, a Practitioner Meeting, and a literature review to identify the most promising retrofit measures for optimizing efficiency and indoor air quality in residential retrofits. A test plan was then developed for a study to compare homes with normal industry practice energy retrofits and a suite of enhanced airflow-control measures.

In 2018, the PARR team substantially exceeded the then-target of field testing 10 homes, ending in 2018 with 22 homes enrolled and 9 homes being monitored.

In 2019, the team prepared a preliminary data analysis for a DOE project review. All of the homes are receiving ASHRAE 62.2-compliant ventilation as part of their retrofits, and so far the data support the expectation that energy efficiency retrofits installed with proper ventilation do not have a negative effect on Indoor Air Quality (IAQ).

**Status**

Field data collection is expected to extend through the third quarter of 2020.

A total of 23 homes are enrolled in the study, with nearly 20 instrumented. The project will likely be extended through another heating season to reach the 40-home goal.

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Codes and Standards for Advanced Gas Technologies

Through interactions with industry associations and code-development organizations, researchers are presenting scientific data and helping refine and update codes and standards so that end users and the environment can benefit from cost-effective advanced gas technologies.

Project Description

While clean natural gas is increasingly used in the energy marketplace, the introduction of advanced natural gas technologies can be challenged by a variety of issues between the prototype stage and full market adoption.

Codes and standards (C&S) issues can often be hurdles to widespread adoption. Advanced technologies are often developed to address issues with existing alternatives; however, new technologies are evaluated using existing criteria which may misrepresent performance, necessitate costly engineering redundancies, and delay market introduction. In many cases, advanced technologies will not be included in C&S. In addition, efficiency levels on existing technologies continue to increase, creating impacts with regard to installation, vent systems, durability, and reliability.

Efforts under this research project include participation in the development of:

- ASHRAE 124 Methods of Testing for Rating Combination Space-Heating and Water-Heating Appliances, which included new laboratory data.
- ASHRAE standard 204, Method of Test for Rating Micro Combined Heat-and-Power (CHP) Devices. The project team’s participation was critical in the development of this new micro-CHP test standard.
- NFPA 54, the National Fuel Gas Code (where sidewall vent penetration locations for high-efficiency equipment are restricted based on rules developed for lower-efficiency products).
- ASHRAE 103 furnace and boiler standards, recommending changes based on test results.
- Codes related to condensing heat exchangers and condensate disposal from furnaces and boilers, rooftop heaters and unit heaters.

The objective of this project is to help overcome C&S barriers to use cost-effective advanced gas technologies by addressing gaps in standards development and testing, building code requirements and enforcement, and performance information for analytical tools used for energy code compliance.

Benefits / Market Implications

Information tools, cost-effectiveness calculations, case studies, technical data, and other products developed through this project will help consumers and the environment benefit by increasing the options of efficient, market-appropriate gas technologies. By providing compelling technical data and market-impact analysis, advanced gas technologies can be more rapidly developed and introduced to benefit gas consumers and help energy providers meet energy-efficiency-program goals.

Technical Concept & Approach

By partnering with the U.S. Department of Energy (DOE), ASHRAE, Natural Resources Canada (NRCAN), the International Code Council (ICC), the American Gas Association (AGA), enforcement bodies, and other organizations, the research team is helping to ensure that advanced gas technologies are appropriately characterized and evaluated.
Results

With UTD support, the project team provides representation and technical input for natural gas technologies across a wide range of codes and standards committee development activity.

Progress includes:

- **ASHRAE Standard 118.1 Method of Test (MOT) for Commercial Water Heating**: With project team input, the scope was broadened to include all types of gas-fired heat pump water heaters (GHPWHs). Figures and equations were also adjusted to permit commercial GHPWHs, with some added considerations for sorption GHPWHs.

- **ASHRAE Standard 118.2 MOT for Rating Residential Water Heaters**: The committee is responding to the first round of public comments. Efforts continue to issue a final draft standard, which will include a new product category for residential gas-fired heat-pump water heaters. Release of Standard 118.2 is expected for 2019, running in parallel to the companion standard 118.1.

- **ASHRAE TC 6.3 Forced Air Heating and Cooling Systems**: The project team contributed to the development of a Research Topic Acceptance Request to assess the impact of existing assumptions of furnace cycle times on AFUE ratings, in light of recent changes in technology (e.g., modulating burners, variable speed fans, smart thermostats, etc.). The project team continues to work with TC 6.3 members on ASHRAE-funded research proposals related to thermostat cycling rates with smart thermostats, and simplification of the ASHRAE 103 MOT.

- **ASHRAE TC 6.10 Fuels and Combustion Forced Air Heating and Cooling Systems**: The project team developed ASHRAE seminars and presented information on sidewall venting for high-efficiency natural gas appliances.

- **ASHRAE Standard 40 Revision for Gas-fired Heat Pumps**: Researchers joined with stakeholders to establish the basis for a new standard committee (SPC) to revise Standard 40. The MOT will be updated to consider recent technology developments for gas heat pumps, including absorption, engine-driven, and variant refrigerant flow; residential and commercial; air-source, water-source, and ground-source designs.

- **ASHRAE 124 Combination Space-Heating and Water-Heating Appliances**: Researchers and TC 6.6 are developing new MOT for combination systems. The project team was asked by ASHRAE to develop a draft MOT based on a virtual test home approach. This opportunity allows researchers to shape this MOT so combination performance ratings will accurately reflect installed performance, and to prevent any regulatory barriers that might limit the market for combination systems.

- **ASHRAE 204P Micro Combined Heat and Power (mCHP) Devices**: The working group finalized the new MOT for mCHP (Version 12) for the committee review and letter ballot.


In 2018, project representatives participated in multiple technical committees during the ASHRAE 2018 Winter Meeting. Specific activities were involved in a variety of code committees.

In 2019, the project team hosted a webinar in February to highlight recent updates on C&S for residential and commercial HVAC equipment.

Status

Members of the project team continue to interact with various codes and standards committees and prepare conference papers and presentations of value to end users, engineers, regulators, and the gas industry.

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Innovative Gas Absorption Heat Pump for Space Conditioning

Current market conditions are providing opportunities for high-efficiency, low-emission gas-fired heat pumps to serve residential and small-commercial customers. This project is focused on developing and testing a packaged gas heat-pump prototype for space-heating applications.

Project Description

Gas-fired absorption cooling at the residential/small-commercial scale has traditionally experienced low market penetration due in large part to high first cost. To meet this market need, low-cost gas-fired absorption heat pumps (GAHPs) in heating applications (air source) are being developed, which may be able to offer substantial efficiency gains over typical non-condensing and condensing warm-air furnaces and hydronic boilers alike, with Coefficients of Performance (COPs) estimated at or above 1.5 versus thermal efficiencies of 80% to 95%. Thus, a cost-competitive GAHP could gain market share in the space-heating and/or cooling markets.

This UTD project was initiated to provide cost-share to a 2012-2015 program with the U.S. Department of Energy (DOE), Stone Mountain Technologies Inc., A.O. Smith Corporation, and Gas Technology Institute (GTI). It focused on the development of a residential-size GAHP for space heating.

This R&D effort, now in a field-evaluation phase, is being supported by UTD with cross-cutting efforts across platforms to enhance component reliability and corrosion protection.

Benefits / Market Implications

Natural gas end users may soon have the opportunity to have more gas heat pumps for residential and small-commercial space conditioning to compete with traditional electricity-driven vapor-compression heat pumps. One driver is lower fuel prices relative to other energy sources. Another driver is efficiency gains. Conservative estimates of GAHP heating COPs are 60% to 90% greater than condensing and non-condensing warm-air furnaces.
GAHP units were installed at three residential test sites in La Crosse, WI, for next-generation field trials into the 2018-19 heating season.

The project is near completion, with the primary goals having been accomplished, including: 1) build and perform pre-shipment testing on a prototype GAHP combination system; 2) recruit, screen, inspect, and select residential host sites; 3) perform baseline monitoring of host site’s HVAC and water heater performance; 4) install and commission a prototype GAHP combination system at the host site; and 5) troubleshoot the GAHP and data-collection system and monitor system performance through end of project.

Based on results from the 2017-18 and 2018-19 heating seasons, the GAHP would provide:

- Therm savings of 35%-49% in space-heating only mode, depending on baseline selected
- Therm savings of 55% for domestic-hot-water only mode, and
- Therm savings of 37%-47% overall, as a combined space/water heating system.

Currently, three GAHP combination space-heating systems continue to operate in La Crosse, WI, with support from the technology and manufacturing partner. With record-setting cold temperatures (down to -30°F) and snowfall in the past two heating seasons, the performance of the GAHP held up despite these extreme conditions.

**Status**

The project team is currently wrapping up this project at host sites and finalizing reporting while the team continues to monitor and analyze site data for sites agreeing to continue the pilot for the 2019-20 season.

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For this project, researchers investigated the current challenges and opportunities for the natural gas industry to better serve multifamily new-construction homeowners, architects, and builders. Recommendations for improvement were also developed.

Project Description

There is a significant opportunity for natural gas to better serve the growing multifamily new-construction market; however, there are also significant barriers, many of which have been the focus of research in recent years.

In Phase 1 of this project, researchers investigated national trends regarding gas and electric multifamily market shares, the economics of energy services, building codes, and installation practices.

In Phase 2, the project team provided regional multifamily market paths for advanced products that provide promising opportunities in this sector, a portfolio, and examples and discussion of successful utility initiatives.

Phase 3 recommended implementation opportunities for specific regions or utilities, including holding utility-sponsored design-planning sessions with stakeholders within the development, design, and building communities.

Benefits / Market Implications

Studies on the multifamily market identify key economic issues, code barriers, and product gaps that require investigation and resolution. Addressing these issues, gaps, and barriers will enable more multifamily end-use ratepayers to benefit from the lowest-cost energy option and improve energy efficiency.

Technical Concept & Approach

Key tasks include:

- **Multifamily Market Data Collection & Analysis**

  Researchers used census data and other available resources to obtain a 2015 snapshot of builder and developer energy choices in the multifamily new construction market by U.S. region and by building type. The assessment included, to the extent possible, gas and electric utility rates and incentives, the availability of gas service, market trends, and code differences. The project team will identify up to three regions with unique competitive climates and develop solutions based on regions.

- **Multifamily Market Preliminary Recommendations**

  Researchers reviewed the analysis and developed preliminary recommendations for a path forward in each region. In general, these recommendations focus on investment to resolve installation practices, infrastructure issues, building code barriers, equipment gaps, economic shortfalls, and rebate structure issues.

- **Technology Solutions**

  The project team reviewed the market data and other information to prepare materials describing existing product options and design alternatives.

- **Multifamily Stakeholder Charrette**

  The project team held three stakeholder charrettes in 2018. These collaborative sessions included multifamily property developers, gas product manufacturers, design/build and/or A&E firms, interested participants from the utilities, and code compliance contractors.
The primary aim of the charrettes was to identify the key engagement and decision-making points of the fuel-selection process and address perceived key hurdles to technology adoption.

- **Development of Supporting Utility Programs**

Researchers developed general plan outlines and recommended best practices for utility programs to better support multifamily end users and markets.

**Results**

In 2016 and 2017, the project team held interviews with key national-level players active in the multifamily market, including representatives from industry associations and gas utilities. These discussions covered past activities each of these organizations have undertaken within the multifamily market segment, current challenges, and key concerns of stakeholders. Project representatives also held discussions with many U.S. utilities and performed significant outreach to the building and development community to obtain their perspectives.

Phase 1 research reported on key trends in the housing market, the use of heating fuels, and the use of electricity. The rebounding of electricity as the majority space-heating fuel can be seen in both low-rise (2-4 units) and high-rise (5+ units) buildings, while the volume of gas-heated units shows either modest or no growth. However, this trend is not reflected in water heating, where gas still plays a strong role and has generally kept pace with electricity growth.

Venting issues can become increasingly expensive and complex to address in high-rise structures. Building and appliance codes and standards have presented barriers regarding venting, combustion air requirements, and condensate management. Research and data analysis indicate that the changing codes-and-standards landscape combined with new technology offerings may significantly impact historic barriers.

A key issue in some regions will be addressing economic challenges through new utility rate structures or aggressive multifamily energy-efficiency programs.

In Phase 2, researchers identified the key economic and non-economic factors presently driving the decision behind choosing electric service over gas service in new construction multifamily buildings. U.S. southern states and Atlantic coastal states were identified as particular focus areas for project research.

The southern U.S. has low rates of gas-fired space and water heating – the gas share in the multifamily starts for the South region was just 4% in 2016. Atlantic coastal states show a different set of market conditions and responses; the gas share in new multifamily starts for the Northeast region was 74% in 2016, which was the lowest gas share for this region since the early 1990s. In both regions, some gas utilities are taking innovative steps to better support customer needs and opportunities.

Atlantic coastal states show a different set of market conditions and responses. The gas share in new multifamily starts for the Northeast region was 74% in 2016. Although this share appears strong on the surface, it represents the lowest gas share for this region since the early 1990s. The increasing rates of electric-heating are being addressed differently by utilities in this region.

In 2018, specific UTD members participated in stakeholder charrettes (i.e., focus group sessions) with the goal of recruiting local market participants such as real estate developers, architects, engineers, and others involved with multifamily projects. The regions targeted were in warmer U.S. climates such as the mid-Atlantic and southern areas (Oklahoma City; Charlotte, NC; and Jackson, MS) where natural gas installations on new multifamily construction have been on the decline. Recruitment efforts were successful at surpassing the targeted goals for number of attendees and helped provide a good diversity within the group.

**Status**

A Phase 3 Final Report was issued in January 2019.

The Phase 3 report details recommendations that address codes and standards, economic challenges, and technology-based solutions that UTD members can consider to enhance their service to multifamily homeowners, architects, builders, and others.

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> “The Multifamily Infrastructure Challenges project has given us a comprehensive insight into customer concerns. We have used this insight to develop outlines and resources to help build a greater understanding of the benefits of natural gas in multifamily developments.”

- April Arnold
Sales Representative II
ONE Gas, Inc.
Advanced Systems for Self-Powered Water Heating

Research in this project is focused on developing an advanced technology to increase the efficiency of gas-fired water-heating systems for homes and businesses, while retaining the simplicity and economy of traditional storage water heaters with no moving parts and no need for electricity.

Project Description
In this project, researchers are investigating Two-Phase Thermo-Syphoning (TPTS) technology and ultra-low-power gas-water-heater control technology in an effort to develop a prototype “unplugged,” cost-effective, mid-efficiency, near-condensing gas water heater.

Benefits / Market Implications
A TPTS water heater offers the potential for scalability, rapid startup, long life, minimal standby heat loss, minimal scaling, self-power capability, low emissions, and substantially higher efficiency than conventional atmospheric storage water heaters.

The replacement market opportunity for self-powered high-efficiency water heating is approximately 150,000 units per year, representing a savings of eight million therms annually, or $6.4 million in avoided cost for gas customers while mitigating 52,000 tons of CO₂.

Technical Concept & Approach
Similar to heat pipes, the TPTS technology is more like a passive, closed-loop, flash boiler. The TPTS technology was initially developed to augment solar water-heating systems.

The key is the integration of three technologies:

1. **TPTS Technology.** A TPTS loop is evacuated and then partially charged with liquid water. Upon firing, a two-phase (steam/water) flow accelerates from the evaporator up to the submerged condenser. Condensing steam transfers latent heat to the hot water and travels through the condenser coil towards a vertical restriction. This restriction builds up condensate, increasing pressure head for circulation.

2. **Surface Combustor-Heater Concept as Evaporator.** The surface combustor-heater is a combustion heat transfer device that is based on the concept in which the relatively cold heat-exchange
surface is embedded in a stationary bed (porous matrix) where gaseous fuel is combusted. As the bed is heated by the combustion products, the heat is extracted from the bed by the embedded heat exchanger and is transferred to a working fluid circulating in the tubes.

3. **Dimpled or Twisted Tube Condenser.** The use of dimpled or twisted tubes in the condenser allows for effective, rapid heat transfer with minimal use of materials in a compact space.

**Results**

In 2014-2015, parametric testing of the TPTS technology (1980’s design) determined that the efficiency of the technology as tested is not optimal. The evaporator was found to be undersized and required optimization and redesign to reduce cost and improve performance. An analysis of the evaporator design identified a 20%-plus reduction in copper using thinner copper tubing and improving upon the evaporator fin design. In addition, better flow distribution between evaporator tubes can minimize dryout and the development of hot spots in the evaporator. Other findings concluded that:

1. Better diagnostics to determine the recirculation rate and mixture quality as functions of evaporator loading and tank temperature can result in better control of the technology and

2. To prevent evaporator dryout, improved treatment of interior tube surfaces or “pickling” is required.

The project team subsequently:

- Developed TPTS performance curves to guide sizing and design options
- Developed design correlations between the heating rate, water charge volume, and heat sink temperature under standardized and non-standardized conditions, and
- Developed a basic prototype design validated with numerical models.

Activities focused on a redesign of components to minimize size and cost, and to optimize performance. The TPTS 1980’s design utilized a commercial-size storage water-heater tank with a six-inch bottom access for inserting the condenser heat exchanger. While this served the purpose to prove the concept, a design is required that can be cost-effectively manufactured. Consequently, investigators evaluated methods to reduce the condenser size to minimize the size of the diameter hole in which the condenser is inserted into the storage tank.

A preliminary cost analysis of the TPTS water heater determined that: 1) A TPTS water heater must be comparable in price or less than the competition, 2) TPTS components must be lower in price to the components replaced or eliminated, and 3) The cost of TPTS system components to a water heater’s final price is between $130 and $200.

An iterative approach to TPTS evaporator optimization estimated a 28% savings in material costs. A new concept that embeds the evaporator tubes within an ultra-low-NO\textsubscript{x} burner is being evaluated and offers a potential 80% cost reduction in materials. A finned-tube concentric condenser design offers a 58% potential cost reduction in materials compared to the existing condenser.

In 2018, the project team developed a computational fluid dynamics model of the surface combustor with embedded tubes. This model was used in the design, validation, and optimization of the prototype system. Researchers also conducted a review of critical relative research for input into the model. Based on the modeling and computational analysis, a preliminary design was developed for a TPTS evaporator with multi-pass embedded tubes. An alternative approach separating the embedded tubes from the burner was also designed and evaluated. It offers potential advantages in component manufacturing and in-field servicing. It also offers advantages in its design in that it is adjustable and allows for quick iterative testing to fully characterize the technology.

**Status**


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Next-Generation Advanced Residential Gas Clothes Dryer Development

In this project, researchers are investigating next-generation technologies for a residential gas dryer that would provide gas consumers with a model that is very efficient yet economical.

Project Description

In this project, researchers are investigating next-generation technologies – including heat recovery, indirect firing, direct venting, and advanced burners – to determine potential efficiency boosts for residential dryers. All of these techniques and technologies have been shown to increase efficiencies in other areas, but scaling them to a residential dryer size, determining the additional cost to the dryer, and quantifying the efficiency increases will help dryer manufacturers determine the best path to further advance gas-fired dryers while minimizing cost increase.

UTD’s guiding Technical Project Committee indicated that there is also an interest in reducing drying times if possible. This is an advantage that gas dryers have over electric units: the potential to increase firing rates to reduce drying times. The research team will also study drying times as technologies are evaluated. For instance, modulation may allow a high firing rate in the early stages and a low firing rate later to both reduce drying time and save energy.

Project deliverables include an early-stage prototype incorporating the most promising technologies and reports detailing the performance improvement provided by all of the technology options investigated.

Benefits / Market Implications

Gas-fired dryers have not had many technological advances in recent years and there is potential to enhance the technology. With about 81% of U.S. households having a clothes dryer, the potential improvements in the design of gas dryers represent sizable savings to residential ratepayers.

Although electric clothes dryers represent the majority of U.S. residential dryers, a 2011 study by others indicates that it is not consumer preference for electricity that is the driving force. Although 60% of survey respondents are currently using electricity for clothes drying, only 34% stated that they actually preferred electricity. In contrast, 40% of respondents stated they currently used gas for clothes drying and 53% said they would prefer to use gas. These results indicate that the cause for gas dryer’s minority market share is not due to the inherent characteristics of gas as a fuel, but is driven by other factors such as cost, availability, and other regional factors.
Technical Concept & Approach

The project team is investigating high-efficiency dryer technology options including, but not limited to, heat recovery, modulating burners, indirect firing, direct venting, and advanced burners. Researchers are also investigating the potential for technologies to reduce drying times.

The original model and each technology change being evaluated is being tested to standard methods to determine the performance improvement of each technology (efficiency, drying time, etc.). The most promising technologies will be incorporated into an early prototype for demonstration.

A project goal is to demonstrate a very high efficiency gas-fired dryer comparable on a source-energy basis to electric heat-pump dryers, but at a much lower target purchase price for the ratepayer.

Results

Phase 1 of this project focused in part on assembling a test station in an environmental chamber to maintain temperature and humidity to ensure accurate testing. It had become apparent during previous UTD dryer research that room temperature and humidity have a very large effect on the dryer efficiency rating. Although the test standard allows for 40%-60% relative humidity (RH) during the test, a dryer will be much more efficient at 40% RH than at 60% RH. With that in mind, researchers decided that it was necessary to arrange the test in an environmental chamber.

In 2016, technicians completed the first modifications to the dryer. The unit was fully instrumented to allow for testing different design changes, including changes to primary aeration and air-to-fuel ratio, followed by potential heat-recovery options. Designs to recover heat from the flue were implemented and show promise for improved efficiency in testing. Overall, the heat recovery appears promising while providing a small cost added to the dryer, but still potentially making it appealing to manufacturers.

Researchers attempted many different configurations for sealing the dryer to maintain stable combustion, and investigated simple heat-recovery options with many different alterations. In the end, it was determined that a novel heat-recovery setup, along with a newly configured and sealed dryer combustion chamber, showed the most promise, with a 4% boost to the dryer efficiency while adding very little cost to the dryer. Research suggests that with further optimization this approach could result in over a 5% boost in dryer efficiency.

For the study, a total of 42 temperature sensors, five gas sample points, a gas meter, and electric power meter were fitted to the dryer.

In the current Phase 2, researchers are investigating additional heat-recovery options, modulation techniques, indirect-fired methods, direct venting, and alternate burners.

In 2018, researchers set up a new dryer in the dryer test stand in the environmental chamber to provide the needed temperature and humidity for the test procedure. The project team also set up a new washer test stand to provide clothes with the needed temperature and remaining moisture content for dryer testing.

In 2019, the research team developed a slightly modified test procedure to improve variability of the results and provide repeatable results that will allow comparison of technology improvements on a common basis. After this modified procedure was adapted, baseline testing was completed. Researchers also investigated the effect of firing rate on the dry time and efficiency.

It was noticed from previous dryer research that results of dryer efficiency testing according to the U.S. Department of Energy (DOE) test procedure can vary based on a few factors. The current standard requires allowing the automatic moisture sensor to automatically stop the load. An issue is that the moisture sensor can add a lot of variability to the test results based on when it determines the load is dry. In many instances, the load is fully dry, but the dryer keeps running before the moisture sensor eventually shuts it off. Researchers need good repeatability to compare the baseline testing of a standard dryer to each technology that is being tested to improve efficiency.

The project team was able to achieve good repeatability by creating a slightly modified test procedure that measured flue RH and determined when the clothes were dry based on the flue RH.

Status

Researchers are testing the affects of various firing rates on efficiency and drying time. This will be followed by modulating testing and additional heat-recovery testing.

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Residential Kitchen Cooking Ventilation Effectiveness

In this project, a project team evaluated existing residential ventilation systems for their effectiveness at capturing and exhausting heat and airborne particles in residential applications. Researchers are also developing designs for improving the performance of these products for end users.

Project Description

While commercial foodservice facilities are required to operate most cooking equipment under a ventilation hood, residential cooking does not have the same requirements. And while most residential kitchens have a ventilation system above the stove, most homeowners do not use the system unless excess smoke is being produced. Also, many existing residential ventilation systems are not maintained and/or are ineffective at capturing food and combustion emissions. These factors have led to growing concerns about the effect that cooking has on indoor air quality.

Publications on residential indoor air quality suggest that emissions from cooking can negatively affect a home’s air quality. Specific emphasis is put on combustion emissions and strongly suggests electrical cooking results in better air quality than cooking with gas. However, a comparative study of the volume of emissions produced from the food, whether cooked using electric or gas equipment, to the emissions from the gas burners has not been fully studied. Also, published information does not point out that an effective ventilation system would not only remove the food emissions, but also the gas combustion emissions.

In this project, researchers evaluated the effectiveness of existing ventilation systems at capturing and exhausting heat and airborne particles in residential applications. In addition, the project team will develop designs for improving the capture effectiveness and methods to improve the system performance.

Researchers will also investigate the advantages and issues with adding a feature that automatically turns on the hood when the oven is in operation.

Benefits / Market Implications

A properly designed residential ventilation system should allow for the preparation of food while maintaining safe indoor air quality. The systems effectively remove heat and food emissions from the residential environment.

Technical Concept & Approach

The project team identified typical designs for residential ventilation systems. Each design was tested in the laboratory to determine the capture rate of heat, food emissions, and combustion emissions. Subsequently, researchers determined the effectiveness of each design for a residential kitchen ventilation system and developed improved redesigns.

Results

The project constructed a Residential Kitchen Ventilation Test Setup that is specially designed for quantifying the capture effectiveness of the hoods. In 2017, the team installed a shadowgraph system to quantify capture effectiveness and a data-acquisition system for measuring temperature, emissions, and energy usage.
A test matrix was prepared to determine the capture effectiveness of heat and emissions from all the burners on the rangetop and the oven, and baseline testing of the range was completed.

The project team collected data to measure the emissions profile of each burner and determine the capture effectiveness of the hood for combustion emissions. The team tested several methods for measuring the capture effectiveness of the emission from the burners.

The following is a summary of the results:

- Hood capture and containment performance testing was done in accordance to ASTM F1704 Standard Test Method for Capture and Containment Performance of Commercial Kitchen Exhaust Ventilation Systems. The range hood performance was evaluated using the flow visualization apparatus and procedures outlined in the test method. The shadowgraph image was used to determine the amount of capture or spillage of the thermal plumes as a fractional assessment of the projected image. Trace amounts of smoke were also used as a seeding mechanism.

- The hood capture and containment performance evaluation was completed for five burners on a standard range. The hood evaluation was done at the high-speed air flow rate. The evaluation was done on burners separately and in combination. In general, the hood captured and contained the thermal plumes from the rear burners and failed to capture the thermal plume from the front burners. Sensitivity testing showed a cooking pot positioned on the front burner did not require a reduction in the firing rate to maintain capture and containment.

- When the thermal plume from the front burners spilled, a visual assessment of the shadowgraph image determined that the plume volume spilled 20%-40% along the front edge of the hood and 10%-20% along the sides of the hood. The poor hood performance of the front burners was due to the amount of set-back of the hood over the range. Increasing the depth of the hood would increase performance along the front edge. Adding side panels would increase hood performance along the sides of the hood.

In 2018, the initial evaluation of heat capture using the shadowgraph test setup was completed for all the burners on the rangetop. The hood was modified and retested to improve capture effectiveness by adding side shields and an extension to the front of the hood.

Initial analysis of both configurations suggests that the changes had some improvement in terms of capture effectiveness, but not as much as expected. Based on these results, a truly effective capture hood for residential applications would require more than just slight modifications of existing designs.

Status

A Final Report for Phase 1 of this project was issued in June 2019.

The next phase of this project is to further investigate other design changes and issues associated with indoor air quality of using gas-fired appliances for cooking.

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Maintenance-Free Approaches for Tankless Water Heaters

In this project, researchers are investigating maintenance-free approaches to hard-water remediation on heat exchangers for tankless water heaters in order to minimize operating, maintenance, and lifecycle costs of these highly-efficient units for end users.

Project Description

Condensing tankless water heaters eliminate the standby energy loses associated with tank-type heaters, offering consumers significant increases in efficiency – a 95 Uniform Energy Factor (UEF) compared to a 59 UEF for a minimum-efficiency tank-type water heater. However, tankless products have compact copper heat exchangers, and in areas of hard water they are susceptible to scale and mineral accumulation. Scale is about 400 times less conductive of heat than copper per unit thickness, so daily efficiencies can dip down to 72% if left untreated. Furthermore, scale and mineral accumulation can reduce equipment life to as short as 1.6 years.

Tankless water heaters represent about 12% of the water-heater market. The application and use in combination space- and water-heating systems offer opportunity for expanded market share. Addressing water-quality issues and identifying the correct remedy is critical to enabling broad adoption of these technologies in the U.S. and maintaining the effectiveness of energy-efficiency programs aimed at tankless water heaters.

In Phase 1 of this project, researchers investigated various low-cost, maintenance-free approaches to hard-water remediation on tankless heat exchangers.

Phase 2 involved an investigation of various coatings in order to physically assess their potential and provide data that supports product development.

The objective of the current Phase 3 is to transfer to major OEMs the findings from Phase 2 to prevent or minimize mineral scale buildup in the heat exchangers of tankless water heaters.

Benefits / Market Implications

Scale buildup on heat exchangers as a result of hard water is shown to reduce equipment performance and life. This issue could have a detrimental effect on equipment energy efficiency, natural gas savings, and market transformation.

Through this project, the industry will gain increased knowledge of the scale buildup issue and options available for remediation.

Technical Concept & Approach

Specific project tasks:

- Identify and prioritize potential maintenance-free approaches
- Prototype heat exchanger development
- Hard-water testing, and
- Coatings testing.

Phase 3 will evaluate a selected coating or coatings under more rigorous testing in tankless water heaters and in partnership with water-heater manufacturers.

A key is devising testing protocols that allow the manufacturer to compare test results without divulging information to competitors. To achieve this, the project team will construct a special test loop to provide baseline test results shared by all manufacturers.
Results

In Phase 1:

- A literature review was conducted of maintenance-free approaches for tankless heaters. Select vendors providing near-commercial or commercially available technologies were contacted for further information.

- A Nickel-Teflon® (Ni-PTFE) coating was selected for prototype heat-exchanger development. The project team employed industry references and relationships to demonstrate and become familiar with a recommended coating process. Researchers collaborated with a coating manufacturer to coat the interior surface of copper tube samples to be used in the hard-water test loop and to plan for future coating processes for the interior of an entire copper tube heat-exchanger bundle.

- A hard-water test loop was built. Six copper tube samples (three coated and three uncoated) were installed in the test loop and tested for 45 days, after which the samples were removed and analyzed. Due to the mixed results and degrading condition of the experimental setup, the test was terminated after 45 days in favor of re-scoping the project.

- Phase 2 of the project involved evaluating multiple coatings with coupon testing in a modified test loop before moving to full-scale heat-exchanger testing.

In 2017, research on existing coating technologies identified four coatings that may provide scale resistance in tankless water heaters:

1. A fluorsilane coating that is currently implemented on oil and water separating membranes to prevent fouling

2. A hydrophobic hybrid inorganic polymer coating developed for aerospace applications such as anti-corrosion on landing gear, anti-fog and abrasion on aircraft canopies, and de-icing on wings

3. Nano-particle coatings made of hydrophobic ultra-fine particles applied by inert gas evaporation or inert gas deposition used in chiller applications to prevent water fouling, and

4. A Teflon-impregnated nickel coating that has shown positive results for corrosion resistance.

A test plan was developed involving a circulating hard-water test loop to evaluate coated and uncoated copper coupons. Coupons are fixed to a coupon holder and installed in the test loop. Each coupon holder has two coupons fastened, one coated and one uncoated. Test loop conditions are as follows: water temperature is set at 160°F, the water flow rate is three gallons per minute, and the water loop pressurized at 40 psig. The test loop operates at 24 hours per day, seven days per week, with continuous safety monitoring and redundancy checks. To minimize coupon handling and still document scale growth (non-growth) over-time, periodically each coupon set is be removed, air dried, photographed, and weighed.

In 2018, a modified test plan was developed and sent to water-heater manufacturers, coupon suppliers, and coating manufacturers for review and comment.

Status

The test loop was completed in early 2019. Shakedown and safety controls calibration delayed the start of testing to late second quarter 2019. Periodically, visual observation and a gross weighing of coupon sets (coated and uncoated) are being made to assess scale formation. Testing will continue until a definitive amount of scale has formed for comparative analysis.

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High-Performance Building Initiative

Researchers are developing and communicating design approaches for mixed-fuel houses that meet or exceed the criteria for high-performance-home programs, and supporting utilities in their efforts to assist architects, builders, and homeowners.

Project Description

The U.S. Department of Energy (DOE) has several initiatives to develop technology for high-performance houses and recognize builders of high-performance houses.

In its Building America program initiative, DOE is investing in measures that reduce the energy used by new houses by 50% from a 2006 baseline. This program includes thermal envelope improvements, ventilation standards, equipment options, and the development of the BEopt modeling tool that offers cost-based tradeoffs to select the optimal set of measure packages to drive energy efficiency.

In the DOE Zero Energy Ready (ZER) Home Program, builders are recognized for building homes that are 40%-50% more energy efficient than a typical new home. This generally corresponds to a Home Energy Rating System (HERS) Index in the low-to-mid 50s. A HERS index of 100 is the baseline for standard homes (first introduced in 2006), and an index of 0 means the houses uses a total of zero purchased energy over a year.

While natural gas remains the most cost-effective fuel for many new and existing buildings, it is often left out of the high-performance-home design process because of the difficulty in applying electricity-based renewables to natural gas consumption and the challenge in identifying and installing cutting-edge hardware. Also, in some cases, the tools for the analysis of natural gas system benefits are insufficient.

The objective of this project is to develop an approach to be used for supporting mixed-fuel high-performance buildings, covering several fronts, including: zero net energy (ZNE), renewables, clean power, modeling engines, application guidelines, demonstration houses, and case studies.

Phase 2 focused on the methodologies and analysis tools for high-performance homes, home designs that meet the goals of the leading methodologies, and case studies from selected climate zones. In Phase 3 of the program, researchers are exploring strategies for gas utilities to better support high-performance home programs.

Benefits / Market Implications

This project will help homeowners, ratepayers, regulatory agencies, and others achieve goals for high-performance or ZNE homes by developing best practices and tools and identifying gaps and barriers. It will also provide market-based information to guide R&D and utility energy-efficiency programs in the near future.

A focus on the high-performance home market will prepare the gas industry to be competitive in the future as green buildings grow in market share and legislative initiatives in states like California move all houses toward becoming high-performance or ZNE.
This project explored design tools and metrics for high-performance mixed-fuel homes, and developed five case studies in representative North American climates.

Research suggests that the recipe for a high-performance mixed-fuel home include:

- A tight, well-insulated building envelope. While some high-performance homes employ unconventional wall systems to achieve super-insulated walls, a good envelope can be achieved at reasonable cost using 2x6 or 2x4 framing, advanced framing techniques, careful attention to air sealing, and a layer of exterior rigid foam insulation to reduce thermal bridging.

- Ducts in conditioned spaces, either routed within living spaces, or though sealed, conditioned attics and basements.

- A right-sized space-conditioning system with appropriately sized ductwork. There are several good gas-heating options which will provide both efficiency and low operating costs for space heating, including condensing gas furnaces and hydronic fan-coil combination systems.

- An efficient hot-water distribution system paired with a condensing tankless gas water heater, or efficient gas storage water heater.

- High-efficiency LED and CFL lighting and energy-efficient appliances.

- Photovoltaic and (less commonly) solar hot water systems for homeowners looking to further reduce their energy and emissions footprint.

### Technical Concept & Approach

In Phase 1 of the project, researchers cataloged programs that focus on high-performance housing, addressing criteria for inclusion of the program, the number of houses that qualify, design tools used, equipment selection, and other criteria. The project team also developed a best-practices guide for high-performance mixed-fuel houses. The guide incorporates designs, approaches to meeting program requirements, case studies, and mixed-fuel solutions.

Phase 2 involved the investigation of tools and methods used to design ZNE homes and development options for high-performance mixed-fuel homes in different climate zones. Researchers evaluated metrics and energy simulation software used to analyze high-performance homes, with a focus on those relevant to key programs identified in Phase 1. Then, in cooperation with five builders, the project team to developed energy models and case studies for high-performance mixed-fuel homes in diverse climates throughout the United States.

The focus of Phase 3 is on advancing utility involvement to promote high-performance home programs.

### Results

Researchers found that there are many high-performance buildings initiatives from a variety of sponsors. Researchers reviewed 19 of these programs to understand key program requirements related to natural gas appliances, as well as the most promising opportunities for utilities to participate.

Programs such as ENERGY STAR for New Homes are showing that big U.S. builders and consumers are embracing energy efficiency, and labeling programs such as HERS are allowing consumers to quantify energy efficiency.

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Low-Capacity Heating Systems Portfolio

Research was conducted to identify competitive products for low-capacity, efficient natural gas heating systems that provide comfort and good performance, with evaluations conducted in the laboratory and homes. Primary objectives were to provide end users and others with meaningful comparisons of fuel choices and to identify technology gaps and solutions.

Project Description

Initiatives by the U.S. Department of Energy (DOE), the California Energy Commission (CEC), and others are driving residential new construction that requires very low energy consumption for space heating and cooling. The DOE’s Zero Energy Ready Homes have performance targets such that homes can achieve zero energy consumption with the addition of solar photovoltaic (PV) systems. CEC’s goal is that all new single-family residential buildings built after 2020 consume zero net energy on a time-dependent valuation metric. That metric is such that the energy consumption of the building is offset by renewable energy, yielding a zero energy cost.

With these initiatives increasing the thermal performance of buildings and reducing energy demand, smaller-capacity heating and cooling systems are needed to meet the smaller load. With smaller-capacity heating and cooling systems, there is an opportunity to reduce the size of the duct system and bring it fully within the thermal envelope (no longer in attics, basements, crawl spaces, or below the floor).

At 10 Btu/hr per square foot of conditioned space, low-load homes can have heating loads as little as 12 to 24 MBH, and loads across the heating season are often less than 12 MBH. The dominant solution for low-load homes is electric-based systems, including ductless mini-split heat pumps, resistance heating, and air-to-water heat pumps.

Gas products can also efficiently serve these loads. Combination units can provide a low-load solution, as can through-the-wall vertical furnace/AC packages, which are point-source gas solutions. Various manufacturers have brought through-the-wall condensing systems to the market. However, these systems face reported market challenges, including uncomfortable air flows and temperatures, condensate icing and disposal, and home air-tightness concerns.

Low-capacity modulating furnaces are also a low-load gas solution. One manufacturer is marketing a sub-30MBH modulating furnace in the U.S. While the U.S. market is dominated by central forced-air systems, the cost per Btu to build low-capacity furnaces is higher than traditionally-sized furnaces, and the demand for them may not justify mass production yet.

In Phase 1 of this project, the focus was on assessing and cataloging products and options for low-capacity gas-heating systems, including those that are consistent with small-duct high-velocity (SDHV) distribution.

The objective of Phase 2 was to help end users, designers, and others better understand low-capacity gas heating system solutions and show their competitiveness in the market by addressing the gas systems’ technology gaps and barriers highlighted in the first phase, as well as comparing to electric heating systems.

A key tangible goal was to compare demonstrated performance of gas and electric heating systems and quantify the potential benefits. A portion of this UTD project cofunded a NYSERDA research project to evaluate condensing modulating hybrid furnace heat pump systems in New York residential applications.
Benefits / Market Implications

Low-capacity heating systems are largely unexplored in the gas industry, with the exception of one or two manufacturers. As new houses become more efficient, a full portfolio of gas solutions will be necessary in order to continue to provide low-cost, efficient heating options to gas ratepayers.

Technical Concept & Approach

- Establish dialogue with furnace and SDHV OEMs regarding technology gaps and potential solutions
- Research case studies focused on low-capacity heating systems (gas and electric)
- Cofund a NYSERDA project to install/monitor five low-capacity condensing modulating furnaces at residential project sites in New York state, and
- Evaluate low-capacity electric heating systems such as heat pumps and develop modeling strategies to quantify the impacts of advanced low-capacity heating systems.

Results

Phase 1 research found that in the 45MBH-and-under heating equipment landscape there is significantly more electric-heating equipment than gas-fired solutions. Where the majority of gas-fired solutions are in the 40-45MBH range, electric-heating equipment is evenly spread with a large selection between 15-40MBH.

A laboratory virtual test home provided the ability to compare space-heating and water-heating systems on a level playing field – particularly in simulated-use conditions to provide an understanding of delivered energy and associated efficiencies in the real world. Moreover, researchers developed detailed gas space-heating performance characteristics that were used to calibrate building energy modeling software to accurately represent various types of space-heating systems and quantify annual energy savings potentials.

Through this project, preliminary evaluations were conducted on a 15 SEER 9 HSPF 60 MBH single-stage electric heat pump that showed significant part-load and cycling inefficiencies on top of ambient temperature de-ratings typical to heat pumps. Initial assessments indicated better annual heating performance, even in mild climates, with an ACCA-sized condensing single-stage furnace than the ACCA-sized electric heat pump.

Seven residential field sites were secured in New York for the NYSERDA project to demonstrate and evaluate the performance of low-capacity condensing modulating furnaces integrated with electric heat pumps. The project team conducted long-term performance monitoring for two of the NYSERDA sites to disaggregate energy savings from weatherization and HVAC upgrades, and tailored short-term monitoring for three of the NYSERDA sites in order to assess performance and energy savings.

Observations from testing in the virtual test home and subsequent modeling were as follows:

- As expected, in cold and mild climate models the electric heat pump evaluated in the laboratory could not meet the space-heating loads without substantial supplemental heating when it was below about 35°F outside.
- Research indicated part-load operation along with supplemental electricity requirements had very significant and negative impacts on performance on the electric heat pump evaluated in the laboratory.
- The electric heat pump evaluated in the laboratory delivered about 80°F to less than 100°F air at the supply air discharge. While that may seem warm, when compared to the average body temperature of 98.6°F, it can feel cold, especially if diffusers create drafts. The condensing furnace consistently delivered about 110°F air at the supply air discharge.

Hybrid gas/electric forced-air configurations were also assessed for this project. Results from the hybrid analyses indicate marginal benefits, if any, over the gas tankless combi configuration. However, these results reflect performance of only the one system evaluated for this project.

The virtual test home has proven to be a valuable alternative to lengthy and costly field tests – particularly when long-term performance comparisons of various appliances are needed. However, field tests provided valuable data for short-term performance validation of equipment. It was determined there were very strong correlations between field and virtual test home performance characterizations.

Status

This project is complete. A Phase 2 Final Report was issued in June 2019.

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EnergyPlus Models for Advanced Gas Space-Heating Systems and Combination Systems

Efforts are under way to develop built-in models of advanced gas space-heating equipment and combination systems in an EnergyPlus simulation engine to expand choices to evaluate these advanced technologies by architects, builders, engineers, regulators, facility managers, and others.

Project Description

EnergyPlus™ is a whole-building energy-simulation program developed through the U.S. Department of Energy (DOE) that engineers, regulators, and researchers use to model both energy consumption for heating, cooling, ventilation, lighting, and plug-and-process loads as well as water use. However, the limited capability of EnergyPlus to simulate advanced residential gas-heating systems makes it difficult to correctly compare these systems with electric-driven HVAC competitors.

Data indicate that current models in EnergyPlus are inadequate for estimating the dynamic efficiency of condensing furnaces, gas absorption heat pumps (GAHP), and combination systems. Having no module in EnergyPlus to estimate the performance (or, even worse, to do it incorrectly) would significantly limit choices by regulators and general users to consider these advanced systems during the initial screening used to evaluate HVAC options. It is the objective of this project to address these gaps and limitations in EnergyPlus.

In Phase 1 of this project, researchers leveraged technology-performance data collected as part of other projects to develop functions in EnergyPlus, and then used them to estimate energy savings potentials. In Phase 2, the project team is focusing on a more expansive market analysis and further function refinements.

Benefits / Market Implications

Through this project, researchers will develop EnergyPlus built-in models for advanced furnaces, gas heat pumps, and combination systems to allow the general users to adjust the parameters such as system size, performance curves, or design features, which are necessary to describe any of such gas systems from any manufacturer.

It is anticipated that the simulation results using these models will be used to estimate annual energy savings for each type of system, which can be further adopted for the gas utilities to provide incentives in energy-efficiency programs.

Technical Concept & Approach

In Phase 2 of this project, researchers are updating and refining the prototype EnergyPlus models for advanced condensing furnaces, gas absorption heat pumps (GAHPs), and combination systems that were developed in Phase 1.

A technical and economic-potential analysis will be conducted for each system using the new tools from the National Renewable Energy Laboratory (NREL) for the entire U.S. single-family housing stock.

Specific Phase 2 tasks include:

- **Advanced Heating System Model Refinement**

  Phase 1 utilized furnace data from a laboratory evaluation of products from a single manufacturer. Parallel non-UTD projects are gathering additional performance data for furnaces, combination systems, and GAHPs. These new data will be incorporated into refined models of advanced gas-heating systems.

- **Technical and Economic Analysis Tools Development**

  Custom software will be developed to automatically implement energy-efficiency upgrades in the En-

Researchers are reviewing laboratory tests of various furnaces.
ergyPlus models. A post-processing program will be developed to synthesize simulation results into useful information.

- Technical and Economic Analysis of Advanced Gas Heating Systems

A national-level analysis will be conducted to estimate the total potential energy savings of each technology using the NREL ReStock simulation tool set.

Advanced gas-heating models refined in Phase 2 will be disseminated in a future EnergyPlus release, along with the other advanced residential heating system models developed.

Results

To achieve the project objectives, the current limitations of the furnace and GAHP models were reviewed and a new approach for modeling was developed, taking advantage of extensive part-load performance data collected on five condensing furnaces from a single manufacturer and prototype GAHP units.

In Phase 1, using simulations of modern homes in mild and cold climates, the new approach helped demonstrate how a modulating furnace can consistently save 10% on the natural gas consumption annually compared to single- and multi-stage furnaces, and an additional 2% if it is right-sized for the home.

A new custom model was developed for the GAHP, and implemented on a prototype basis in EnergyPlus as a combined space- and water-heating system. Performance data was used to accurately represent the performance of an 80MBH-output heating system.

In the retrofit analysis, using a standard efficiency gas furnace and water heater as the baseline, the GAHP combination system saved nearly twice as much source energy (gas and electric) and an additional $150-$250 in annual operating costs compared to a condensing furnaces and standard water-heater retrofit alternative.

In the new construction analysis, the GAHP combination system was compared to an electric heat pump with three different water-heater alternatives (gas, electric, and electric heat pump water heater) with a condensing furnace and a premium water heater as the baseline. It was demonstrated that the lower-capacity GAHP combination systems were competitive with electric heat pump and electric heat-pump/water-heater alternatives in the milder climates of Seattle and Portland, with respect to source energy savings and operating cost savings ($100-$200 per year). The GAHP combination system was the only option offering energy and operating cost savings in the colder climates of Spokane and Helena. With further reductions in the electricity consumption of the GAHP, even better all-around savings for the GAHP are possible.

The modeling approaches developed for the GAHP and combination system are more broadly applicable for any gas-driven heat pump as well as combination systems powered by boilers and tankless water heaters.

In 2019, the basic assumptions of a GAHP model were revised to better account for cold-weather performance (e.g., effects of defrost at low ambient temperatures).

The model for tankless-based combination units was partially validated. In parallel, a separate study involved collecting data on tankless-based combination units using advanced hydronic air handlers capable of >90% efficiency in space heating.

Additional updates to the GAHP model are being made using the most up-to-date data for the 80MBH prototype.

The most significant limitation of the new furnace modeling approach is the detailed performance data utilized is specific to only one manufacturer. Efforts are under way to more broadly characterize condensing furnaces, combination systems, and GAHPs using 24-hour load tests. During Phase 2, this new data will be integrated into more generic performance curves and modules that can then be published in a future EnergyPlus release.

Using the tools developed in this project, national-level analysis will estimate the total potential energy savings of each technology (i.e., technical potential). Using maximum payback period of five years or a positive net present value the total number of cost-effective installations will be identified (i.e., economic potential).

Status

The primary engineering documentation is being developed into an ASHRAE Technical Paper that is anticipated to be presented at a 2020 ASHRAE Conference.

The remainder of the project will focus on executing analyses for techno-economic potential of advanced space-heating technologies.

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Thermal-Efficiency and Performance-Gain Mechanisms for Gas Storage Water Heaters

The objective of this project was to review existing technologies and their potential for adoption into gas storage water heaters (SWHs) to increase efficiency and overall performance. The overlying goal was to determine the effectiveness in providing additional performance benefits to SWHs.

Project Description

Residential gas-fired storage water-heater (SWH) equipment is well established and the technologies associated with a SWH (e.g., burners, controls, dampers, etc.) are also widely adopted. There has been fairly limited advanced development of next-generation gas-fired SWH models or technologies.

The purpose of this project was to provide information on potential next-generational technologies to be introduced into a SWH in order to provide a preliminary avenue to evolve the standardized technologies used within the SWH market. Activities were limited to a preliminary technological assessment and laboratory validation, with potential next steps leading to commercialization. This project sought to identify commercialized or near-commercialized technologies that have the potential for integration into gas-fired SWHs that are currently deployed in unrelated applications and/or products. The overlying goal was to determine the effectiveness in providing additional performance benefits to SWHs and study the cost effectiveness of these technologies in the context of usage in a SWH.

Through the review of technologies, researchers identified potential increases in overall system efficiency gains as well as potential for significant manufacturing cost savings.

It is the overall goal of the project to provide feedback to manufacturers and inform project partners of the current initial evaluation of these technologies in order to drive potential adoption within industry – thereby furthering the efficiency, economy, reliability, and safety of gas-fired storage water heaters in the water-heating market.

Benefits / Market Implications

In this project, research and development was conducted to improve both condensing and non-condensing SWH units. Activities include analyzing options to reduce the raw material cost of SWH assembly, with the intent to reduce end-use cost to consumers.

An additional intended benefit of this project is to allow SWHs to become more viable when space is limited and a consumer must currently choose an electric unit if they prefer a storage-style water heater. Initial research shows natural-gas-style units to be about 10 inches taller than a similar electric unit, limiting installation opportunities.
Technical Concept & Approach

An assortment of technologies were evaluated using available information both from scientific journals and manufacturer-supplied documents to determine ideal candidates for further review and potential laboratory verification testing.

The scope was fairly limited in terms of technology readiness advancement, with only initial evaluations completed. The scope outlined allows for potential next-step evaluations with manufacturer engagement if there is a strong enough business case for a given technology.

Results

The initial goal was to identify the top four candidates for laboratory evaluation based on published information, including previous studies, cost, and vendor availability. The four to be investigated were:

- Enhanced efficiency thermoelectric generators
- In-situ flue burner
- Oxygen membrane enhanced burner, and
- Enhanced heat-transfer mechanism for increased thermal efficiency.

Two of the technologies – thermoelectric generators and oxygen membranes – showed potential improvements from both market literature and previous scientific studies. However, these technologies were ultimately ruled out after extensive research due non-feasible installation within a SWH, both from a cost and practicality standpoint.

The in-situ flue burner showed strong potential for at least maintaining current SWH efficiencies while providing a novel approach for burner installation, potentially reducing the vertical footprint of a SWH. The test results indicated similar efficiencies to existing standardized burners with limited work available within the project timeline for extensive efficiency improvement techniques.

The enhanced heat-transfer mechanisms identified showed minor improvements in terms of radiant loading from the burner to the SWH body, resulting in a reduced flue gas temperature. This trade-off resulted in negligible increases in overall system efficiency; however future work may lead to a conclusion that a reduced stack size is possible with this technology.

Additional technologies and methods reviewed showed potential increases in overall system efficiency gains as well as potential for significant manufacturing cost savings. In addition, the technologies reviewed were determined to not significantly modify the overall envelope of a SWH (e.g., large volume of water heated by a burner to a constant temperature), as to prevent significant rework on the manufacturing side as well as certifications.

Recent developments in the residential furnace market are providing technologies that use highly-localized radiant heat-transfer mechanisms, thereby reducing overall flue gas temperatures in lieu of significant increases in radiant loading. This provides for potential of a significant reduction in overall height of the unit due to unnecessary length of the stack to transfer the combustion heat via convection, instead replacing that mechanism with a higher degree of radiant loading. A highly-radiant burner was installed within the stack of a SWH, bypassing the traditional placement of burners within the combustion chamber. The goal of the testing was a preliminary check on the efficiency of the unit as compared to a storage water heater using both a pancake style burner as well as a next-generation ultra-low-NOx burner. The radiant burner initially developed for residential furnaces indicated exceptional reduction in NOx generation.

A test was performed using a stainless-steel 15-gallon pot, filled with 10 gallons of water drawn from a sink and brought to 212°F. The test was completed above a residential grade stove, similar in flame structure to an open-flame pancake burner. The pot was placed above the largest burner with a firing rate of 35,000 Btu/hr, achieving an efficiency gain of approximately 13%.

Selective membrane technologies were developed to effectively remove undesired components of combustion air, such as nitrogen and other inert constituents, in order to increase the effective oxygen concentration of the combustion air, thereby allowing for a hotter flame and potential for increased efficiencies. Testing was completed with a ceramic porous tube coated with the membrane inserted within a stainless-steel tube. Testing successfully demonstrated the potential for coating to increase the effective oxygen in a sample; however, effectiveness is heavily determined by the effective back pressure applied to the system.

Status

This project is complete. A Final Report was issued in 2018.

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SuperPerm Burner for Water Heaters

**Efforts in this project focus validating a novel efficient, compact, low-emission ceramic-coated foam-metal-matrix burner design for next-generation water heaters in both un-humidified and humidified combustion-air conditions.**

**Project Description**

Hot-water use in commercial service is application-specific. From continuous flow rates (both high and low volumes) to large-volume dumps over a short time period, manufacturers have many models designed to meet the specific needs of a customer’s application.

Adding complexity to the number of models are the different regional and local requirements, which adds cost not only to the low-NOₓ burner, but to business infrastructure expenses such as stock keeping, inventory tracking, and certification.

In response, researchers evaluated a permeable metal foam burner with superior performance that includes ultra-low emissions, increased heat transfer, increased flue-gas dew-point temperature, and condensing efficiency at lower cost than the current commercially available power burners. Called the SuperPerm™ burner, the patent-pending burner is the result of research conducted in collaboration with the Institute of Chemical Physics for the Russian Academy of Sciences in Moscow.

The objective of this current project is to develop the ceramic-coated foam-metal-matrix burner design at commercial scale for application in a commercial water heater (down-fired firetube heat exchanger) in both un-humidified and humidified combustion-air conditions.

In Phase 1 of this project, researchers completed a numerical analysis of a volumetric permeable matrix burner design. Testing with flat-plate metal foams of varying porosity, density, and metals was conducted to develop baseline characteristic data on metal foams for both volumetric and flat-plate burner designs. For benchtop testing, the project team designed and fabricated a single-burner design.

In the current Phase 2, the project team is testing and characterizing at least three higher-density (15% to 20%) metal foams, coated and uncoated, for use in flat-plate and volumetric burner designs; fabricating and installing the burner in a commercial water-heater simulator; analyzing results; and refining the burner design for water-heater integration.

**The key features to achieve for the burner are:**

- Surface stabilized combustion on a high-conductivity metallic permeable matrix coated with a low-conductivity ceramic material that increases the temperature of the matrix surface and therefore radiant flux at the surface of the material (i.e., increased thermal radiation efficiency by more than 20%)
- Operation at low flame temperature and low excess air (10%-15%), with reduced NOₓ emissions to 3-5 vppm while maintaining low (10-20 vppm) CO and unburned hydrocarbon emissions, and
- Higher thermal efficiency attributed to decreased excess air.

**Benefits / Market Implications**

The goal of this project is to provide lower-cost, high-efficiency condensing technology for water heating by developing an advanced burner with:

- 20-30 % increased radiant heat transfer
- Increased thermal efficiency (excess air ratio α=1.1)
- Potential for ultra-low NOₓ (<3vppm), and
- Potential for ultra-low CO (<5vppm).
Validated methods to reduce and eliminate the risk of auto ignition and flashback in SuperPerm burners operating at high air-preheat temperatures, up to 1,562°F.

In Phase 2, the project team:
- Completed characterization of the SuperPerm technology by validating:
  - An operational range from 17 to 65 W/cm².
  - Ultra-low-NOₓ emissions (≤10ppm@ 3%O₂) range: 17 to 45 W/cm² (potentially lower NOₓ and a wider range for improved metal performance, namely, uniform metal foam porosity and density).
  - Superior performance of coated metal foam over uncoated metal foam validated.

Other Findings:
- 60 ppi metal foam product was well-developed (e.g., met product specifications).
- <60 ppi and >60ppi metal foam product were not well-developed; samples purchased were not uniform in air-fuel mixture flow as well as surface combustion, and were missing quality control for the porous material uniformity. More research and development is necessary by the product manufacturer to ensure consistent product specifications.

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Elevated-Gas-Pressure Water-Heater
Market and Technical Evaluation

Research is being conducted to evaluate the market and technical opportunities and barriers to operate appliances at elevated-gas-pressure, in order to reduce appliance cost, increase efficiency, and enhance self-powered resiliency.

Project Description

Using elevated-gas-pressure infrastructure in residential and commercial buildings could help reduce the incremental cost and complexity for builders to construct mixed-fuel Zero Net Energy homes and meet both customer preferences and regulatory compliance.

In addition to the infrastructure savings, there may be cost, emissions, and efficiency benefits to operating appliances at elevated pressure. In this project, research is being conducted to 1) define the current market opportunities and barriers to operating elevated-gas-pressure appliances in residential and commercial buildings and 2) prove the technical feasibility and benefits by operating both non-condensing and condensing gas storage and tankless water heaters at elevated gas pressures.

In recent years, a number of technical changes have occurred that may affect the benefits of operating at elevated gas pressure. These changes include:

- The minimum water-heater efficiency requirements increasing from an Energy Factor of 0.54 (2003) to a unified Energy Factor of 0.62 (2015)
- The California NOx emission requirement changing from 20 ng/J (2004) to 10ng/J NOx (2005)
- New burner technology emerging on the market with metal porous matrix styles, and
- Electronic circuitry, including power-harvesting technology, that has come down in price and electronic components that consume less power.

The ability of the appliance to be self-powered, free from a powered connection, is a desirable feature that will be examined in this project. An “unplugged” appliance can offer lower installation costs, operate continuously in a power outage, and minimize the contribution of overall energy use in the home.

Benefits / Market Implications

Elevated gas pressure has the potential to lower costs and simplify gas-system installations inside buildings by allowing for the use of smaller-diameter rigid and flexible gas piping with manifold or parallel branch pipe layouts. Flexible gas piping reduces the number of
fittings by changing direction easily within walls and floors or around appliances, and the smaller diameter allows more length for each roll of pipe. Additionally, the elevated-pressure layout can more readily integrate future expansion for pool heaters and other emerging technologies.

Technical Concept & Approach
Specific tasks for this project include:

- A review of the market, manufacturers, codes, opportunities, and barriers for a 2psi infrastructure with elevated gas appliances
- A residential water heater baseline evaluation
- Elevated-gas-pressure combustion systems development, and
- A modified residential water-heater testing and analysis.

Results
In Phase 1, research validated that existing atmospheric burners (the lowest-cost burner approach) can be adapted or modified to run on elevated gas pressures. The 3G burner (used in atmospheric water heaters to meet California emission requirements) performed well as 2psig with little modification.

The pancake-type burner could be made to operate at 2psig, but would need modification/redesign to meet California emission requirements. In unmodified testing, a pancake-type burner demonstrated stability when operating gas pressures 4 to 8 in. w.c. Above 8 in. w.c., the air/fuel ratio imbalance resulted in increased emissions and excess port loading (flame lift off), creating unsafe conditions. In modified testing, where the orifice was changed and air intake was restricted, the range of stability increased from 4 to 50 in. w.c. with a 3% efficiency increase compared to the baseline and a decrease in NOx emissions from 75.6 ppm to 49.1 ppm NOx@3%O2, and an increase in CO emissions 5.1 to 9.1 CO@3%O2.

In unmodified testing, the ultra-low-NOx, 3G semi-radiant burner demonstrated stability at operating gas pressures 4 to 5.4 in. w.c. Above 5.4 in. w.c., the air/fuel ratio imbalance resulted in flame instability and lift, creating unsafe conditions. In modified testing, where the orifice was changed and air intake was limited, the range of stability increased from 4 to 45 in. w.c. with a 9% efficiency increase compared to the baseline and a decrease in emissions from 10.4 to 8.0 ppm NOx@3%O2, and 20.1 to 9.8 ppm CO@3%O2. In a final test, the burner was fired at elevated gas pressure in a sealed combustion chamber and was able to operate with the necessary air for complete and efficient combustion, similar to the way in which a blower-less water heater would operate. Based on results of burner testing, researchers initiated a more critical modeling analysis to determine to what extent 2psig gas supply pressure could displace or eliminate a blower in a combustion system of a high-efficiency water heater.

Computational Fluid Dynamics modeling and numerical analysis on the use of an ejector for mixing at 2 psig determined there was not enough buoyancy and momentum to exhaust flue gas. Researchers developed a turbo-compressor design which may not only eliminate the blower but also could displace the appliance gas valve/regulator. Initial numerical analysis tend to confirm that this design would be able to provide the momentum and buoyancy for safe flue gas venting, although a much more rigorous analysis is required.

In Phase 2, research is focused on eliminating the blower on a condensing water heater, which is necessary to achieve the 30% component cost reduction for condensing appliances. Researchers analyzed the use of an ejector for mixing and found that at 2 psig there was not enough buoyancy and momentum to exhaust flue gas. The project team is seeking to conduct a laboratory experiment to validate the turbocharger concept, where elevated gas pressure is used to entrain air for efficient combustion. The turbocharger would displace the electric blower (19% of water heater cost) and could potentially displace or modify the gas control valve (17% of water heater cost). Testing of metal foam burners in an experimental burner validates the burner type as an ultra-low-NOx burner option operating at 2 psig.

A turbo-compressor concept is being investigated to eliminate both the blower and the appliance gas valve/regulator. Initial numerical analysis tended to confirm that this design would be able to provide the momentum and buoyancy for safe flue gas venting, although a much more rigorous analysis is required.

Status
A micro-turbo compressor for benchtop demonstration of elevated gas to entrain and achieve 10:1 air-gas mixing is currently being fabricated.

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The objective of this project was to validate that a Thermoelectric Generator Heat Exchanger (TEG-HX) device can generate enough electric energy to power a tankless natural gas water heater. The overall goal is to develop a self-powered, gas-fired tankless water heater to save ratepayers money and energy while enhancing resiliency.

**Project Description**

Many consumers are embracing tankless gas-fired water heaters for their high efficiency and compact size, including significant adoption in Europe. According to Persistence Marketing Research, tankless water heaters sales will grow at an annual rate of 5.3% from 2016 to 2024.

Currently, all gas tankless water heaters require a connection to the electrical supply to maintain operation. Unlike gas storage water heaters, tankless heaters do not hold reserve hot water that can be used during a power outage. However, advances in thermoelectric generators (TEG), low-power components, energy harvesting, and energy storage may make it possible to develop an unpowered gas-fired tankless water heater for the residential market.

In previous efforts, researchers evaluated the potential for thermoelectric concepts for water-heater integration. All of the concepts used a water-cooled TEG device for gas-to-liquid thermoelectric power generation. While difficult to implement in a gas storage water-heater design, the water-cooled TEG concept may be ideal to implement in a tankless water heater where electronics, heat exchangers, and water flow are in close proximity to each other. Components such as the spark ignitor, a gas valve, a flue damper, and energy harvest and storage circuitry may have additional application in the development of a self-powered tankless water heater.

The objective of this project was to validate that a Thermoelectric Generator Heat Exchanger (TEG-HX) device can generate enough electric energy to power a tankless natural gas water heater.

**Benefits / Market Implications**

A self-powered tankless water heater would preserve one of the key value propositions that traditional gas storage water heaters offer to its customers – hot water availability during a power outage – and may reduce installation costs if backup electric power (e.g., batteries) is otherwise required by the user.

TEG-HX laboratory testing above radiant burner matrix.
power for start-up operations. This project focuses on the design and development of the TEG-HX power generating component.

The TEG device generates electricity by converting heat (temperature differences) directly into electrical energy. Water-to-water, gas-to-water, and thermal fluid-to-water are three methods of heat transfer that this project investigated to generate electric power from the heat of combustion for a self-powered tankless water heater. Daily hot-water demand creates flows in both hot and cold water. Hot water, gas, or thermal fluid flow through the hot side of the TEG-HX and cold water flows through the cold side of the flow through the TEG-HX.

The TEG efficiency at the temperature difference range is about 1-3%, or heat flow through a TEG to achieve 1W of power is 30-100 W. This is rather small compared to the enthalpy flow of hot water (10-25 kW), thus showing potential for this concept.

The project began at a Stage 2 (Technical Feasibility Analysis) that characterized through technical evaluation both the power requirements and operational constraints of a tankless water heater and ended at a Stage 3 (Research implementation) to validate the TEG-HX design through the analytical model and benchtop TEG-HX concept testing.

Results

During the project, a technical analysis of three selected TEG-HX designs to generate electric power from the heat of combustion was conducted; electrical energy storage mechanisms available for tankless water heaters were analyzed; a study of tankless water-heater component power consumption completed, and energy-consumption profiles initiated.

The project team identified that the most effective and reliable heat-exchanger design for thermoelectric generator is gas-to-water TEG-HX. Based on Phase 1 project results, researchers identified the preferred electrical energy-storage mechanism and proposed modifications that reduce the power requirements of a tankless water heater, specifically, a new radiant burner was proposed to be used with the TEG-HX for tankless water heating, which allows effective harvesting power from natural gas combustion for self-powered operation of the water heater while achieving ultra-low NOx emissions (<5ppm).

The project team developed, designed, fabricated, and tested the TEG-HX device in a laboratory environment and at simulated tankless water-heater conditions. This was done in close cooperation with a leading manufacturer of TEG devices.

The new burner is an effective replacement of the existing blue flame burners used in tankless water heaters, providing higher combustion efficiency, lower pollutant emissions (NOx and CO) and efficient operation in the gas-to-water TEG-HX design.

Two electrical energy storage mechanisms (battery and capacitor storage) were evaluated to operate the water heater at stand-by conditions, start-up, and purge (excluding freeze protection) when the gas burner is off and TEG is not generating power. The capacitor was chosen as a preferred energy storage mechanism based on cost, dimensions, and research experience in the energy-storage mechanisms for water-heater operation.

With the new burner, the opportunity for a 20%-50% electric power reduction in tankless water was identified.

Based on the project research results, it was concluded that the TEG module and developed TEG-HX design together with the new burner can provide enough electricity from the TEG module to cost-effectively power a tankless water heater.

Status

Phase 2 of this project was completed in June 2019 with the release of a Phase 2 Final Report, which included recommendations for specific future research.

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Gas Heat Pump Combination Space/Water-Heating System Design

Through this project, a research team is developing best practices for end users to utilize gas heat pumps that are currently or nearly commercialized (including absorption, adsorption, vapor compression, and other technologies) in order to maximize economy and efficiency for end users.

Project Description

UTD has a long history of supporting the analysis, evaluation, and development of combined space- and water-heating systems (“combi” systems) for residential applications. This project extends these analyses to an emerging class of residential-sized gas heat pump products.

Conventional combi systems are driven by a gas-fired water heater, most commonly a tankless water heater (potable) or a combi boiler (non-potable), with the latter the standard for heating in Europe where forced-air distribution is less common. Combi systems have been demonstrated to be flexible and can accommodate multiple installation types, including forced-air heating, in-floor/radiant or other hydronic heating, and domestic hot water (DHW) with or without storage.

With shifts under way to require condensing efficiency in space heating, research is being conducted to develop and demonstrate cost-effective gas heat pump (GHP) technologies as the next step in efficiency. These GHPs are best deployed as combi systems in single/multifamily applications as these technologies 1) generally have a higher first cost and, as a result, have more favorable economics with year-round operation and 2) commonly are deployed as air-to-water heat pumps or “split” systems with heat recovery, which in both cases are suitable for combined space/water-heating operation. As such, early field demonstrations of the gas engine heat pump (GEHP) and the gas absorption heat pump (GAHP) have used this combi-system approach.

In this project, researchers will perform target experimental testing and simulation development, and outline best practices for GHP-based combi system design.

Some important considerations for GHP-based versus conventional gas water-heater/boiler-based combi systems are:

- **“Higher mass” system**: In a way, GHPs have more in common with high-mass boilers than tankless water heaters and low-mass boilers commonly used in conventional combi systems. Particularly for thermally-driven GHP systems, bringing up the GHP to temperature and starting the “heat pumping” process can take several minutes and the system controls must account for this.

- **Low turndown ratio**: Similarly, GHPs are limited to dual-stage or even 4:1 turndown, unlike the 20:1 turndown common for tankless water heater-based conventional combi systems. As a result, and to meet the refrigerant-to-DHW heating ANSI requirement of a “double wall,” an indirect storage tank is required for the majority of GHP-based combi systems. The management of this thermal storage and the dynamics of shifting from space heating to DHW recovery require a different strategy than conventional combi systems.

- **Influence of operating conditions**: As a heat pump is installed outdoors (most commonly), the operating efficiency and capacity are influenced by ambient...
Using split media: In some cases, the GHPs are more akin to an electric heat pump, as a direct-expansion system. Space heating and DHW are provided by separate media (refrigerant/water-glycol, respectively) and considerations for combi system best practices are affected accordingly.

Engineered systems: With these operating characteristics taken into account, it is possible a unique engineered system (tank, coil, GHP) is required as is used with “all-in-one” multi-function electric heat pumps.

Benefits / Market Implications

The development of GHP-based combi systems supports the broad commercialization of these technologies for single/multifamily buildings. GHP technologies can offer 30% or greater savings to ratepayers over condensing gas heating products and, with year-round operation as a combi system, the financial payback can be as low as three years. Other benefits include a simplified installation, ratepayer energy savings, and carbon savings associated with the direct use of natural gas year-round.

Technical Concept & Approach

Best Practices for GHP-Based Combi System Design

This effort involves a review of literature on combi systems and GHP equipment, and development of a database of laboratory and field combi system performance data to establish baseline for: typical and extreme space/DHW heating loads, the dynamics of conventional combi systems, and opportunities to refine system component design (coil, storage tank, etc.).

Design and Testing of “Smart” GHP-ready Combi Controller

To enable a lower cost, non-engineered system approach to GHP-based combi systems, researchers will develop and prove the concept of a “smart” GHP-ready combi controller. The controller will use onboard sensors to infer properties of the major components (GHP, tank, coil) and optimize performance while allowing for setback controls, safety monitoring, and user-defined operating modes (high efficiency, high output, etc.). The combi controller will be tested with a simple simulation tool.

With a control strategy developed, a laboratory prototype will be built and evaluated in an experimental simulator. The team will recommend a control strategy and learning strategy for this controller.

Results

Testing involves a tankless water heater and a standard air handler. Researchers investigated the potential “hacking” of this testing unit to 1) read and respond to the internal flow sensors, 2) read/write to the thermostat setting, and 3) read and respond to internal temperature measurements. Results indicate that read/write of the temperature setting is feasible; however best achieved with external actuation of the inputs. On reading internal flow sensors, the team found that sensors use an integrated “water flow servo assembly” device, which is outfitted with a hall-effect-type flow sensor and other sensors on the cold-water inlet. The flow sensor typically produces a square-wave output, which could be calibrated with a known volume of water. This would eliminate the need for a flow sensor within the device, which would use the tankless water-heater hardware flow sensor output for control algorithms in DHW, space heating, and simultaneous hot-water/space-heating loads.

In 2018-19, the project team completed the design and assembly of the hydronic heating hub. This involved the completion of custom parts and assembly and installation in the laboratory for integration with a tankless water heater and hydronic air handler. Researchers finalized and executed an experimental test plan and learning framework for the controller.

To represent the heating hub itself, the project team assembled a flexible breadboard on a 19-inch portable rack system with final parts to be assembled through automated machining. This first alpha prototype of this controller will be assembled in this manner to allow for flexible adjustments to system hardware, in addition to software.

Status

Ongoing activities include:

- Finalize analysis and testing of the laboratory test rig to validate the controller’s learning framework, and
- Continue a patent application and initiate outreach to commercial partners.

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Emerging Combination Air-Handling Units

The objective of this project was to test emerging forced-air combination system technologies against replicable 24-hour space- and water-heating loads typical of low-load residential applications to provide more meaningful energy-performance data to end users, engineers, energy-efficiency program designers, and others.

Project Description

Forced-air heating systems account for more than 75% of the North American market—and as performance for new homes continues to improve, alternative low-capacity electric technologies are affecting the competitiveness of gas-fired forced-air technologies.

Forced-air combination systems (“combis”) are competitive gas-fired alternatives in low-load homes. They can serve the home with a single condensing appliance that can improve the net cost of an energy-conservation program. Laboratory and field research proved that forced-air combis utilizing condensing water heaters together with off-the-shelf hydronic air-handler units (AHUs) tend to operate at sub-condensing efficiencies that generate insufficient energy savings. Until recently, the combi system market consisted of mix-and-match field-engineered systems with a myriad of water heaters and off-the-shelf hydronic AHUs provided by separate manufacturers.

Various industry research efforts focused attention in the industry on the challenges in achieving adequate combi performance for the high-performance home market. As a result, some water-heater manufacturers have aligned their condensing water-heater products with emerging hydronic AHU products under development by companies positioning for a new generation of high-performance combi systems in the market.

The research team investigated two specific emerging combi systems: the NTI GF 200 Combi Furnace (left) and the iFLOW system (right).

The objective of this project was to evaluate emerging forced-air combi system technologies in a laboratory virtual test home (VTH) to validate claims that the combi systems have overcome technical barriers preventing traditional combis from consistently reaching condensing efficiencies.

Results are used to compare the emerging combi systems to low-capacity condensing furnaces and tank water heaters also evaluated in the VTH.

Performance characterizations can be used to calibrate building energy modeling software to quantify potential energy savings.

Benefits / Market Implications

Forced-air combis are particularly attractive for energy efficiency programs because they can improve the economics of upgrading to a high-efficiency water heater for domestic hot water (DHW) use, as the combined DHW and space-heating loads are accomplished with one program measure.

Other ancillary benefits of combis include space savings, single-combustion air, and vent piping with one heating appliance.
Technical Concept & Approach

The research team used a methodology for testing heating systems against characteristically repeatable real-world space-heating loads under controlled conditions in the laboratory. The test methods were developed in order to compare performances of heating systems (including furnaces, water heaters, and combis) particularly in part-load simulated-use scenarios as opposed to standard test methods where steady-state and cyclic operations are tested at specified rating points.

The laboratory research was complemented by building energy-modeling techniques to provide an opportunity to properly quantify potential energy savings from different types of natural-gas-fired systems in various building types and climate conditions.

Results

The project team focused on two specific emerging combi systems, including the NTI GF 200 Combi Furnace, which is the only completely integrated combi system with the tankless water-heater engine built into the furnace. The second combi system was the iFLOW/Navien system, which researchers believe is the only combi system that dynamically monitors air and water temperatures and modulates water flow to maximize efficiency and comfort. Both of these systems claim high efficiency ratings as tested in accordance with the “P9” Canadian combi rating method (no comparable rating standard exists in the U.S.).

Researchers evaluated these units against the P9 standard as well as the VTH methods that were used for other combi testing and furnace testing.

The iFLOW/Navien technology produced the best part-load space-heating and water-heating performance of any system evaluated in the VTH; but its performance was underpinned by novel control logic that was implemented in order for the system to maintain very high efficiencies at very low part-loads while delivering adequate space-heating comfort. Fortunately, the iFLOW/Navien system has all the elements required to accomplish these principle goals.

The NTI combi furnace part-load space-heating and water-heating performance in the VTH performed nearly as well as the iFLOW/Navien system, and superior to traditional readily available gas space-heating and water-heating equipment. However, offered at only one capacity – 80 MBH – the system is less likely than the iFLOW/Navien system to perform well at very low part-loads. As such, it is a good fit for homes with higher space-heating loads than the iFLOW/Navien system might serve. Its cost about $5,800 and weighs at 250 pounds.

Results from this research indicate these advanced combi systems performed much better than traditional combi systems. Moreover, the advanced combis performed significantly better than condensing furnaces, especially in part-load conditions where these low-load appliances operate the majority of time. However, these advanced combis still have some challenges, including first cost. The NTI combi weighs about 250 pounds, and is available in only one capacity – 80 MBH. The iFLOW/Navien system is still under development as the manufacturers develop the control algorithms necessary to achieve consistent performance at low part-loads.

Researchers developed performance curves for the advanced combis, as was previously done with condensing furnaces and traditional combis. Those performance characterizations were built into building energy-modeling software to predict potential annual energy savings in various climates for the various space heating systems.

Status

This project was completed with a Final Report issued in December 2018.

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Combination Heating/Cooling Vuilleumier Cycle Heat Pump

This project is supporting the development of an innovative gas-fired Vuilleumier heat pump to substantially increase efficiency over current gas heat pumps that operate using vapor-absorption and vapor-compression (engine-driven) cycles.

**Project Description**

Regulatory and societal pressures are making key impacts on space heating, a core market for natural gas end users. In regional markets, the drive towards building electrification and net zero energy (NZE) building is shaping building code developments, state requirements, and the broader industry. With pending furnace regulations instituting a 92% AFUE minimum for large furnaces in the U.S. (and similar requirements already in place in Canada and Europe), the industry is responding by developing and promoting gas-fired heat-pump technologies. These technologies, including the gas-fired Vuilleumier heat pump (GVHP), can have an edge over electric heat-pump products that are faced with aggressive refrigerant phase-outs.

The underlying principle is a heat pump based on the Vuilleumier cycle, a closed-loop system similar in nature to the Stirling cycle, utilizing a working fluid (helium) driven across a number of heat exchangers which interact with the environment. The working fluid flow is driven through two linked displacers located in opposing cylindrical ends known as the “hot end” where heat input to the cycle occurs, and the “cold end” where heat removal from the environment occurs. Competitive to an absorption cycle heat pump, the Vuilleumier cycle heat pump shows potential for a greater coefficient of performance (COP).

The objective for this project was to support the development of the GVHP, which, if commercialized, would represent a step-change in efficiency over the current gas heat pumps that operate with vapor-absorption and vapor-compression (engine-driven) cycles, with a cooling COP of greater than 1.0 and a heating COP of greater than 2.0.

**Benefits / Market Implications**

As a gas-fired technology providing year-round heating and cooling, with projected COPs of 2.0 or greater (heating) and 1.0 or greater (cooling), it is estimated that the lifetime fuel savings of a GVHP over a condensing furnace is $9,760, with the potential for cooling-season cost savings as well. Using a benign working fluid (helium) with cost-effective design to accommodate higher working pressures (~1,450 psia), the GVHP may offer a premium gas heat-pump product with compelling emission and cost savings for future gas ratepayers.
Results

Phase 1 included:

- Initial consulting and analytical assessment of the first generation hot-end assembly, including recommendations to revise the recuperator design, fuel/air mixing method, and hemispherical dome burner/heat exchanger to maximize radiant heat transfer

- Open-air tests and Computational Fluid Dynamics (CFD) simulation-based evaluation of hemispherical combustion system, hemispherical burner, and further recommendations on recuperator design and ignition controls

- Building and testing a simulated hot end for evaluation of the first-generation hot-end system, effectively measuring and controlling thermal loads for up to 15 kW output as required

- An analytical assessment of an auto-ignition issue, including a literature review

- Design and fabrication of a custom fuel/air mixer to support the mixing design with fuel introduction downstream of recuperation

- Prepared fabricated recuperator, and

- Performed a simulation-based review of options for inward-firing burner designs, which are better suited for the first generation hemispherical dome.

Phase 2 included:

- Technical support to a re-design effort, including limited CFD modeling and validation

- Performed an experimental and modeling study into whether air and fuel could be preheated in excess of 600°C safely and identify conditions at which auto-ignition would occur

- Evaluated commercial off-the-shelf burner samples from five manufacturers for potential use with the GVHP, and

- The development of a new test apparatus to evaluate the efficacy of each hot-end sub-component and as a full system.

With open-air testing of the hot-end heat exchanger complete, the project team made modifications to the recuperator to assure that 1) the recuperator sealed effectively against the combustion chamber to avoid cross-leakage, and 2) that it accommodated the modified operation with controlled air cooling of the “air-side” of the recuperator to characterize its heat transfer separate from the balance of the hot-end assembly. This fabrication was complete, to assure proper sealing, cooling air flow control, and instrumentation access.

Status

A Phase 1 Final Report was issued in November 2018. Phase 2 is under way.

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Researchers are conducting an analytical and laboratory investigation on pollutants contributed by gas and electric residential cooking. The objectives are to determine the impact on indoor air quality and the implications for range hood design.

**Project Description**
Commercial foodservice facilities are required to operate most equipment under a ventilation hood that captures food and grease emissions and exhausts heat from the kitchen. However, residential cooking does not have the same requirements.

Despite the fact that most home kitchens have a ventilation system above the stove, most homeowners do not use the system unless excess smoke is being produced. Also, many existing residential ventilation systems are not maintained and/or are ineffective at capturing food and combustion emissions. Another issue is that the emissions for gas-fired ovens and foods being cooked are not fully understood and quantified for NOx, acroleine, and small particles. These factors have led to growing concerns about the effect that cooking has on residential indoor air quality.

Current studies being conducted by others have questioned if gas cooking is a safe and viable option for use in tighter, more efficient homes. Some of these conclusions on the surface appear to lack a scientific basis and overestimate the emissions from combustion compared with heat and water generated during residential cooking.

In this project, researchers are conducting an analytical and laboratory investigation on the pollutants (NOx, acroleine, 2.5 micron particles) contributed by gas and electric residential cooking, the impact on indoor air quality, and the implications for range hood design.

**Benefits / Market Implications**
With increased concerns about tight homes (or, Net Zero Energy homes), the viability of keeping gas-fired ovens in residential locations may become increasingly difficult and consumers’ energy choices restricted. Data is needed to fully understand the impact that residential cooking has on indoor air quality and what changes may be needed to existing residential oven designs to meet consumer’s needs. Results will be published in a paper that scientifically addresses potential concerns, issues, and best practices with residential gas cooking.

**Technical Concept & Approach**
In this project, a research team is evaluating and quantifying residential cooking emissions and further evaluating existing residential ventilation systems and ovens for their effectiveness at capturing exhaust heat, airborne particles, and other emissions in residential applications.

Researchers are using an existing residential cooking setup to complete an analytical and laboratory investigation on the pollutants contributed by gas and electric cooking for a standard residential range that included range-top and oven cooking.

Established testing protocols and procedures for emissions capture will be used to quantify the emissions. A comparison will be completed for gas vs. electric ovens and an evaluation completed to establish emission-capture impact on indoor air quality and implications for range hood design.

**Results**
In 2017, an initial evaluation of heat capture using a shadowgraph test setup was completed for all the burners on the range top.

A Residential Kitchen Ventilation Test Setup was specially designed for quantifying the capture effectiveness of the hoods. The setup was built using standard resi-
dential construction practices and accurately represents a typical residential cooking area.

The team also installed a data-acquisition system for measuring temperature, emissions, and energy usage. The system was calibrated and new background added to the laboratory to improve the effectiveness of the system.

The range-hood performance was evaluated using a flow-visualization apparatus. The shadowgraph image was used to determine the amount of capture or spillage of the thermal plumes as a fractional assessment of the projected image. Trace amounts of smoke were also used as a seeding mechanism. The hood evaluation was done at the high-speed air-flow rate on burners separately and in combination.

In general, the hood captured and contained the thermal plumes from the rear burners and failed to capture the thermal plume from the front burners. At maximum firing rate, the hood captured the thermal plume from the rear burners when they operated separately (i.e., 5,000 Btu/hr or 12,000 Btu/hr) or in combination (17,000 Btu/hr). If the firing rate of the front burners was turned down to a dial setting of 2 or 3, then the hood would capture and contain the thermal plume from the front burners. Sensitivity testing showed a cooking pot positioned on the front burner did not require a reduction in the firing rate to maintain a capture and containment.

When the thermal plume from the front burners spilled, a visual assessment of the shadowgraph image determined that the plume volume spilled 20%-40% along the front edge of the hood and 10%-20% along the sides of the hood. The poor hood performance of the front burners was due to the amount of set-back of the hood over the range.

The team tested several methods for measuring the capture effectiveness of the emission from the burners, including using CO₂ as a tracer gas.

In 2018, testing of the ventilation hood was completed and the capture rate determined. The hood was modified and retested to improve capture effectiveness by adding side shields and an extension to the front of the hood. Initial analysis suggests that the changes had some improvement in terms of capture effectiveness, but not as much as expected.

**Status**

Some public information released by others implies or directly states that using natural gas as an energy source for cooking creates harmful or dangerous emissions in a residential environment, and suggest that electric is much safer than gas and much more efficient. While some of the claims hold some scientific value and are backed up with credible results, other aspects are misleading, incorrect, or imply an advantage of electric over gas that does not exist. In association with gas industry and commercial foodservice (CFS) partners, the project team is currently compiling and sorting information sources, including existing responses from the industry as part of this project. A special report detailing these issues was sent to the project sponsors. Additional testing is under way in 2019.

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Integrating Thermal Energy Storage in Advanced Gas/Renewable Homes

The objective of this project is to expand the thermal energy storage capabilities in a virtual test home in a laboratory to more rapidly develop, test, and optimize thermal energy storage options that increase energy efficiency and reliability, reduce energy costs, and better integrate natural gas with renewable energy in homes in all climates.

Project Description

The residential rooftop solar market continues to outpace expectations and transform how homes are powered.

The National Renewable Energy Laboratory (NREL) documented the impressive decline in both photovoltaic (PV) module and installation costs, which indicate less than $3/W installed. As a result, residential PV capacity and output has increased considerably in the U.S., increasing capacity by nearly four times since 2014 to 2017. These trends continue despite uncertainty regarding incentives, net-metering policy, and other market interventions that were instrumental in PV’s initial success decades ago.

The U.S. electric utility industry is going through an historic change due to the growth of PV. This represents an opportunity to showcase the strengths of gas-fired equipment with proven track records on providing highly-reliable, cost-effective service and low emissions. In response, the project team is coordinating an experimental program to develop system-level solutions by integrating thermal energy storage, ultra-high-efficiency heating technologies, and micro combined heat and power (CHP) equipment.

This effort involves the development and demonstration of equipment designs, controls, and system integration architectures. The ultimate goal is to evaluate solutions in an experimental virtual test home with gas-fired heating equipment (e.g. gas heat pumps), micro-CHP equipment, and a PV array with simulated climate conditions and building loads.

In this effort, the primary research questions are:

- What is the minimum level of thermal energy storage required for a given set of HVAC and micro-CHP equipment?
- Is standalone domestic hot water (DHW) equipment required?
- Are there opportunities for latent energy storage in addition to sensible energy storage?
- Can chilled water energy storage enable gas-fired chillers for air conditioning at residential scale?
- Over what timescales is thermal energy stored and deployed?
The project team will design, commission, and test the thermal energy storage network to simulated loads and advanced heating equipment using simulated 24-hour heating loads based on building energy modeling and prior field data collection. In parallel, researchers will build and calibrate analytical capabilities to extrapolate results from the experimental program.

**Benefits / Market Implications**

This project represents a system-level technology development program to demonstrate methods and technologies to effectively integrate gas-fired equipment with on-site renewable generation. If successful, the project team will outline products, system integration strategies, and building practices that will facilitate the expanded integration of gas and renewable energies in homes.

**Technical Concept & Approach**

In this project, researchers will build and test experimental controls and test its capabilities with an integrated tankless water heater, boiler, and gas heat pump water heater (HPWH). In parallel, the project team will build a calibrated simulation tool for modeling different combinations of thermal storage with other heating equipment in a gas/renewable home.

Specific tasks include:

- **Design and Construct Thermal Storage Experimental Test Stand**
  
  Researchers will frame the range of thermal loads expected for the simulated gas/renewable homes, including DHW and HVAC loads, and develop the range of homes simulated by the test stand. A range of specifications for thermal energy storage equipment will be developed.

- **Commission the Test Stand and Evaluate DHW Technologies**
  
  Research will begin with the tankless water heater-based DHW system and move into a water boiler and gas HPWH-based DHW system. The project team will analyze test data and refine control strategies iteratively, coupled with micro-CHP and HVAC considerations. Findings will be summarized in a test report, disseminated to high-level key stakeholders (high-performance homebuilders, heating-equipment manufacturers, etc.)

- **Develop and Calibrate Simulation Tool**
  
  Using building energy simulation software, the project team will create several model gas/renewable homes and generate baseline performance for multiple equipment configurations. Upon completion of testing, researchers will calibrate experimental findings with baseline equipment (e.g., tankless water heater). As needed, custom sub-models will be generated to capture transient effects of PV generation, thermal energy storage, and thermal loading dynamics. Researchers will use the calibrated model to evaluate alternative sizing and controls scenarios for further optimization.

**Results**

Researchers accelerated the completion of the project that previously occupied the site of the future test station. Decommissioning and modifications are being made to the test station.

The project team is developing a test plan and initiating implementation of the test rig modifications, including procurement of additional controls and instrumentation.

**Status**

The project team is determining range of thermal loads expected for the simulated homes, including DHW and HVAC loads, and developing the range of homes simulated by the test stand.

Parts are being procured for building the base thermal storage portion of the experimental test stand.

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Field Evaluation of Central Condensing Tankless Water Heaters for Energy Savings

A field evaluation will be conducted of a central condensing tankless water-heating system (CCTWH) for high-efficiency generation of hot water at two multifamily buildings in Minnesota. The project team will quantify energy savings and develop tools, guidance, and measures to support this emerging technology for more ratepayers.

Project Description

Central condensing tankless water heaters (CCTWHs) were recently commercialized by several manufacturers as novel standalone packaged systems or as extensions of more prevalent residential tankless water heating systems (“racking” systems).

A field evaluation of CCTWHs will be conducted in this project to develop important datasets concerning energy savings, system performance, installation barriers, and end-user/contractor feedback. If successfully demonstrated, the team will develop assessment tools, industry guidance, and custom measures/incentives to support this emerging technology.

As a replacement to conventional central hot water systems, CCTWHs primarily yield therm savings by two methods: 1) minimizing standby heat losses and 2) maximizing the “condensing” efficiency of the thermal engine. For multifamily buildings, schools/universities, and hospitality, occupancy is highly variable with peaks in daily and monthly loading patterns. As a result, standby heat losses from the hot-water storage tanks and circulation loops can make up a large fraction of total energy consumption. CCTWHs largely eliminate standby losses by removing storage.

A well-known issue with recirculating boilers and, to a lesser extent, commercial water heaters is that the equipment rated for “condensing” efficiency (90% or greater) do not always operate in a condensing, high-efficiency mode. For the central water heating systems with storage, unless the system is meeting a significant demand wherein the storage tank is partially or wholly cold and the return water to the boiler is below 120°F, the equipment rated for 90% efficiency will operate in a non-condensing mode (85% or less). By contrast, CCTWHs are able to operate consistently in a condensing mode.

Through consistent condensing operation and a reduction in standby losses, retrofitting to CCTWHs from boiler/commercial storage water heating systems may result in significant natural gas savings. Under this field evaluation, a project team will quantify the performance and cost effectiveness over an eight-month period. Results will be compared to the existing baseline equipment and extrapolate findings to other building types and loading patterns. Since recognizing the energy savings from the CCTWH and the resulting economics will be heavily influenced by installed conditions and building type, the project team will develop a sizing and assessment tool for CCTWHs when applied to multifamily housing, hospitality, and schools or universities.

The objective for this project is to perform a field demonstration of the CCTWH at two multifamily buildings in Minnesota to quantify the energy savings potential of CCTWH over conventional direct-fired gas storage and indirect (with dedicated boiler) systems in this application.

Partners in this project include the State of Minnesota Center for Energy and Environment.

Benefits / Market Implications

CCTWHs have several advantages over other high-efficiency gas technologies as they build on a mature, high-volume technology which has achieved cost effectiveness in the tough residential water-heating markets.

Example racked tankless CCTWH. Credit: Intellihot and PHCP Pros.
Specifically, “racked” CCTWHs can adapt product modules and components from the high-volume (~450,000/year) U.S. residential gas tankless market. Coupled with the competition amongst several large, mature manufacturers, this reduces the price of CCTWHs to yield competitive system paybacks.

In the residential gas water heating market, a cost comparison across products has resulted in condensing-efficiency with tankless water heating gaining significant market penetration, while condensing gas-storage water heaters continue to struggle due to high equipment costs. If demonstrated as a cost-effective solution for substantial energy savings, through a combination of improved equipment and system efficiencies, the CCTWH product category could support ratepayers and utility energy-efficiency program design in serving the important commercial niche markets of 1) mid-/high-rise multifamily housing, 2) hospitality, and 3) schools and universities.

Technical Concept & Approach
The overall project scope is as follows:

- **Field Demonstration Planning and Preparation**
  In this task, the project team will develop a test plan; perform a literature review and manufacturer interviews; and solicit, screen, inspect, and finalize two field demonstration sites in the Minneapolis/St. Paul region.

- **Baseline Monitoring**
  The project team will perform a eight-month baseline monitoring on existing equipment, deploy high-resolution data-collection/analytical methods to assure transient energy/water/waste is quantified.

- **CCTWH Demonstration**
  The project team will specify, procure, install and commission CCTWH systems at two multifamily sites, with systems expected to have aggregate output between 800-1,400 kBtu/hr.

- **Measure Assessment and Knowledge Transfer**
  The research team will finalize the CCTWH modeling and assessment tool, extrapolate savings and performance to other building types and regional locations, and summarize project results as a draft measure for efficiency programs.

In this project, researchers will attempt to answer the following questions:

- What proportion of energy savings is due to reduction in standby losses through the elimination of system storage?
- With an estimated installation costs of $40/peak MBH output, is a five-year simple payback feasible?
- Do highly dynamic loading patterns typical of multifamily buildings result in fluctuating delivered hot water temperatures?
- How do seasonal variations and distribution system types affect savings?
- What knowledge gaps exist concerning the CCTWH technology that may hinder broader market acceptance?
- As multifamily building owners consider CCTWHs, what sizing guidance is appropriate for Minnesota and what is a representative CCTWH retrofit installation cost?

Results / Status
In the first quarter of this project, the research team engaged a CCTWH manufacturer, recruited a host site, and edited the test plan.

The manufacturer provided specific installation/sizing guidance and pricing of its CCTWH products to support site recruitment. As sites are expected to cover a portion of the installation costs, having an estimate of site costs is critical. This information will be added to the survey deliverable.

Sites were selected and baseline monitoring equipment installed at two multifamily buildings in St. Paul, MN. The team is preparing for CCTWH installation in late 2019.

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Quantifying Methane Emissions from Tankless Water Heaters

Research is being conducted to quantify the amount of emissions and determine the conditions under which tankless water heaters may release unburned hydrocarbons into the atmosphere, in order to identify best practices or design features to reduce methane emissions.

Project Description

Some appliances are coming under increased scrutiny due to perceived emissions of unburned hydrocarbons. Of specific focus are high-input compact burners (e.g., tankless water heaters). However, field-derived emissions measurements are difficult to perform accurately and representatively.

In principle, it is possible for tankless water heaters (TWH) to modulate directly in response to end-user loads. In order to maintain outlet temperature stability while handling variable inlet water temperature and flow demands, these units ramp up and down their firing rate quickly, with 20:1 turndown ratios common for products available (unheard of for most gas-fired equipment). This is achieved in a number of ways.

Staging multiple cassette burners is the most common method. Several burners (~16) are staged in groups, on and off, as sequenced by proportional gas valves. This allows for the highest possible turndown.

A single ceramic “plaque” or flat woven/knitted fiber mesh, large enough and with an adequate thermal mass to permit such a wide turndown ratio, is added to the burner. As the tankless water heater shifts to the load, either rapidly staging burners on/off or modulating the single plaque/mesh burner, temporary loss of flame stability and delayed ignition can lead to temporary emission of unburned methane. While this transient effect is present with all cycling gas-fired equipment, tankless water heaters by their nature are constantly adjusting the flame through staging or rapid and drastic modulation.

Tankless water heaters offer high efficiencies and are increasingly popular, but could be subject to future regulations or regulatory scrutiny due to perceived methane emissions. As with the control of conventional criteria
Air pollutants, appliances are a ready target as they have large populations and fast turnover, such that establishing emission limitations can result in swift changes in product offerings and thus, emissions reductions.

Tankless gas water heaters are currently the second most popular type of gas water-heating equipment, representing more than 10% of gas products sold in North America and more than 50% in the Europe.

This project will establish the first laboratory-based greenhouse gas emission rate for tankless gas water heaters. The objective is to quantify the amount and determine the conditions under which TWH may release unburned hydrocarbons into the atmosphere in order to identify best practices or design features to reduce methane emissions.

Models from at least five different manufacturers of TWHs will be tested under specific operating conditions and representative use patterns.

Benefits / Market Implications

Over the past 15 years, TWH sales have grown from less than 1% to more than 12% of gas water heater sales in North America. The ability to clarify and, if necessary, mitigate the impact of TWHs on greenhouse gas emissions would protect the continued growth and option of this high-efficiency water-heating technology for ratepayers. This is important since tankless water heaters offer a Uniform Energy Factor of 0.82 or more, which is steadily becoming a minimum requirement under numerous green building codes. Thus, potential restrictions that limit ratepayers’ options to use this type of high-efficiency device should be based on sound, reproducible scientific study, and address product and technical advancements to minimize potential releases.

Technical Concept & Approach

A project team will first conduct a literature review on unburned methane release from appliances. Input will be solicited from TWH manufacturers regarding system operation, compact burner modulation/ignition methodologies, and system controls with respect to the emission of unburned fuel.

Researchers will develop methods to accurately measure the dynamic emission rate of methane from a modulating TWH and represent end-user behavior through various dynamic tests.

At least five TWHs will be used for testing, representing a range of combustion system designs and the most popular models and manufacturers. The units will be tested using steady-state, “step ramp-up,” and simulated use patterns to establish typical methane emissions across products and combustion system designs.

Through data analysis, researchers will identify tankless designs, features, and operating conditions that result in excessive methane emissions. A list of recommendations for detection and mitigation of such conditions will be developed.

The project team will compile results and report to cross-section of TWH manufacturers via a webinar or in-person meeting, reviewing methods and results.

Results / Status

In this first quarter of this project, researchers initiated two tasks in parallel, developing the test plan including specification for the methane analyzing methodology and procuring and installing the TWHs. A non-condensing TWH was secured and a condensing TWH secured for use in the project. Plumbing and system controls were put in place to operate the TWH units.

In parallel, the team reviewed recent methane emissions studies and is currently finalizing the procurement of a methane analyzer suitable for this project. Vendors from several portable greenhouse gas emission analyzers were consulted with quotes solicited for comparison.

Additionally, the project team discussed potential cooperation with a major university regarding the test plan, as a complement to their field sampling of TWHs.

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Project Description

The residential rooftop solar photovoltaic (PV) market continues to outpace expectations and transform how homes are powered. The National Renewable Energy Laboratory (NREL) documented the impressive decline in both PV module and installation costs, which indicate less than $3/W installed. As a result, residential PV capacity and output has increased considerably in the U.S., nearly four times since 2014 to 2017.

These trends continue despite uncertainty regarding incentives, net-metering policies, and other market interventions that were instrumental in PV’s initial success decades ago. As a result (in tandem with a significant increase in utility-scale wind generation), governmental carbon reduction and renewable-generation targets are much more attainable and are becoming more aggressive.

The objective of this project is to expand the advanced gas heating and cooling capabilities in a virtual test home in a laboratory to more rapidly develop, test, and optimize advanced options in system-based solutions that increase energy efficiency and reliability, reduce energy costs, and better integrate natural gas with renewable energy in homes in all climates.

In this project, researchers will design, commission, and test space-conditioning options, which include integration with a laboratory environmental chamber for simulated indoor/outdoor environments, equipment for controlling transient hydronic loads for 24-hour periods, integration with forced-air heat distribution for hydronic air coil (combi) equipped and furnace-based systems, and test stations for gas heat pumps (GHPs) and low-capacity warm-air furnaces. In parallel, the project team will build and calibrate analytical capabilities to extrapolate results from the experimental program, focusing on the HVAC equipment.

This project includes a three-pronged approach:

1. Evaluate solutions and design practices to assure high-efficiency, low-impact gas-fired heating technologies are able to maintain thermal comfort in all climates
2. Develop solutions to deploy and store thermal energy, the primary connective tissue from efficient gas-fired heating to the home’s other systems; and
3. Develop sizing guidance and system controls to balance on-site micro-combined heat and power (mCHP) with available renewable resources and thermal energy needs.

Installation of operating 6 kW GHP.
This approach is expected to illustrate and inform how the direct use of natural gas in modern homes support policy pushes towards Net-Zero Energy (NZE) building designs, including through the widespread deployment of both on-site renewable PV electricity generation and integration of “smart” devices with HVAC equipment through mobile software platforms.

Benefits / Market Implications

When some advocates imagine a NZE home or a home with significant on-site renewable power generation, they often imagine a home with a large rooftop PV array, electric heat pumps for DHW and HVAC, and smart electric appliances (including cooking). This may be due to the lack of robust, peer-reviewed analyses and case studies demonstrating that mixed-fuel homes can reach similar levels of emissions reductions and renewable energy utilization but at lower cost and higher reliability and resiliency for ratepayers. In addition are the lack of market-ready equipment and system-integration strategies to demonstrate the effectiveness of coupling on-site renewable generation with efficient gas-fired heating equipment.

This effort is intended to address the latter by developing and demonstrating equipment designs, controls, and system-integration architectures through experimental integration of PV generation, mCHP, ultra-high-efficiency gas heating, and thermal energy storage.

This represents a system-level technology development program to demonstrate to industry and homebuilders methods and technologies to effectively integrate gas-fired equipment with on-site renewable generation.

If successful, the project team will outline products, system-integration strategies, and building practices that will facilitate the expanded integration of gas and renewable energies in homes.

Technical Concept & Approach

The focus of this project is to build the space-conditioning portion of an Integrated Natural Gas/Renewable Test Stand, with thermal energy storage (DHW) and mCHP/PV integration. This space-conditioning portion includes integration with environmental chambers for indoor/outdoor conditions, hydronic and forced-air load control, test stands for furnaces and GHPs, and a link to thermal energy storage.

The project team will build and test experimental controls for this portion and test its capabilities with GHP equipment, a combi system through integration with DHW/mCHP equipment, and a low-capacity furnace. In parallel, researchers will build a calibrated simulation tool for modeling space-conditioning equipment as part of a building energy simulation for hourly heating/cooling loads, including multiple types of GHP and low-capacity heating equipment with or without thermal energy storage integration.

Findings and data will be summarized in a test report disseminated to key stakeholders (high-performance homebuilders, heating equipment manufacturers, etc.)

Using building energy simulation software, the project team will create several model gas/renewable homes and generate baseline performance for multiple equipment configurations.

Results / Status

The project team leveraged an opportunity to build GHP testing capacity in support of the virtual test home through adding a) capabilities to test low-load gas heat pumps, b) improved calibration of hydronic measurements, and c) expanded sensible and latent heating control of the climate chamber. This effort was performed in parallel with the laboratory evaluation of a 6 kW (20 kbtu/h) output gas absorption heat pump. This opportunity was used to accelerate some of the changes to the virtual test home while the low-load GHP was on-site during the reporting period.

Testing was ultimately successful, with the chamber alterations permitting operation at 7°C, 2°C, -7°C, and -15°C.

Additionally, the project team built out capabilities in a separate, cold-climate chamber to evaluate performance of combustion equipment at temperatures as low as -20°F (-29°C), and developing instrumentation, controls, and best practices for testing at these low temperatures.

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Economical High-Efficiency Residential Gas Absorption Heat Pump with Integrated Cooling

This project involves adding cost-effective cooling to a low-cost gas absorption heat pump pre-commercial product that currently provides only heating and domestic hot water. This project will add a vapor-compression module (using ammonia as the refrigerant) to provide air conditioning, which will broaden the number of ratepayers who can benefit from this emerging high-efficiency product.

Project Description

The gas absorption heat pump (GAHP) provides a low-cost whole-house heating option with significant improvement in efficiency over condensing furnaces and boilers. In addition to cost-competitive therm savings of up to 45% over conventional residential gas heating equipment, the GAHP delivers stable, comfortable temperatures without the need for auxiliary heating or backup and is projected to be ultra-low-NOx compliant with all combustion occurring outdoors.

One significant remaining issue preventing this low-cost GAHP from succeeding broadly is that it currently doesn’t provide cooling. The economics of the heating-only GAHP (sized at nominal 80 kBtu/h output), with the aggressive equipment cost target of $5,000, are generally suitable in cold climates and for large, single-family homes. For example, as a simple estimate, in a space-heating-only application, the GAHP would have a five-year simple payback over a condensing furnace in homes that have an average monthly heating bill of $200 or greater during the heating season. This may be feasible in cold climates, for large homes, or both, with economics of combination systems improving; however, the economics worsen in mixed or cooling-dominated climates, especially in the U.S. Southeast. As a result, cost-effective cooling is necessary for this product to succeed broadly and serve many ratepayers.

This new project builds on the prior and current UTD efforts to bring this heating-only, low-cost GAHP for home heating to market with the addition of electrically-driven cooling.

The all-weather system will offer source-energy-based heating COP of 1.40 or greater to end users/ratepayers, exceeding the majority of electric or gas-fired options.

While GAHPs offer high efficiency and low emissions, existing GAHPs commercial products tend to be costly and have seen limited adoption in the Americas. While GAHPs are available with integrated cooling, the approach proposed here is targeted to be a more economical. What’s new in this project will be the addition of
cost-effective, vapor compression as a hybrid arrangement, wherein the GAHP would have an electrically-driven compressor designed for ultra-low-charge ammonia vapor compression, sharing internal heat exchangers with the absorption heat-pump sealed system. This could provide a simple payback of less than three years for a hybrid system.

This system would be designed for low-load homes, with 40 kBtu/hr output of heating and 1.5 RT of cooling; however, scaling up or down at a later date to fill out the product family is not expected to be problematic.

This project will leverage cofunding from the Canadian Gas Association (CGA) and will move from the development/design stage to a laboratory version proof-of-concept of a packaged alpha prototype.

Benefits / Market Implications

The prevalence of air conditioning (A/C) in the United State is, in part, why furnaces are more common than in other developed nations. Of all U.S. single-family homes, 73% have central A/C. Early feedback from contractors and homeowners on the heating-only GAHP is that very few homeowners will permit having two large pieces of HVAC equipment outdoors, which may limit the application of the heating-only GAHP. This issue (coupled with technological advances in electrically-driven heat pumps, which operate reversibly for heating and A/C) has led to their growth in the residential sector.

The hybrid GAHP with A/C is intended to broaden the energy and emissions savings potential of the GAHP, expanding the marketability of this technology by providing applicability for mixed and cooling-dominated climates, where the GAHP heating-only system may have challenging economics, and by addressing the “two boxes” issue, requiring only one piece of outdoor HVAC equipment for homeowners while requiring only a single air-handling unit indoors.

The advantage offered by operating with a chilled-water loop for A/C, using the single indoor coil, is that this is not a direct expansion system. This severely reduces the refrigerant charge volume as it is only contained within the hybrid GAHP unit, helpful in preventing fugitive greenhouse-gas emissions and minimizing risks with an ultra-low-charge ammonia system. In addition, many HVAC manufacturers are looking to refrigerants at higher pressures or with moderate flammability, which is challenging for conventional split A/C system design.

Technical Concept & Approach

This project is similar in scope to a previous effort to commercialize a gas-fired heat pump water heater (GHPWH), scaling up the same absorption heat pump technology by an eight-fold factor. Using a single-effect absorption cycle with the ammonia-water working fluid pair, at the heart of the GAHP is a direct-fired absorption heat pump comprised of standard heat exchangers (e.g., shell and tube, finned tube coil, etc.) as with the GHPWH.

The project team seeks to demonstrate an economical GAHP with integrated cooling for a projected target equipment price of $5,000.

Results / Status

Early in this project, researchers supported the GAHP technology developer with negotiations with the CGA and its Natural Gas Innovations Fund, the project to which this UTD effort provides cofunding.

As technical support to the cofunded program, performance curves for the GAHP heating module (absorption cycle, test data) and the module (simulated), a hybrid GAHP system with a hydronic air coil will be created and updated.

Researchers will develop models of single-family homes for several UTD member metropolitan areas, covering multiple climate zones and housing types (size, construction, occupancy). The project team will perform an annual energy assessment of hybrid GAHP. Multiple baseline scenarios (allelectric, high/low efficiency, etc.) will be created.

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iGEN Self-Powered Furnace

The objective of this project is to assess the merits of the iGEN self-powered vapor-expansion cycle furnace through laboratory breadboard testing and to support continued technical refinement. Essentially, the iGEN unit could provide users with a self-powered hydronic forced-air space-heating system at a reported 95% total efficiency.

Project Description

In recent years, the U.S. energy infrastructure has been exposed to frequent and extreme weather events leading to extended power outages. As such, the need for energy resiliency has become an increasingly important issue for many end users.

The iGEN system is a drop-in furnace with 45 to 80 MBH heating capacity that generates one kilowatt (1 kW) of power to: charge an on-board battery pack; power its blower, compressor, and exhaust fan; and provide nominal surplus power to an on-board power strip that can be used to power minor loads. Essentially, the iGEN could provide users with a self-powered residential space-heating system at a reported 95% total efficiency that is fed by the highly-reliable natural gas distribution system.

The company has a patent for a novel method of generating heat and power in a vapor-expansion cycle as part of an air-handler unit (furnace).

The iGEN product is in a pre-commercialization state with prototype units ready for preliminary field trials planned in Canada. It uses R245fa refrigerant in a vapor-expansion cycle, which includes a typical compressor, condenser, and evaporator. However, the iGEN employs a custom scroll expander instead of a typical thermal expansion valve. The scroll expander recovers energy from the refrigerant expansion process and converts it to 1kW of power.

The liquid refrigerant compressor (pump) is powered by an on-board non-synchronous inverter. Heat via natural gas is applied to a direct-fired evaporator coil where the liquid refrigerant is changed to vapor. A heat exchanger recovers exhaust heat from the natural gas combustion process where it is circulated to the evaporator and used in a combination power generation and heat-pump cycle. The refrigerant vapor is passed through the scroll expander and its temperature and pressure are reduced. Water passes across a condenser, which heats the water and changes the vapor back to liquid. The heated water
is then used in conjunction with a hydronic forced-air handler unit for space heating.

All internal and external power loads would be fed by:

- The expander up to 1 kW when the thermostat is in heating mode and there is a call for heating
- The battery pack up to about 500 to 1,000 W-hrs when there are no thermostat calls, or
- The electric grid via an automatic transfer switch when the batteries are uncharged.

During a power outage, the iGEN system runs when there are calls for heating, and also to charge the batteries. When the furnace is not running during a power outage, the batteries would provide power until they are uncharged (estimated 2 to 10 hours depending on charge at outage and external loads).

iGEN’s go-to-market product is a 45MBhr system, which would generate 1 kW of electrical power.

The objective of this project is to assess the merits of the iGEN system by conducting laboratory breadboard testing. Tangible goals for the project are to:

- Expand upon system design evaluations conducted under earlier research by the project team
- Evaluate the iGEN furnace limited to the vapor-expansion cycle components, and
- Assess opportunities with iGEN to provide additional technology development support.

**Benefits / Market Implications**

As with other heating technologies, the iGEN self-powered space-heating system is certainly more attractive in heating-dominant climates than in cooling. iGEN reports an incremental installed cost of about $1,500 compared to a traditional condensing furnace, which would serve similar markets. In a cold climate, the furnace typically runs for about one third of the time during heating months; the furnace on-time might be about 1,500 hours per year. At 1 kW of power, electricity savings would be 1,500 kWhrs; and at 12 cents per kWhr, electricity cost savings would be about $180 per year.

While there are electricity cost savings associated with the iGEN, there is also quantitative and qualitative value from improved home energy resiliency. Consumer demand for emergency generators has grown substantially during the past decade – at costs on the order of $400/kW to $600/kW. Netting out $400-$600/kW as a reliability premium drives the incremental cost down, and brings simple paybacks for this self-powered furnace technology close to about five years for users in many cold climates.

**Technical Concept & Approach**

Technicians instrumented the internal components of a prototype iGEN unit and conducted bench-scale testing. The primary goal was to gather initial data for the air, refrigerant, water, and power cycles in order to evaluate performance and provide recommendations for further development. A second prototype was then provided.

**Results**

In April 2018, iGEN announced it acquired all assets related to the mCHP business of UK-based Flowgroup. Following iGEN’s acquisition, iGEN provided the project team with an evaluation unit designed around the acquired Flowgroup IP, iGEN and UTD researchers discussed potential areas for improvement.

The Flowgroup concept was a boiler used for hot water radiant heating systems, which iGEN modified to be a forced-air system. The unit is still expected to generate about 45 MBhr of heating and 1 kW of power, of which most will be used to self-power the system.

The project team concluded preliminary testing of the initial bench-sale prototype iGEN unit designed around the acquired Flowgroup system. The bench-scale unit was determined to be in the proof-of-concept stage. The second unit provided was ready for simulated use testing, specifically in a virtual test home (VTH).

For the second prototype, researchers coupled the iGEN unit with a hydronic air handler to provide hydronic forced-air operation. The air-handler heating capacity was rated at about 35-45 MBH with supply water at about 120°F. The system produced about 45-50 MBH of usable heat off the air handler with about 400 watts of supplemental power that could be used to power the air handler plus other nominal loads. Total operating efficiencies were about 90% with electrical efficiency at about 4%-5%. It is now being tested in the VTH.

**Status**

The project team continues to work with and support iGEN. Testing in a virtual test home is under way.

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COMMERCIAL APPLICATIONS
In this project, researchers are developing new models based on the laboratory and field performance of the Yanmar gas-engine-driven heat pump to provide a more accurate prediction of seasonal performance for different climates, and identifying best applications of these products for end users.

**Project Description**

In 2016, Yanmar introduced a 14-ton gas heat pump (GHP) with a three-pipe heat-recovery variable refrigerant flow (VRF) configuration that provides simultaneous heating and cooling, an important new option for the GHP market. In addition to improving the response to building loads, a three-pipe system potentially reduces energy use by recovering heat from zones in cooling mode (e.g., internal loads) and redistributing it to meet heating loads in perimeter zones.

In an early phase of this project, researchers developed GHP models based on field and laboratory data from the NextAire™ 15-ton unit. These results were compared to modeled results for conventional rooftop units (RTUs) and electric heat pump VRF (EVRF). This modeling study provided some valuable results highlighting the importance of part-load performance for VRF systems paired with dedicated outdoor air systems (DOAS). Based on these models, part-load performance of both electric and gas VRF systems, particularly from 20%-40%, was the key indicator of overall system performance.

Measured performance data from the NextAire GHP laboratory and field monitoring showed reduced efficiency at lower part-loads adversely impacted the total seasonal performance. The lower part-load performance of the Next-Aire GHP may be due to design tradeoffs in the system control strategies or engine controls for this specific model.

In this project, researchers will assist gas end users by developing energy models of new GHP technology and providing a more accurate estimate of seasonal performance in different climates. This study will also assist in identifying the most cost-effective target markets for GHPs, as well as performance or cost targets for continued development. The ultimate goal is to expand the use of high-efficiency GHPs by identifying regions and commercial applications where GHPs generate the most energy savings or economic benefits.

**Benefits / Market Implications**

Gas-engine-driven heat pumps offer gas end users a high-efficiency option to compete with electric heat pumps. Several of these products have a multi-zone VRF configuration, an increasingly popular option in the small commercial market.

For the customer, the key value proposition for GHPs are lower operating costs due to reduced peak electric demand and low natural gas prices. GHPs significantly reduce peak electric use during periods of high demand, especially peak summer loads, as well as peak winter loads in regions with widespread use of electric heating. GHP operating costs are projected to be 30% less than electric heat pumps. GHPs also offer potential savings in source energy and full-fuel-cycle greenhouse gas emissions.

Another key advantage for GHPs is improved heating performance at low ambient temperatures. Heat recovery from the engine jacket and exhaust is used to supplement heat output, increasing heat capacity at low
temperatures and improves heating efficiency. This also allows GHPs to maintain supply temperatures. In contrast, electric heat pumps typically require inefficient resistance heating to supplement heat output at low outdoor temperatures.

**Technical Concept & Approach**

Under Phase 3 of this project, researchers will update existing GHP models to incorporate performance data from the Yanmar three-pipe GHP. These models will be used to predict energy savings, operating costs, and reductions in peak electric demand for various climates.

The project team will use existing published models of EVRF configurations to determine the relative energy savings and environmental benefit of GHPs compared to equivalent EVRF systems. Researchers may also investigate approaches such as sizing, controls, or operations that might improve GHP part-load performance.

The project team will update existing GHP models, incorporating Yanmar performance data with respect to ambient temperatures and the range of heating and cooling loads.

Researchers will:

- Select up to five locations in North America in different climate zones
- Conduct hourly energy analysis for three equipment types (GHP, RTU, EVRF), two building archetypes, and up to five climate locations
- Determine the seasonal energy use; specifically gas and electricity consumption, and peak electric demand
- Determine economic benefits of GHP as compared to EVRF systems
- Analyze savings in operating costs and lifecycle costs, and
- Compare source energy and full-fuel-cycle greenhouse gas emissions based on the U.S. average marginal electricity mix.

**Results**

A baseline U.S. Department of Energy reference building model was developed for a multi-zone office building. Space conditioning loads and energy use were compared to measured field data for validation. An EnergyPlus GHP model was developed based on measured data from the NextAire unit to validate the model. The project team also developed a new EnergyPlus model for an alternative GHP VRF system based on manufacturer performance data (Yanmar) and measured field data from UTD project 1.17.G.

Existing EnergyPlus electric heat pump VRF models (Mitsubishi PURY-P108TGMU) were revised based on manufacturer performance data for the Daikin IV cold-climate VRF heat pump. These performance curves were adjusted and validated based on measured field data.

**Status**

Hourly energy simulations will be conducted for a small office building and a retail building in five different climates using the updated EnergyPlus models for GHP and EVRF paired with a conventional DOAS. Total energy use will be validated with measured field data. This analysis will determine the potential energy savings, reduction in peak electric demand, and economic benefits for GHPs in multiple climates.

"Southwest Gas has always supported natural gas air-conditioning technology. We are extremely encouraged that more than 350 NextAire gas heat pump units have been installed in our service territory. Using natural gas for cooling saves energy, reduces costs, and lowers greenhouse gas emissions. It’s a win-win for all!"

- Anthony Hills, PE
  Director
  Southwest Gas Corporation

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COMMERCIAL APPLICATIONS

PROJECT NO. 1.13.B

SUMMARY REPORT

COMMERCIAL FOODSERVICE TOOLS AND CALCULATORS

In this project, a research team analyzed tools and/or calculators used by the commercial foodservice industry and combined information from various sources into a single web-based resource that helps end users determine the economic and environmental benefits of using new, more advanced equipment.

PROJECT DESCRIPTION

Results from a UTD commercial foodservice (CFS) audit and survey showed the growing importance of addressing “green”-related issues — such as sustainability — in the CFS industry. Sustainability includes elements such as environmental compliance, recyclable materials, material usage, packing, energy usage, water usage, and disposal. The North American Association of Food Equipment Manufacturers (NAFEM) developed a spreadsheet that calculates many of these values; however, the calculator does not fully address the source-energy consumption and air emissions for appliances.

The focus of this project is to create tools and/or calculators that combine information available from various sources that can be used by the CFS end users to determine the economic and environmental benefits of using new, more advanced CFS equipment. The tools and calculators show the potential energy and cost benefits of replacing or buying more energy-efficient equipment.

For this effort, the project team developed a website with links to energy calculators and easy access to a wide variety of information on commercial foodservice equipment.

BENEFITS / MARKET IMPLICATIONS

CFS owners and operators have traditionally been hesitant to replace functioning equipment or buying new, more efficient equipment because of first costs. The objective of this project is to identify and simplify access to different calculators and tools for the CFS industry for information and data that can demonstrate the energy and cost savings of replacing out-dated or under-performing equipment with energy-efficient models.

Tools and calculators can also show how rebates and long-term cost savings will reduce the burden of increased purchasing costs of new equipment.
Technical Concept & Approach

In the initial phase of the project, researchers interacted with various organizations to evaluate existing calculators and determine the elements that are useful to the CFS industry. Available databases for the stock efficiency of CFS appliances, information for available rebates in North America, and ENERGY STAR ratings were compiled into a website. The web interface includes a list, explanation, and links to other calculators that could be of use to the industry.

Results

A Commercial Foodservice Tools and Calculators webpage was created to consolidate available information from different sources for CFS into a single location. The information and tools are designed to be used by the end user and restaurant industry to determine the economic and environmental benefits of using new, more advanced CFS equipment. Information is organized into a web-based interface and a calculation page developed to allow the comparison of standard vs. energy-efficient equipment usage in typical restaurants.

The project team developed links to various tools, calculators, and general information, including:

- FSTC: The Energy Efficient Kitchen Tool
- GFEN: Comparison of Natural Gas versus Electric Rates for Foodservice Operations
- ENERGY STAR: Guide for Restaurants
- ENERGY STAR: Savings Fact Sheet
- ENERGY STAR: CFS Program Administrator Guide for Utilities
- NRA: Conservation Guide Rebate and Incentive Information
- GFEN: Utility Pricing and Rebate Information
- ENERGY STAR: Commercial Food Service Equipment Incentive Finder
- Consortium for Energy Efficiency: High Efficiency Incentive Guide
- U.S. DOE: Database of State Incentives and Renewables & Efficiency Energy Cost Calculators
- FSTC: Life-Cycle $ Energy Cost Calculators
- NAFEM: Equipment Life Cycle/Total Cost of Ownership
- ENERGY STAR: Commercial Kitchen Package Resources Other Calculators
- ESC: Commercial Carbon Calculator

- NAFEM: Sustainability Calculator.

An added feature to the website allows for a comparison of efficient vs. existing appliances with a “Build Your Own Restaurant” page. On the page, a population of different appliances with energy-efficient options can be chosen and the energy savings calculated.

Efforts are being made to increase the awareness of the website via presentations at CFS-related events and other distribution avenues. In 2018, the website was demonstrated at the Louisiana Foodservice & Hospitality EXPO and the Oklahoma restaurant show, with more than a dozen restaurants modeled using the website and information provided to the owners and operators.

In 2018, a one-day cooking demonstration was conducted showing the energy usage for an energy-efficient fryer, a standard gas fryer, and an electric fryer using a new CFS tool developed for this project. The tool has a live display that showed the energy usage of each fryer as food was cooked and displayed the estimated lifetime energy costs and savings of using an energy-efficient fryer.

The website was demonstrated at the 8th Annual So-CalGas Foodservice Equipment Expo. The focus was on displaying different types of burner technologies with information about the advantages of new energy-efficient equipment.

In 2019, the webpage was featured in presentation at an Energy Solutions Center Workshop hosted by NW Natural in April and at the 2019 Louisiana Foodservice Expo.

Information on NOx regulations and rebate information was compiled and a beta page developed. The site was beta tested phase and new information was added to the existing webpage.

Status

Existing tools and the calculator webpage are being maintained and updated with new information as it becomes available.

The webpage is publicly available at:

\[http://cfscalc.gastechnology.org/\]

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SPC204 mCHP Test Method Standard Support

In this project, a research team helped develop a draft standard method for testing micro combined heat-and-power (CHP) devices (50kW or less) in order to help end users evaluate and assess these highly-efficient devices.

Project Description

While micro combined heat-and-power (MCHP) systems are becoming well established in Europe and Asia, the technology has been under-utilized in the United States and Canada. Among the barriers to entry in the North American market is the lack of a standard test method to determine the net electrical-generating performance and heat-recovery performance of MCHP systems.

Since 2010, ASHRAE Standard Project Committee 204 has been actively developing a test method for rating MCHP devices. The standard test method currently under development (ASHRAE SPC204) provides a level playing field for MCHP manufacturers in establishing product efficiency for a large market. Such ratings provide a valuable metric for end users to compare products or for utilities to evaluate a class of products for inclusion in energy efficiency and rebate programs. Allowing potential users of the test method to assess, in general terms, its usefulness in proposed applications would help to validate the test standard. Such a validation process would not intend to duplicate results in every user’s laboratory. Rather, the validation process would offer guidelines regarding the type of variability that can be expected among test results when the method is used in one or more reasonably competent laboratories.

Previously, Gas Technology Institute (GTI) played a major role along with Underwriters Laboratories in developing a distributed generation and CHP laboratory testing protocol for systems in sizes ranging from 30kW to 1 MW. The protocol was adopted and used by the Association of State Energy Research and Technology Transfer Institutions.

In this project, a research team developed and provided to the SPC204 Committee a draft MCHP test method in the ASTM format for consideration and further consensus refinement by the committee.

The project was conducted in collaboration with Canada’s Natural Gas Technology Centre (NGTC) to ensure that the draft provides a harmonized approach to standards development for the North American MCHP market.

Benefits / Market Implications

Of the approximately 35 manufacturers of MCHP worldwide, experts report that less than half are evaluating entry into the North American market.

A standardized method of testing and rating would provide a path towards consistent and clear treatment throughout North American markets.
Technical Concept & Approach

- **SPC204 Standard Development**
  
  The research team developed a draft standard, which was submitted to the SPC committee.

- **Intra-Laboratory Testing**
  
  The standard applies to CHP devices whose maximum net electrical power output is less than 50 kW and whose maximum thermal output is less than 300 kW. Appliances covered by the standard are stationary systems that use, but are not limited to, an internal combustion engine, a turbine, a Stirling engine, or a fuel cell as the thermal engine heat-and-power generating source. The standard provides a test method for determining the net electrical-generating performance and heat-recovery performance of MCHP devices at various conditions.

  To assess repeatability and address variability between test results, researchers conducted independent tests of the same system. The tests were conducted using equipment and instrumentation requirements specified in the standard.

  The standard incorporates a battery of tests including:

  - Thermal measurement for heat recovery
  - Intake air temperature for various ambient conditions
  - Emissions measurement
  - Electrical transient load (load change response)
  - Electric power quality, and
  - Power factor testing (grid isolated).

- **Inter-Laboratory Coordination**
  
  The research team coordinated a round-robin test program with laboratories. The tests were conducted in the same manner as those conducted at GTI’s test facilities.

Results

In 2015, a subcommittee that included GTI, the SPC204 Chair, Natural Resources Canada, NGTC, and MicroCogen Partners LLC presented a draft standard to the full committee. At that time, a list of unresolved issues were presented to the committee. The list included resolution areas of boundary, definition, calculations, and test procedures. The committee members volunteered to address these unresolved issues in small subgroups. At the ASHRAE summer meeting, the full committee reconvened to assess revisions to the draft standard. While most issues have been resolved, it was determined that one more iteration of draft was necessary prior to having the document released for public comment and review.

In July 2015, the U.S. Department of Energy (DOE) announced that it was developing a new evaluation, measurement, and verification (EM&V) protocol for CHP programs. Researchers initiated dialogue with the DOE to ensure that methods and procedures for in-field EM&V will have consistency as necessary with the SPC204 Method of Test.

Updates to the draft standard were prepared throughout 2015. A final draft of the standard was sent to the SPC committee in November 2015.

In 2016, EC Power XRG1, a 24kW packaged CHP system, was tested against the draft standard in an effort to validate the standard. Based upon testing, some revisions to test procedures were made. Project representatives are approaching manufacturers of other systems for additional validation testing.

In January 2017, a draft version of 204P *Method of Test for Rating Micro Combined Heat and Power Devices* was reviewed and final recommendation made at the January 2017 SPC204 Committee meeting. In June 2017, the committee met in teleconference to resolve issues regarding test boundaries, reporting higher vs. lower heat value, and thermal energy calculations.

A draft White Paper was prepared to develop a logic tree for determining the test boundary of a micro-CHP device for testing under Standard 204P. Only natural gas, propane, or diesel are covered as a fuel source.

Status

This project is complete. A Final Report was issued in October 2018.

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Next-Generation Commercial Foodservice Burners

This project focuses on designing, developing, and testing a prototype commercial foodservice appliance using an advanced burner concept based on designs proven for other markets and products (e.g., residential furnaces and water heaters) to improve equipment efficiency and reduce emissions.

Project Description

Improvements in efficiency and emissions have been limited in commercial foodservice (CFS) equipment due to a reluctance of many end users to pay a premium for units with advanced combustion systems. Because of this, most gas-fired CFS appliances use relatively simple and inexpensive technology.

While controls, construction materials, and insulation have improved products for the CFS industry, burner designs have varied little. Most of the efficiency gains for gas-fired CFS burners over the past few years have been attributed to the structural design of the unit (e.g., enlarged heat-transfer surfaces and the use of insulation). However, with increased emphasis on efficiency and potential emissions concerns, interest in new burner technologies has grown.

Through this project, researchers are investigating existing higher-efficiency and lower-emission burner technologies developed for other markets (e.g., residential furnaces and water heaters) and working with CFS equipment manufacturers to adapt them to CFS appliances. The objective is to design and test prototype CFS appliances using an advanced burner concept based on designs proven in other markets.

Benefits / Market Implications

The reason CFS appliances are not approaching efficiencies of other gas-fired appliances with similar firing rates is partially due to the fact that the technology is not as advanced as other appliances. Generally, the market has been unwilling the pay the cost of advanced technologies. However, the growing emphasis of “green” technologies will leave most gas-fired appliance end users at a disadvantage because of existing limitations with current burner designs. This project is addressing this limitation by adapting existing advanced technology to CFS equipment designs.

Technical Concept & Approach

In previous phases of this project, researchers investigated existing higher-efficiency and lower-emission burner technologies such as metal mesh and foam burners with a combustion blower. The current phase involves incorporating an advanced burner technology into a new design for CFS equipment, and testing of other novel low-emission burners.

Results

Initially, the project team identified a fryer and griddle concept using metal mesh and metal foam burner designs. The fryer concept was developed by a manufacturer for a large chain account, but with a traditional burner. Both units were evaluated and burner concepts were developed.

A burner concept based on a furnace in-shot burner developed for this project was incorporated into a commercial fryer. A new burner design was made available that operates as both a power burner and an atmospheric burner with a venturi attachment.

In 2016, the South Coast Air Quality Management District (SCAQMD) of California released its updated Air Quality Management Plan (AQMP). Included in the plan are proposed new NO\textsubscript{x} emissions regulation on commercial and residential cooking appliances, including commercial charbroilers, ranges and ovens, and residential ranges. Because of the immediate need
to assist the CFS industry with NOx emissions concerns, this project is focusing more on burners that are typically used in the types of appliances in the 2016 AQMP.

In 2017, researchers teamed with a major range manufacturer to design a new fryer. The goal was to modify the burner to get an efficiency that qualifies for ENERGY STAR but a lower cost point than for most ENERGY STAR-listed fryers. The design developed was able to improve efficiency from mid 40s to 54%, thus qualifying as ENERGY STAR. Since its introduction, the fryer was awarded the 2016 Blue Flame Award by GFEN (Gas Foodservice Equipment Network) as innovative product of the year and a KI (Kitchen Innovations) Award at the 2017 National Restaurant Show.

Project team representatives visited a manufacturer that has developed a low NOx burner that might have applications in CFS. The manufacturer built a set of burners with a typical firing rate for commercial foodservice equipment. Testing has shown the burner capable of achieving NOx emissions of less than 10 ppm and 10 ppm CO (both corrected to 0% O2) at firing rates in the range of 40,000 to 70,000 BTU/hr.

The project team investigated available burners that claim to be low NOx for potential use in CFS applications. Burners were tested for a series of firing rates, air-to-fuel ratios, configuration of the gas supply, spacing for the fuel supply to the burner, and burner lengths. Testing for NOx characterization of rangetop burners demonstrated a measurable difference in the emissions characteristics of the back burner compared to the front burner. Testing was also conducted to characterize the NOx emissions from the pilot lights for each burner.

In 2018, testing of the a burner was completed and data from the testing used as the basis for a proposal to SCAQMD to develop an ultra-low-NOx CFS fryer.

The project is also investigating ways to improve NOx emissions of atmospheric and power burners. A power burner with a special mesh fabric burner face was tested to determine it emissions characteristics. In both atmospheric and power modes, the burner was tested for different firing rates and air-to-fuel ratios. For atmospheric mode, firing rate was adjusted by supply pressure and orifice size. For power mode, firing rate was adjusted by blower fan speed. Initial data analysis suggests that by changing the operational parameters of the atmospheric burner, the air shutter inlet results in small changes in NOx emissions, but large changes in CO emissions. Tests were also completed comparing emissions for the atmospheric burner at the same firing rate but for different supply pressures and burner orifice sizes.

The project team was approached by a CFS manufacturer for assistance with evaluating combustion technologies for a new appliance for a major chain account.

Researchers tested two burners: a radiant metal mesh burner and a metal foam burner. The burner was set up in a burner test stand to measure emissions as well as firing rate and temperature distribution of the burner with a metal plate and thermocouples located above the burner.

In 2019, researchers completed site NOx testing for five manufacturers, including NOx data for 49 unique appliances and burner configurations.

The project team initiated a new SCAQMD-funded project for the development of two ultra-low-NOx fryers. One fryer will be based off an existing fryer and another will be a new prototype design using a burner tested in this project.

**Status**

Laboratory testing was completed for more than 20 different burner designs. NOx testing was completed at five manufacturers sites.

Researchers are focusing on the characterizing and testing existing burners. The project team is meeting with CFS manufacturers to address issues regarding the measurement of existing burner performance characteristics and assist with developing new technology and products to meet end users’ needs.

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"I was involved in the fryer testing program, and I found the fryer to be beyond superb. It takes frying to the next level. I have never seen a fryer that can attain, retain, and sustain its temperature the way it does. All the while, its energy-saving features alone make it a hit. Great machine!"

- John Proctor
Chef
New Orleans Mission
Commercial Foodservice Demonstrations

Through restaurant and commercial-cooking field demonstrations, researchers are gathering valuable data to quantify the operating and efficiency benefits of gas-fired commercial foodservice equipment in real-world situations.

Project Description

Researchers and gas-industry representatives are conducting demonstrations of gas-fired commercial foodservice (CFS) equipment to quantify the benefits of the equipment in real-world situations.

Demonstrations are designed to address the reluctance of CFS operators to replace existing equipment with newer models because of concerns with costs and the uncertainty that the new equipment will be able to prepare the food as expected. Chain restaurants – which represent about 50% of the CFS industry – are recognizing the long-term cost benefits of newer equipment; however, this information is not generally available to the rest of the industry.

In UTD-supported CFS demonstrations, technicians test selected equipment in the laboratory and/or at commercial demonstration sites and document performance. Testing is being conducted with some of the industry’s most recent market introductions, including a steam kettle, range, wok, conveyor oven, convection oven, boilerless steamer, low-oil-volume fryer, and griddle. Any other appliance of particular interest could be targeted for laboratory performance testing or field demonstrations.

Activities in this project are divided into two types areas, one focusing on a single-utility-sponsored demonstration and the second focusing on conducting whole-kitchen assessments at as many locations as possible.

Benefits / Market Implications

Verifying the performance of a CFS technology in the laboratory or the field will demonstrate the advantages of specific technologies and provide valuable performance information.

This project provides end users and utilities with the ability to quickly evaluate appliances, whether a gas-fired technology or an electric competitor, and understand the true performance of the appliance.

Technical Concept & Approach

The research team and the utilities determined preferred appliances to demonstrate and identified test sites. In cooperation with the gas utilities in UTD, initially four sites within Oklahoma Natural Gas (ONG) and Peoples Gas territories were identified for conducting kitchen assessments.

The appliance performance and feedback from the test sites were incorporated into a report detailing the benefits and performance of the systems.

Opportunities for demonstrations are being identified at other utilities as additional project funding is provided. The time and cost varies based on the appliance and scope of the tests.

Results

Whole-kitchen assessments were conducted at:

- A 120-seat restaurant that serves a wide variety of dishes and is especially known for its extensive

Chef Joel prepared a menu that included fried pickles, French fries, catfish tacos, tempura vegetables, shrimp, and beignets.
dessert menu of pies. **Findings:** Replacing the existing fryers, convection ovens, and griddle with energy-efficient models would save 2,597 therms ($1,346) per year of energy usage. Assuming an operational life of 12 years, the total savings is 31,164 therms and $16,152.

- A full-service caterer. **Findings:** Replacing the existing convection oven, combination oven, and griddle with energy-efficient models would save 668 therms ($349) per year of energy. Assuming an operational life for 12 years, the total savings is 8,016 therms and $4,188.

- Two counter restaurants with menus that focus on hot dogs, burgers, sausages, and French fries. **Findings:** Replacing the existing fryers and griddle with energy-efficient models would save 2,721 therms ($2,535 per year) of energy. Assuming an operational life for 12 years for both appliance types, the total savings is 32,652 therms and $30,420.

Overall, the whole-kitchen assessments showed the potential savings of 109,000 therms and $85,716 over a 12-year appliance lifespan if the standard equipment used in just these four locations were replaced with existing energy efficient options.

In 2017, a fryer comparison demonstration was initiated at a casino. The demonstration will compare three different models from different manufacturers. Three baseline fryers were monitored. After about a month of monitoring, the baseline fryers were replaced with ENERGY STAR equivalents from three different manufacturers.

In 2018, the project focused on conducting a cooking demonstration in Tulsa, OK, where the energy usage for four fryers were compared with each other and with standard gas and electric units. Data collected during the demonstration showed that a CFS facility could achieve significant operational savings by using energy efficient natural gas-fired equipment compared with standard gas-fired and electric fryers. Annual energy cost savings for highest efficient fryer tested was $540 per year when compared with a standard gas fryer and $785 per year when compared with an electric fryer.

The next phase of the project includes initial evaluations of two new demonstration sites. One site is a fryer demonstration within ONG’s territory. The initial set of baseline data was downloaded and analyzed. Researchers and the manufacturer are determining an installation date for the demonstration fryers.

The other long terms sites will be within Naturgy’s territory. A host site has been identified and field test agreement has been signed.

The project team is currently working in identifying potential demonstration sites within the city of Chicago. Discussions with the host utility have identified the type of demonstration they prefer, and the team is exploring several options.

A one-day cooking demonstration for energy-efficient fryers was conducted at the fall 2018 UTD meeting. At the demonstration, a live cooking demonstration was conducted, showing the energy usage for an energy-efficient fryer, a standard gas fryer, and an electric fryer. A live display showed the energy usage of each fryer as food was cooked, and displayed the estimated lifetime energy costs and savings of using an energy-efficient fryer compared to a standard gas and electric fryers. Based on these results, several utilities approached the project team about doing future demonstrations or helping to design a system for use at their facilities.

In 2019, baseline testing of two fryers at separate locations in Tulsa was completed and a fryer was installed for use as a demonstration fryer. Baseline testing for the ovens for the Madrid location was completed and new ovens ordered.

**Status**

A Phase 3 Final Report was issued in October 2018.

The current phase of the project includes evaluations at

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Demonstration of High-Production Fryers

In this project, commercially available high-production fryers are being evaluated in a test kitchen and in operating restaurants to compare their performance to alternative gas and electric models for end users.

Project Description

High-energy-density electric fryer models are capable of delivering more heat in a given amount of frying space than gas fryers on the market. However, today’s advanced gas heat exchanger designs can transfer more heat from a burner in a given frying space than electric models, allowing gas models to better serve end users who need high-production capacity.

To demonstrate current technology, in this project a research team will test and evaluate two high-production fryers at test kitchens, followed by demonstrations at field sites.

Sites within the sponsors’ territories will be chosen to demonstrate the efficiency, cost, and production benefits of commercially available gas fryers.

Benefits / Market Implications

The continued production of high-performance gas-fired fryers will maintain gas fryers as the leading option in commercial kitchens. Generally, gas-fired models will save end users money and reduce emissions (on source-energy basis) versus their electric counterparts. Producing high-production models that cook well and deliver even greater cost savings will further serve end users in the fryer market.

Technical Concept & Approach

Leading high-production gas fryers will be compared to standard electric and gas fryers.

Sites will be sought to show the energy efficiency and performance advantages of high-production fryers and include baseline monitoring of previous fryers to demonstrate the potential cost savings. Sites with both legacy electric and gas fryers will be sought to show the advantage over both electric models and previous older-generation gas models.

Site surveys will not only quantify the energy-savings benefits but also obtain direct feedback from users on the performance advantages of the new systems.

In addition, the fryers will be demonstrated at utility test kitchens.
A Final Report will be prepared detailing the performance in test kitchens and in the field.

Results

The project team is investigating potential test site options for the fryers.

Sponsors are being sought for participation in field demonstrations. Efforts are under way to identify potential sites that currently have an older gas or electric fryers.

In 2018, the research team conducted a field demonstration of a high-production fryer in Oklahoma, with a one-day test demonstration comparing four different fryers. A public document summarizes the energy-efficiency results. The fryer was installed at a field test site and data and results are currently being collected.

Researchers are preparing a list of potential fryers and their specifications for potential participants in the demonstrations.

A high-production fryer was demonstrated in collaboration with the general UTD CFS demonstration project 1.14.B. This high-end gas fryer was compared in a test kitchen one-day evaluation with a low-cost ENERGY STAR gas fryer, a baseline gas fryer, and an additional standard gas fryer the site had on hand (as well as a comparison to an estimated electric fryer). Energy usage was monitored real time with gas and electric meters, while also measuring recovery time with thermocouples in the oil. Results showed that the unit saved 56% energy use while also recovering quicker and cooking the food faster than the baseline gas model. The unit also saved 32% over a low-cost ENERGY STAR gas model.

The project team purchased one of these same fryers for installation at a barbeque restaurant in Tulsa that had already been baselined.

In 2019, the new fryer was delivered and installed in Tulsa. Monitoring is being conducted now at this first field test site.

Status

A second test site was found in Detroit and data-collection equipment is being installed to monitor baseline energy usage of the existing electric fryer.

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Demonstration of Demand-Control Kitchen Ventilation System

The objective for this project was to demonstrate and quantify the benefits of using demand-control kitchen ventilation (DCKV) systems in a commercial food-service kitchen. Researchers also investigated issues with developing a communications protocol and methods for interlinking appliances with a DCKV system.

Project Description

Commercial foodservice (CFS) facilities are required to operate equipment under a ventilation hood that captures particulate emissions and exhaust heat from the kitchen. Standard hoods that operate at a single-fan flow rate are sized to properly exhaust as if all the appliances under the hood were operating at full capacity, which rarely happens. Typically, only a couple of appliances are being used and generally not at full capacity.

Because the ventilation is always on and operating as if the kitchen is a maximum capacity, large volumes of conditioned air are vented from the kitchen and pulled in from other areas in the facility. Also, excess fan power is used.

In response to this issue, demand-control kitchen ventilation (DCKV) systems were developed that adjust the fan speed when the appliances are not operating at full capacity. Fan speeds are adjusted based on data such as temperature or airborne particulates (e.g., grease or smoke). The main issue with DCKV systems is that the current inputs are not necessarily a good measure to adjust the fan speed. The input sensors are located well above the appliances at the entrance of the hood where the appliance emissions are diluted by air from the kitchen. Also, the temperature above an appliance is not a consistent indicator that the appliance is on and the rate it is being operated.

The objective of this project was to install and operate a demand control kitchen ventilation (DCKV) system to determine the operational characteristics and the energy savings of using a variable speed fan. The system tested saved significant energy and airflow during the cook tests. The ventilation rate automatically adjusted for warm up time, cooking loads, idle time, and cool down.

Benefits / Market Implications

A properly designed and optimized demand-control ventilation system saves energy because the fan is capable of running at the exact speed required to properly vent the room instead of only at its highest rated speed. The reduction in the fan usage requires less energy to run the fan and exhausts less already conditioned air that is generally pulled into the dishroom from other parts of the facility such as the kitchen and dining room.

Overall, the DCKV was capable of adjusting its ventilation rate to exhaust heat, moisture and grease without having to operate at full fan power.

The DCKV was measured to exhaust 25.6% less cubic feet compared to a hood that operates only at the maximum ventilation rate of 3,000 cfm. This resulted in 34.6% reduction of exhaust fan power.
Research was conducted to develop test protocols for the project and specifications for the test site. The project team evaluated different data-acquisition methods and equipment for measuring the energy use of the cooking appliances under the hood. It was decided to monitor each appliance under the hood to determine the total energy usage of the cooking equipment instead of just monitoring the energy usage of the entire line.

Researchers designed a remote data-acquisition system for monitoring the ventilation system and the appliances being used, and installed the system in 2018.

The project team completed a series of cook tests to characterize the savings of the demand-control system. Testing included warm up, idling, and cooking tests with different types of food for each appliance.

The system moves into cooking mode when an infrared sensor detects cooking activities under the hood. The exhaust fan speed adjusts the airflow in the hood to a design flow to assure sufficient capture and containment of heat, moisture, and grease. Once cooking is completed, the hood idles down to low flow rate until the heat is dissipated.

Based on a typical restaurant operational profile of 12 hours open with six hours for cooking, five hours of equipment idle time and one hour for cool down, the DCKV is estimated to exhaust 25.6% less total cubic feet compared to hood that operates only at the maximum ventilation rate of 3,000 cfm. The data for the exhaust fan power showed a reduction of 34.6% from the DCKV system, resulting in a yearly savings of about $250 for the site in Alabama based on an energy cost of $0.1111 /kWh. The real savings from a DCKV system is the reduction in air exhausted from the facility that has been space conditioned for cooling or heating. Because this was a test site and not a fully operational kitchen, the kitchen and connected spaces were not being mechanically conditioned.

Status
This project is completed. A Final Report was issued in April 2019.

Technical Concept & Approach
Through this project, researchers demonstrated the benefits of using variable-speed ventilation systems in CFS kitchen. Performance was quantified, including for areas such as energy savings and kitchen comfort.

The project also includes the development of a communications protocol and investigating methods for interlinking appliances with a DCKV system.

The project team designed a system to integrate the operation of a set of typical CFS appliances with a control system for the ventilation system. The project specifically investigated the outputs from the appliances to be used to modulate the fan in the ventilation system and its integration.

A series of tests using the DCKV and appliances was conducted to determine the benefits of the system and what potential control methods could be used to improve performance.

Results
Demonstrations were conducted at a training center near Birmingham, AL, with a specified a hood design based on the cooking equipment planned for the site. The facility is used for various training activities including operation of commercial foodservice equipment by students from the area.

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COMMERCIAL APPLICATIONS

Gas-Fired High-Efficiency Liquid Desiccant Air Conditioning and Humidity Control

A research team is partnering with a chemical manufacturer, two HVAC manufacturers, and others to develop and demonstrate a very-high-efficiency gas-fired liquid-desiccant-based air-conditioning and humidity-control system that uses a novel, non-corrosive, non-toxic desiccant.

Project Description

The goal of this project is to develop a gas-fired liquid-desiccant dedicated outdoor air system (LDDOAS) that addresses many of the critical issues now facing owners and operators of commercial HVAC systems.

The LDDOAS is designed to significantly reduce primary energy consumption, on-peak electrical demand, and water use for air conditioning in commercial buildings. The system can deeply dry a building’s ventilation air without inefficient overcooling or reheating, which will enable advanced HVAC solutions (e.g., chilled beams, displacement ventilation, and other approaches) to essentially eliminate fan power for recirculating air within buildings.

In this project, a research team is partnering with a manufacturer to compare the current state-of-the-art LDDOAS technology to other advanced systems, including a concept involving a sub-atmospherically-regenerated LDDOAS system with internal water recovery and reuse capabilities.

The current Phase 2 involves demonstrating a novel technology in a laboratory to determine its value to potential end users. In Phase 2, the project team will design and experimentally evaluate a breadboard LDDOAS test rig rated at approximately 100 CFM capacity using a novel non-corrosive, non-toxic desiccant initially evaluated and characterized in Phase 1 of the project.

Benefits / Market Implications

New cooling designs that integrate desiccant drying and indirect evaporative cooling in compact cost-effective configurations have the potential to be competitive with electric options in residential and commercial markets.

A successful LDDOAS will enable advanced HVAC systems for commercial buildings to significantly reduce primary energy consumption, on-peak power demand, and water use. For a summer design day, the LDDOAS’ primary energy Coefficient of Performance (COP) is 18% higher than the conventional alternative. This advantage is projected to increase to 30% when averaged over a cooling season. The effective COP for the LDDOAS is estimated to be 2.77 (where the LDDOAS is credited with energy savings for the advanced HVAC systems that it enables). The LDDOAS can eliminate water use for air conditioning in the more humid eastern U.S. The burden that air conditioning now imposes on electric grids can be eased as peak loads drop 75% from 1.01 kW/ton-hour to 0.26 kW/ton-hour of cooling.

Technical Concept & Approach

Desiccant-based dehumidification and air-conditioning systems can employ an open drying cycle wherein a humid gas (generally, air) comes into contact with a desiccant and is dried. The dried air continues to subsequent processes (e.g., sensible cooling), and the desiccant is regenerated by a thermal input. The desiccant...
loading and regenerating is performed in a cycle, allowing for continuous dehumidification.

The two major system types are liquid and solid desiccants. While solid desiccants have a larger established market presence, the liquid-based systems have gained interest in applications for active dehumidification, enhanced evaporative cooling, and indoor air quality. These liquid desiccant systems, also known as open absorption systems, have had limited market presence due in large part to the inefficiency of current regenerating components and difficulties in handling the caustic strong salt desiccant solutions.

Phase 2 will provide an important next step towards developing a commercial product. Successful completion of Phase 2 is expected to lead into follow-on construction and field trials of alpha LDDOAS prototypes. Phase 2 efforts involve:

- Verification of liquid desiccant and equipment performance at rated conditions
- Verification or assessment of system operational reliability, including the ability to respond to transient events, and
- A techno-economic analysis.

Building on the team’s initial experimental experience with uncontrolled supply or scavenger air, the project team will develop and implement an experimental test plan to 1) optimize the LDAC regenerator and conditioner designs, 2) integrate the two into the first recirculating breadboard test rig, and 3) evaluate LDAC breadboard performance over a range of simulated conditions.

The specific objective of Phase 2 is to prove the LDDOAS’ system operation in the laboratory and determine its value to potential end users. In Phase 2, the project team will design and experimentally evaluate a breadboard LDDOAS test rig rated at approximately 100 CFM capacity (approximately 1/10th scale for small RTUs) using the novel non-corrosive, non-toxic desiccant initially evaluated and characterized in Phase 1. Researchers will partner with NYSERDA, a chemical manufacturer, and two HVAC industry partners in Phase 2.

Phase 2 will provide an important next-step towards developing a commercial product to maintain healthy and comfortable indoor environments while conserving energy and water. The LDDOAS can dramatically reduce primary energy consumption, on-peak electrical demand, and water use for air conditioning commercial buildings. The LDDOAS can deep dry a building’s ventilation air without inefficient overcooling or reheating, enabling advanced HVAC systems (including chilled beams, displacement ventilation, and other approaches) to essentially eliminating fan power for recirculating air within buildings.

Results
In Phase 1 of this project:

- An experimental gas-fired liquid-desiccant air-conditioning (LDAC) system was constructed from inexpensive materials.
- A fluid was demonstrated to operate as a desiccant over a useful range of process air dew points (for space conditioning) and could be regenerated at low temperatures (<200°F).
- The absorption/regeneration tower operated as designed (~0.5-2 lb/hr moisture movement at 50 cfm).
- During regeneration, with heated liquid and cool regeneration air, 50% of the enthalpy rise in the air was latent. This result is within the expected order of magnitude.
- No desiccant/mist breakthrough was observed in the present study, although the liquid flow rate was lower than the design flow rate.

In 2018, the project team also executed an agreement with NYSERDA for initial testing and upgrade of a breadboard test rig. Phase 2 of this UTD project is providing cofunding to this agreement with NYSERDA.

Status
A Phase 1 Final Report was issued in November 2018. Upgrades are being made to one-tower test rig, including incorporation of dew point hygrometers.

Activities in the current phase will focus on optimizing the design and operation of the single-tower experiment. Parametric analysis will be conducted with respect to regeneration operating conditions to map out the performance of the tower in continuous regeneration mode, in order to calibrate a theoretical model for the system to be used to design a dedicated absorption tower. Integrated system (dehumidification and regeneration) testing will be used to scale the results to a practical-sized system for the techno-economic analysis.

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In this project, researchers gathered information about the decision-making process used by chain restaurants when choosing gas vs. electricity for cooking, water heating, and space conditioning.

Project Description

Chain restaurants currently represent about 50% of the commercial foodservice (CFS) industry in North America. While the natural gas industry has actively developed and tested new CFS technologies, a stumbling block has been in obtaining information from chain accounts on how decisions are made as to buying a certain brand of equipment or which energy source (gas vs. electric) equipment to use.

Research in the past showed that, in some cases, electric equipment was chosen over gas for reasons the chain accounts were unwilling to share or based mostly on previous purchases or misinformation about the performance and/or maintenance of gas equipment. Some influences on the decision process have been uncovered, such as: operation costs, cooking characteristics, rebate availability, tradition, corporate recommendations, and reliability. However, the information and parameters that form a definite decision-making process have not been established and makes determining how best to focus CFS research dollars a significant challenge.

In response, in this project researchers surveyed chain restaurants to gather more detailed information about the decision-making process of using gas vs. electricity for cooking, water heating, and space conditioning; and information about the usage of energy and water in commercial foodservice facilities in North America.

Two reports and one presentation were generated that completed an analysis of the cost of gas vs. electric cooking equipment based on the questions of two chain accounts. One was a national account and the other a regional franchisee for a national account. Both analyses showed that efficient, gas-fired fryers and griddles would save significant energy and money over the life of the appliances based on current energy costs.

Benefits / Market Implications

Restaurant industry appliance sales in the U.S. were about $800 billion in 2017. The majority of restaurant appliances used to service these customers use natural gas as the fuel source. However, lack of information or misinformation about the performance of gas-fired
compared with electric units resulted in many locations deciding to purchase electric equipment. In some cases, the advantages of the electric equipment justify its use, but, in most cases, gas-fired equipment would still have the advantage in terms of cooking performance and energy costs.

This project assists CFS end users, equipment manufacturers and researchers by providing information on how chain accounts make the decision on which type of equipment they purchase and the energy source used.

**Technical Concept & Approach**

In this project, research team representatives engaged with national accounts in CFS through participation in industry organizations such as the North American Foodservice Equipment Manufacturers (NAFEM), ASTM International, and the Energy Solution Center Gas Foodservice Equipment Network (ESC/GFEN) to gather information.

Project representatives approached both corporate and franchise accounts in North America. Interaction with chain accounts began with conversations at industry-related events such as the National Restaurant Show, the NAFEM technical committee meeting, and ESC national accounts meetings. The project team followed up with emails and phone conversations.

The project team also surveyed existing equipment manufacturers to identified potential energy- and water-saving opportunities to further discuss with gas utilities and the CFS industry.

**Results**

In 2017, researchers assisted a project sponsor with gathering information about the potential savings of gas vs. electric equipment for a major fast-food chain. The results were presented at a 2017 ESC Technology & Market Assessment Forum (TMAF).

For a second sponsor for the same chain account (but for a regional franchise), the project team completed an analysis of the energy and financial savings of using gas-fired fryers and griddles compared with electric. The analysis was conducted based on the preferred equipment of the chain account.

Based on these discussions, it was determined that chain accounts are much more likely than smaller chains or individually-owned restaurants to consider paying extra initial cost for equipment to achieve lifetime savings due to energy efficiency. In order to address the concerns of the smaller chains and individually owned restaurants, more information was added to a CFS Tools and Calculators webpage at:

http://cfscalc.gastechnology.org

One perception identified was that maintenance issues and costs were more common and costly for gas-fired equipment. To address this issue, the project team referenced a White Paper by Bradley E. Pierce entitled *Cost of Gas vs. Electric Commercial Kitchen Equipment Maintenance White Paper*. The paper states, “A common perception has existed in which operators feel that gas commercial kitchen equipment costs more to maintain and repair than electric equipment. This is an outdated premise that is no longer valid due to a variety of technical changes in the manufacturing of equipment. Pricing of parts, technical labor, equipment engineering, and a real-world look at gas equipment maintenance requirements confirm this premise.”

During the project, chain accounts were reluctant to share information about their decision-making process but expressed interest in getting more information. Specifically, two accounts approached the project team for assistance with gathering information about the cost of gas vs. electric equipment for their specific application.

**Status**

This project was completed in 2018. A Final Report was issued in September 2018.

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Commercial Foodservice Codes and Standards

This project helps address current and developing codes and standards for gas-fired commercial foodservice (CFS) equipment. The project team serves as a voice for natural gas ratepayers and provides key information associated with gas-fired CFS equipment to relevant codes and standards organizations.

Project Description

Compared to other commercial gas-fired products, commercial foodservice equipment has fewer regulations, codes, and standards for efficiency, emissions, and other operational features. However, with the push for more efficient technology and lower emissions (especially in California), newer codes and standards are being developed and implemented by organizations such as ASHRAE, ASTM, and air-quality management districts in different areas of North America.

Current or potential codes and standards of special interest to the gas industry include:

- NOx emission standards being proposed in southern California
- Venting requirements for electric and gas appliances
- Efficiency standards for dishwashing machines
- Venting and operational requirements for countertop fryers, and
- Maintenance costs of gas vs. electric appliances.

The objective of this project is to help address issues and provide information associated with codes and standards for gas-fired, commercial foodservice (CFS) equipment. The goal is to help to ensure a fair and equitable analysis of all fuels for ratepayers and that the gas industry is adequately informed about potential codes and standards in a timely manner to prepare and present information that could help inform the basis of new rules.

Benefits / Market Implications

Restaurant industry equipment sales in the U.S. are estimated at $863 billion for 2019. The majority of the appliances use natural gas as the fuel source. However, concerns with new codes and standards and misinformation about the performance of gas-fired units compared with electric units have resulted in many locations deciding to purchase electric equipment. In some cases, the advantages of the electric equipment justify its use; however, in most cases gas-fired equipment would still have the advantage in terms of cooking performance and energy costs and impacts.

This project assists the CFS industry by addressing issues or concerns with gas-fired equipment during the process of establishing codes and standards through direct interaction with the gas industry and customers, published articles and presentations at CFS industry events, and membership/participation at codes and standards organizational meetings.

Technical Concept & Approach

A research team is identifying issues and concerns associated with existing or potential new codes and standards relevant to CFS in North America. The team serves as a voice for gas consumers at codes and standards meetings for ASTM, ASHRAE, the North American Association of Food Equipment Manufacturers (NAFEM), and other organizations.

The project team provides monthly reports detailing the issues and actions conducted under this project and the responses or results from issues associated with codes and standards within CFS.
Results

The project team is actively interacting with the gas industry and the CFS industry to address issues with new regulations on NO\textsubscript{x} emissions of CFS appliances in southern California. Of specific interest are new NO\textsubscript{x} emissions regulations being proposed by California’s Southcoast Air Quality Management District (SCAQMD).

The project team is assisting with a SCAQMD-funded project to quantify the existing NO\textsubscript{x} emissions of several categories and types of CFS equipment. A Technical Advisory Group was formed to review emission test protocols and NO\textsubscript{x} emission data on select gas-fired commercial cooking equipment. Project team representatives evaluated some of the data and made suggestions on changing the data-collection methods to improve accuracy.

During Phase 1, the project team identified at least nine major issues and concerns associated with existing or potential new codes and standards relevant to CFS. In the current Phase 2 of the project, researchers continue to serve as representatives on industry committees investigating NO\textsubscript{x} emissions. As part of this project, team representatives attended and participated in codes and standards meetings at ASHRAE, ASTM, NAFEM, and SCAQMD. A detailed review of current issues was provided to project sponsors.

Team members met with engineers at a sponsoring utility to discuss results for the NO\textsubscript{x} testing of available CFS equipment, including fryers, ovens, and griddles. These tests will be used to develop protocols and procedures for NO\textsubscript{x} testing of CFS equipment and the data will be used to help establish new NO\textsubscript{x} emissions regulations.

A project member remains an active participant in ongoing discussions about ENERGY STAR products spearheaded by NAFEM. Of interest to gas consumers are proposed changes to ENERGY STAR testing that would make it increasingly difficult for CFS manufacturers to obtain an ENERGY STAR listing.

In 2018, the project team and CFS manufacturers made efforts to determine NO\textsubscript{x} emissions and what changes will be needed to comply to new NO\textsubscript{x} emissions standards, including completing onsite emissions measurements at two locations. Researchers discussed with several CFS manufacturers issues with their current emission analyzers and which analyzers to consider buying in the future to include the ability to measure NO\textsubscript{x} emissions. In May, project representative attended the ASTM F26 codes and standard meetings for CFS.

In October, the project team provided a webinar for GFEN (Gas Foodservice Equipment Network) on combustion technologies in CFS and the impact pending NO\textsubscript{x} emissions will have of the industry. The purpose of the webinar was to educate and inform members of the gas CFS industry of the different types and designs of combustion technologies. Topics included cooking performance, cost, efficiency, and emissions of different technologies and burner designs.

In 2019, results from a SCAQMD-funded project to test existing CFS equipment and develop protocols for NO\textsubscript{x} testing were submitted. A new NO\textsubscript{x} emissions regulation is expected sometime soon.

The project team is contributing to consensus revisions to some ASTM standards, to address issues with changes in natural gas heat content that have certification testing results.

Status

The project team continues to monitor NO\textsubscript{x} regulations from SCAQMD and participate in relevant industry events.

The project team is addressing information released to the public by others that implies or directly states that the use of natural gas as an energy source for cooking creates harmful or dangerous emissions in a residential environment. While some of the claims hold some scientific value and are backed up with credible data, other aspects are misleading, incorrect, or imply an advantage of electric over gas that does not exist. The main issue is the implication that gas cooking is solely responsible with producing large number of ultrafine particles, when ultrafine particles are produced during the cooking process regardless of the energy source, gas or electric.

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Commercial Gas-Fired Heat Pump Water Heater

This project is developing an economical, high-efficiency gas heat pump to serve commercial water-heating applications and end users. Researchers are leveraging recent residential gas heat technology developments, optimizing controls and components, and beginning field trials.

Project Description

While the commercial water-heating market is smaller in volume than the residential market, it is no less competitive for high-efficiency gas technologies, whose product prices are often 15 times that of common residential products. The market drivers are the same: federal requirements, ENERGY STAR ratings, and the test method for rating equipment.

Historically, a key advantage to end users of gas water heating over electric water heating in the U.S. was operating cost savings. With a typical restaurant consuming 30 times the hot water of an average single-family home, the operating cost savings of natural-gas versus electric-resistance heating is readily understood by business owners and property management companies. However, with the advent of electric heat pump water heaters – with operating efficiencies two to three times that of the resistance-heating products, federal/utility incentives, and the option for integration with grid-interactive thermal storage programs – electric products have increased in popularity. New gas-fired heat pump water heaters (GHPWHs) would provide commercial customers the option of even higher efficiencies and lower emissions on a source energy basis.

This project involves the development of a commercial GHPWH and field evaluations at small commercial facilities.

Benefits / Market Implications

The motivation in developing a GHPWH is efficiency-driven. When delivered to the market, the GHPWH will be a cost-effective technology with a primary energy efficiency of greater than 100%. The efficiency gains are substantial – with Energy Factors of 1.5 or greater (88% to 140% greater than condensing and non-condensing water heaters, respectively). Continued regulatory pressure and incentives for high-efficiency water heating help this new gas-fired product be an attractive new option for end users.

Technical Concept & Approach

This effort involves the preparation for a commercial water-heating application of the gas heat pump, focusing on commercial hot-water and pool-heating applications. Field evaluations of the technology are part of this project. Specific tasks are:

- Development of a System Design Model
  The project team is developing a sizing and system design tool that will consider peak/average load patterns, installation cost, North American regional climate, local utility costs, and other factors.

- Design of Commercial-Grade GHPWH Controls
  The team is developing and test modifications to the gas heat pump controls to better facilitate operation as part of a commercial GHPWH system.
Unlike residential water heating, where the vast majority of the products are sized for stand-alone service, commercial water-heating installations have a wide range of installation sizes, often requiring multiple products installed in parallel or for higher-temperature “boost” installations in a series. The challenge for a heat-pump water-heating installation (electric or gas) is the baseline/peaking relationship of the heat pump to the backup/boost conventional heating. As a result, system installations are often site-specific and require prior knowledge of peak loads and load shapes. The sizing of heat pump/conventional components and their arrangement (e.g., parallel, series, include “free” cooling) makes for a large design space.

“Southern California Gas Company supports the development and commercialization of new high-efficiency products like the GHP. This technology can help to address regulatory mandates that require reduction of criteria pollutants and greenhouse gases and meet future zero-net-energy goals.”

- Steve Simons
  Senior Project Manager, Technology Development (retired)
  Southern California Gas Company

Results

The project team will be conducting a field evaluation. Plans in 2019 included:

- **Site Selection:** The team performed an extensive site-selection survey, inspected, and finalized a field-test agreement with a six-unit multifamily building in Evanston, IL. The team gained access to the site’s utility data and performed a preliminary assessment of space heating and domestic hot water (DHW) energy consumption.

- **System Design and Site Planning:** The project team held several design meetings, primarily concerning sizing of retrofit equipment and hydronic design. Researchers determined that the existing 462MBH input boiler is oversized and that the retrofitted 140MBH output GAHP unit will not be undersized including DHW output. Nonetheless, the team will be installing replacement condensing boilers as part of the package. The team arrived at a hydronic design that permits maximum flexibility while limiting disturbance to the site upon removal of the GAHP system.

- **Field Test Plan:** With the draft Field Test Plan complete, the project team received data-collection packages for factory recalibration. A manufacturing project partner will be providing substantial equipment to this effort, including two condensing boilers, indirect tanks, circulation pumps, and heat exchangers.

- **Prototype GHP Installation and Commissioning:** Installation of this prototype for testing is planned for 2019. The site has a heating load such that the GAHP will supply 20% to 50% of the peak load, sizing the GAHP as a nominal 140kBtu/hr unit. Baseline monitoring began in 2018.

Status

Field testing is ongoing.

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Researchers are evaluating the field performance and economics of the Yanmar three-pipe gas heat pump (GHP), the first to provide simultaneous heating and cooling. The ultimate goal is to expand the market for high-efficiency GHPs for commercial building owners and operators.

Project Description

Gas-engine-driven heat pumps (GHPs) combine high-efficiency heating and cooling to significantly reduce peak electric demand and electricity use with potential savings in operating and lifecycle costs as compared to electric heat pumps or conventional HVAC equipment.

In 2016, Yanmar America Corp. Energy Systems introduced a 14-ton GHP with a three-pipe heat-recovery variable refrigerant flow (VRF) system, the first GHP in the U.S. market with the capability to provide simultaneous heating and cooling. This option improves the response to building loads by recovering heat from zones in cooling mode (e.g., internal loads) and redistributing it to meet heating loads in perimeter zones.

This technology provides a unique energy-efficient option, and opens up new markets, where in the past electric systems were the only options for simultaneous heating and cooling.

As an emerging technology, GHPs face economic and market barriers, including high installed costs, which potentially can be offset by savings in operating costs. Performing additional maintenance and establishing service networks are other potential barriers for this technology. Compared to electric motors, GHPs require additional engine maintenance for reliable performance. In addition, engine emissions pose another barrier for some markets. While natural gas is a very clean-burning fuel for engines, the primary environmental concern is NOx emissions.

GHPs have a significant share of Japanese and European space-conditioning markets, but are relatively new to the U.S. market. The Yanmar product line includes VRF systems from 8 to 14 tons. The 14-ton unit is the only available three-pipe GHP offered in the U.S.

For this project, researchers are expanding on previous developments with GHPs in laboratory and field demonstrations to evaluate the field performance and economics of the Yanmar three-pipe GHP.

Benefits / Market Implications

Historically low gas rates are a key driver for the adoption of GHPs to reduce operating costs in areas with high electric rates and demand charges. These operating-cost reductions include not only energy costs but also water costs associated with electric chiller, which can be significant in hot, dry regions such as the southwestern U.S.

Peak electrical demand has been growing in the commercial sector, mainly due to the high cooling requirements of commercial buildings. GHPs offer a cost-effective and environmentally-friendly option to reduce peak electricity demand.

In addition, the increasing number of standards based on source energy (or full-fuel-cycle) is another driver for GHPs, which can potentially reduce both source energy use and carbon emissions compared to conventional heating and cooling equipment. Use of GHPs can qualify for up to 32 LEED (Leadership in Energy and Environmental Design) points in the U.S. Green Building Council’s rating system.
Technical Concept & Approach

For this project, researchers are evaluating the performance and economics of an installed Yanmar three-pipe GHP at a field site. This demonstration will be one of the first monitored installations of the three-pipe GHP system.

Specific tasks include:

- **Site Selection and Field Test Plan**
  
  This task involves the specification and procurement of instrumentation and a data-acquisition system.

- **Site Monitoring and Data Analysis**
  
  The demonstration site will be monitored for a minimum of one year. Performance data will be uploaded via a cell phone and analyzed to determine monthly energy use. Using measured data, researchers will determine seasonal efficiency and economics based on natural gas consumption, electricity use, and electric demand. A Final Report and Case Study document will describe benefits of the technology along with recommendations.

- **Optional Laboratory Testing**
  
  The third task consists of an optional laboratory evaluation. Researchers would conduct laboratory evaluation of the Yanmar two-pipe or three-pipe GHP using an existing VRF test stand to determine performance curves relative to ambient temperatures and part load.

  This task would provide a “preview” of key performance data within a shorter timeframe to impact near-term decision making.

Results

For the demonstration, the project team selected the Lawrenceville Public Works (LPW) facility in Georgia in the service territory of the Municipal Gas Authority of Georgia (MGAG). In 2016, the MGAG launched a 24-month GHP incentive program. The program offers incentives to municipal buildings and supports Yanmar GHP systems.

One of the five GHP VRF systems at LPW was selected to be studied in the demonstration. This unit has ducted fan coils which allow for more accurate measurement of supply and return air temperatures to calculate the heating and cooling delivered.

The GHP outdoor unit and corresponding fan coils were instrumented to monitor energy use and performance. Data was collected for a full heating and cooling season to determine performance across the range of ambient conditions and to estimate annual energy savings.

GHP heating performance was monitored from November 2018 to March 2019. GHP cumulative heating efficiency was 1.2 COPg at mild ambient temperatures (20°F to 70°F). The GHP maintained heating efficiency (COP>1) at part loads as low as 20% rated heating capacity. This GHP system switched over to predominantly cooling operation on March 13th.

The GHP VRF ran in simultaneous heating and cooling mode for only 50 hours during the period monitored (weekends excluded), compared to 250 hours in heating or cooling mode. Simultaneous operation had minimal impact on system efficiency.

Heating preliminary results were presented at a North American Emerging Technology Program meeting in April 2019.

Status

Researchers continue to monitor the Yanmar 3-pipe GHP cooling performance.

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Project Description

Electric warewashers currently dominate the commercial dishwasher market. In addition, a large percentage of consumers choose chemical low-temperature warewashers over high-temperature warewashers, which further reduces the heating load, but causes additional cost and environmental impact from increased chemical use.

With gas-fired equipment, the potential cost savings over basic electric elements is very large. Also, high-temperature gas-fired machines can produce cleaner dishes with no chemical etching compared to chemical machines. And while all warewashers must be installed under a steam hood, gas warewashers can be easily vented into the hood.

This project developed a cost, efficiency, and environmental analysis of gas warewashers to enhance understanding of the opportunity for energy-efficiency savings and environmental benefits.

Benefits / Market Implications

A reliable gas warewasher would provide large savings to commercial foodservice facilities and reduce both source energy use and environmental impacts of chemical use.

Warewashing equipment is a significant part of commercial foodservice equipment loads, with global equipment capital costs estimated to be approximately $4 billion a year. A recent demonstration of a gas conveyor warewasher showed that the technology could significantly reduce the carbon footprint of a restaurant while saving the restaurant more than 60% than if using electricity.

Technical Concept & Approach

This project developed a lifecycle cost analysis and energy and environmental impact of gas versus electric and chemical warewashers, which will be shared with industry contacts to promote gas warewasher development, sales, and marketing.
Results

With the help of a utility that had information from various demonstrations, researchers completed the life-cycle cost analysis model.

The three warewasher types modeled, as well as the varied scenarios within each, showed a wide range in total annual operating and maintenance costs – as low as about $7,900 for door-type, high-temperature gas-fired warewashers with heat recovery up to nearly $37,500 for the current base case of flight-type warewashers. The largest savings potential on a per-unit basis is for energy-intensive flight-type warewashers. However, rack conveyor and door-type units also have the potential to reduce annual costs by at least 30%. Since door-type and rack conveyor warewashers represent significant portions of the total warewasher population, 26.5% and 16.9% respectively, the overall energy and cost savings they could provide are substantial.

For all cases, the gas-fired version was the lowest operating cost for a commercial foodservice site. With flight-type, the gas unit would save almost $9,000 per year in operating cost compared to the most efficient heat-recovery warewasher on the market. A gas-fired version of this unit would be expected to cost less than $1,000 more than an electric unit and payback in less than two months. A gas conveyor type would save more than $5,100 per year in operating costs over an efficient electric unit and pay back in months as well. Even the lower use door-type unit would save over $1,100 per year and payback in less than a year.

The annual savings of gas-fired units compared to standard baseline electric, efficient heat-recovery electric, and low-temperature chemical warewashers save up to $26,000 per year for flight type warewashers and up to $3,000 per year for lower use door type warewashers. New technological developments could yield energy savings up to 50% in rack conveyor warewashers.

Results of this analysis were used to support discussions with manufacturers at the North American Association of Food Equipment Manufacturers conference in February 2019. As a result, discussions with a major manufacturer to advance the development of a gas-fired warewasher are ongoing.

Status

A Final Report on this project was issued in June 2019.
Researchers are developing an advanced nozzle burner for commercial water heaters with improved efficiency, turndown, emissions, stability, and compactness. The goal is to demonstrate a high-efficiency, ultra-low emissions burner for water-heater manufacturers to commercialize.

Project Description

Current commercial water-heater burner designs are not able to achieve all the technology targets of ultra-low emissions, high efficiency, good turndown, and reduced first costs and payback periods. Then often have retrofitability limitations and are not scalable.

The advanced nozzle burner being addressed in this project originate in UTD project 2.15.D and has the ability to overcome some of the key challenges and be an enabling technology for gas-driven commercial and residential water heaters. This new project will demonstrate the advanced nozzle technology in a water heater for manufacturers to review, evaluate, and commercialize.

Key performance indicators and goals to measure the success of this project will be:

- Improve efficiency by 2%-4% for the same emissions
- NO<sub>x</sub> emission of <5 ppm and CO emissions of < 20 ppm corrected to 3% O<sub>2</sub>, and
- Achieve turndown of 10:1.

Benefits / Market Implications

Forty-four percent of the 225,000 commercial water heater units sold annually are gas driven, with associated positive impacts on source energy efficiency. Similarly, data shows that 55% of commercial buildings heat water with electricity while 42% heat with natural gas. Low-cost, low-emission, compact commercial gas-driven burners could significantly reduce source energy use.

The technology to be advanced in this project can substantially reduce energy consumption in commercial buildings. Of the 40 quads used by U.S. buildings, 9% is utilized by the water heaters. An average 3% improvement in efficiency will lead to at least 0.12 quads of annual energy savings.

Other benefits of the advanced nozzle burner technology are expected to be:

- Scalable to multiple designs and capacities
- Significant reduction in NO<sub>x</sub> emissions >75%, turndown of 10:1 with CO emissions of < 20 ppm
- Simple, robust, and potential for reduced first costs
- Installer and manufacturer focused
- Reduced weight and size of the water heater, hence cost savings and ease of installation in tighter locations
- Improved manufacturing ease and significantly reduced time to market
- Increased customer growth (e.g., fuel switching)
- Reduced noise, hence more comfort, and
- Capable of integrating smart controls for smart-building applications.
Technical Concept & Approach

In this project, researchers will 3D print and test the advanced nozzle burner design in a commercial water heater.

Specific tasks include:

- **Baseline test of conventional burner in a commercial water heater**

  The project team will evaluate the baseline existing burner and review the performance and operability benefits and challenges to compare and improve the current advanced nozzle burner. Researchers will investigate ignition characteristics, turndown, and emissions at certain oxygen concentrations and firing rates for data comparison.

- **Adapt and install the advanced nozzle burner in the commercial water heater**

  The project team will design the burner to be adapted to the commercial water heater. The dimensions will be matched to have a drop-in design to replace the current burner. The advanced nozzle will be installed within the water heater. Researchers will build components that will help to assemble the burner within the water-heater chamber. Also, design of the igniter, fuel and air flows, and other duct work to the burner will be performed. Modifications to the water heater for measuring emissions, oxygen concentration, and temperature at a certain location will be performed. Shakedown testing of the air and fuel flows and ignition device will be conducted prior to firing up the burner to ensure smooth and safe operation. Pressure drop, firing rates, emissions, and temperature recording will be performed.

- **Evaluate ignition, emissions, stability, and turndown**

  Researchers will test the advanced 3D burner to evaluate its performance for various key parameters, including efficiency, emissions, turndown, and reliable and smooth ignition. After performing shakedown testing of the burner, multiple ignition tests will be performed to ensure that the burner ignites reliably and at variable firing rates. This will determine the reliability and repeatability of the ignition process, even though the water heater usually operates at a constant firing rate. This will provide greater confidence in the ignition process.

  After successful ignition testing, performance testing will be performed. The burner will be started at a certain (lower) firing rate and then gradually ramped up to a higher firing rate. This will help determine the operability and turndown characteristics of the advanced nozzle burner. The testing will be performed for different firing rates and different air/fuel ratios to evaluate the emissions and efficiency characteristics. The firing rate will be varied to ensure operability and oxygen concentrations will be varied for evaluating emissions and efficiency performance.

- **Implement prototype improvements**

  During testing of the burner, design changes will be made. Researchers will perform design review and analysis to address operability and performance concerns, and modify and adapt the design for desired improvements.

Results

In 2018, technicians completed installation of the conventional burner in the commercial water heater, added instrumentation to measure key parameters, and reviewed the factory settings to conduct performance testing. Preliminary shakedown testing to ensure the water heater and burner operates well has been performed. In addition, the researcher team initiated a review of the design modifications required to install the advanced nozzle burner in the commercial water heater.

Testing of the baseline burner at different firing rates and oxygen percentages was performed and data recorded for emissions, pressure drop, and performance for comparison with the 3D-printed burner.

Researchers evaluated ignition characteristics with the advanced burner and made modifications.

The flame sensor was modified to ensure that the flame was detected.

Status

Assembly and installation parts for the 3D-printed burner were fabricated and performance testing is being conducted. Evaluation of emissions, turndown, and overall stability of the burner are also being conducted.

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Gas Heat Pump RTU Cold-Climate Performance Assessment

The objective of this project is to demonstrate and analyze the installed performance of a gas-engine-driven heat pump incorporated in a packaged rooftop unit design to determine its cold-climate performance, reductions in peak electric and peak gas demand, and environmental benefits.

Project Description

Gas heat pumps (GHPs) use a natural gas internal combustion engine in place of the electric motor to drive refrigerant compressors. Two high-efficiency scroll compressors are used to evaporate and condense R410A refrigerant, transferring the heat from one space to another.

GHPs provide high-efficiency heating and cooling (COP>1) using natural gas with minimal electricity use. Preliminary modeling indicates that GHPs can reduce peak electric demand by 6 kW to 15 kW, compared to conventional rooftop units (RTUs) or electric variable refrigerant flow (VRF) systems, respectively.

GHPs are an important gas cooling option for the small-commercial market when considering electric demand reduction initiatives.

GHP RTUs can also reduce peak gas demand. GHPs have high heating efficiency due to the use of engine heat recovery to boost performance during the winter. This increased heating efficiency will reduce peak gas demand, generate energy savings, and reduce full-fuel-cycle greenhouse gas (GHG) emissions when compared to a baseline standard-efficiency packaged RTU. The extent of this peak gas demand reduction and overall efficiency gain will be analyzed in this project.

Compared to electric-driven heat pumps, GHPs have two key advantages in heating operation for cold climates. GHPs use engine heat recovery to: 1) avoid a defrosting cycle and 2) maintain heating capacity and supply temperatures. Electric heat pumps require periodic defrosting at ambient temperatures below 40°F. Conventional defrosting by reverse cycling has an inherent energy penalty because it removes heat from the indoor air during the defrosting period. GHPs avoid the need for a defrosting cycle by controlling the flow of the recovered waste heat from the engine and maximizing the heat-recovery process.

A second concern is reduced supply temperatures, resulting in the “cold blow” effect (delivery of air at less than body temperature) that compromises indoor thermal comfort. GHPs use engine heat recovery to supplement heating output in order to maintain both indoor supply temperatures and heating capacity. In cooling and mod-
Technical Concept & Approach

The following tasks will be performed:

- **Site Selection and Baseline Monitoring**
  
  The ideal site will be a commercial or institutional application with consistent space-conditioning loads for the maximum energy savings and economic return. Examples for this market include health clubs, nursing homes, school gymnasiums, hospitals, retail buildings, and restaurants.

- **GHP-RTU Installation and Demonstration Plan**

  The project team will develop the demonstration plan for the selected site, then specify, install, and commission the instrumentation and data acquisition system (DAS) for the GHP-RTU.

- **GHP-RTU Performance Monitoring**

  Researchers will monitor the performance of the new GHP-RTU for a full heating and cooling season to determine annual energy use and costs across the full range of possible operating conditions. The DAS system will sample data every second and record one-minute interval totals/averages for each measurement.

- **Data Analysis**

  The project team will analyze measured data to determine energy savings, reduction in peak electric demand, GHG emission reductions, and energy cost savings relative to baseline. Researchers will also estimate paybacks, life-cycle cost savings, and cost/benefit ratios based on current costs and projected mature market pricing.

Results / Status

The project team is reviewing potential demonstration sites and developing the terms of the field-test agreement. The demonstration will be conducted along with several NYSERDA demonstrations of the GHP VRF systems in New York City. Per NYSERDA’s direction, these demonstrations will be conducted in stages to ensure performance.

Benefits / Market Implications

GHP-RTUs are expected to provide environmental, economic, and resiliency benefits for commercial buildings and ratepayers.

Environmental benefits include the reduction of source energy and full-fuel-cycle GHG emissions through high-efficiency operation compared to conventional HVAC equipment.

The reduction of peak electric demand offered by GHPs also provides regional utility benefits and may provide opportunities to retire one or more power-generation plants with higher GHG emissions, such as coal-fired plants. Thus, cumulative reductions in peak electric demand can ultimately lead to a cleaner baseload electricity generation mix.

Economic benefits for the customer include life-cycle cost savings due to reduction in time-of-use rates or electric demand charges. Due to historically low natural gas prices, this technology can significantly reduce energy costs, especially in areas with high electric demand charges. Lower peak electric demand can also eliminates costly electric upgrades for building additions or sites that might be electrically constrained.

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High-Efficiency Thermo-Vacuum Commercial Clothes Dryer

The goals of this project are to develop and demonstrate an advanced concept for a natural-gas-fired commercial clothes dryer. The technology has the potential to save at least 50% of the energy used in the commercial clothes drying sector.

Project Description

The most popular clothes-drying method is a combination of electricity-driven centrifuge with consequent residual moisture evaporation by heated air. Conventional methods of drying require a substantial amount of heat approximately equal to heat of evaporation of water that amounts up to 20% of wet laundry mass. The highly energy-intensive process mostly relies on electrical heating in residential and commercial segments. Due to the irrevocable loss of heat and moisture – along with power spent for fan operation – even under ideal conditions the efficiency of the drying process is very low.

Preliminary research suggests that the integration of mechanical centrifuge and a thermal-driven ejector vacuum system can provide significant performance enhancement along with substantial fuel savings and reduction in water consumption.

The objective of this project is to develop the advanced clothes dryer concept and demonstrate the technical and economic benefits of the technology.

Benefits / Market Implications

The most energy-intensive part of the laundry process is water heating and drying. Due to improved efficiency, the technology being developed in this project is expected to have the potential to save at least 50% of energy used in the commercial clothes drying sector.

Preliminary estimated benefits of the clothes-drying concept under development are:

- Higher Combined Energy Factor (CEF): 5-6 (estimated) versus 3-4 (ENERGY STAR, conventional)
- $10K-20K annual savings (payback period under two years), and
- At least 20% reduction in water consumption.

Combining all the factors, the technology could result in at least 250 TBtu cumulative of energy savings by 2030.

Technical Concept & Approach

The thermo-vacuum drying method allows for the intensification of the drying process by reducing operating pressure and temperature in order to remove moisture faster than conventional methods of drying.

The operation relies on the heat produced by the gas-fired boiler circulating mostly in a closed cycle between the vacuum ejector and the rotary drum. This leads to continuous heat recuperation which makes the process highly energy efficient. The technology produces a dynamic vacuum using the heat energy, which is subsequently used for increasing the temperature in the enclosure and then for heat-recovery processes for water or space heating.

The novelty of the technology consists in improved heat-energy use (initially for laundry drying purposes and then for heat recovery) and the application of ejector technology (for continuous heat recuperation). Both factors result in significant energy and water savings. The technology evaluated in this project leverages past knowledge in vacuum drying, but differs from it by using the waste heat produced by gas combustion to drive the ejector-based vacuum system in order to simultaneously provide heat and sustain dynamic vacuum.
This technology should not require replacing the laundry equipment completely; it can be used to upgrade existing dryers to a new technology level. In addition, this technology will allow combining washing and drying processes into one unit in new installations. This will simplify the system design, reduce the cost of the drying process, and reduce the operation footprint.

The project includes a technical and economic feasibility study to assess the performance of the system, followed by bench-scale experimentation under controlled environmental and operating conditions. A bench-scale rig was designed for the experimental validation and performance evaluation of individual system components.

Researchers performed a commercial market review along with a preliminary cost/benefit analysis and estimation of a simple payback period.

This project is a joint effort involving Gas Technology Institute (GTI), Wilson Engineering Technologies (WET), and Oak Ridge National Laboratory (ORNL).

**Results**

A numerical simulation and energy balance analysis of the concept was performed; results of the analysis helped refine the advanced concept refinement. A bench-scale system was then constructed by modifying a commercially available residential clothes dryer with integrated heat exchanger and steam-driven ejector.

Baseline testing was completed with encouraging results. With raising the steam pressure, the ejector efficiency goes down as the raising potential of pressure reduction in the drying volume. That indicates a possibility of either reduced drying time or increased throughput.

In 2018, component-level experimentation was completed.

A joint GTI/WET/ORNL proposal for the commercial laundry energy-water assessment and advanced clothes dryer prototype was awarded by the U.S. Department of Energy.

**Status**

The feasibility study and bench-scale components evaluation (Phase 1) are completed, and the UTD Phase 1 was completed in June 2019. Research ongoing in 2019 under DOE/UTD support will include the design, engineering, and pilot-scale experimentation bench-scale system experimentation for the components performance evaluation and preliminary characterization of the integrated laundry concept.

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Researchers are evaluating a novel sheet metal surface combustion burner through laboratory testing. The laboratory evaluation seeks to validate the performance of the burner in a current boiler, in order to assess best applications for ratepayers and identify broader uses and opportunities.

Project Description

Development of surface combustion gas burners has taken the form of two widespread types.

The first type includes a combustion grid fabricated from a metal or ceramic sheet perforated with small holes of varying size. Typically, these designs produce only a 3:1 modulation ratio.

The second burner type adds a metal fiber mat to the perforated metal sheet as a flame holder (for increased modulation performance) and a thermal insulator (to reduce the temperature of the metal sheet support). The use of the metal fiber mat results in modulation ratios in the range of 5:1, with up to 10:1 achievable.

The addition of the metal fiber layer increases the cost of the burner significantly and requires periodic replacement due to degradation over time.

In this project, a novel sheet metal surface combustion burner developed in Europe is being evaluated. The manufacturer claims that the burner is:

- Lower cost, less than current metal fiber burner designs
- Has a high modulation ratio (40:1) with high flame-retention performance while maintaining the flame above the burner surface for increased burner lifetime, and
- Provides a reduction in emissions (up to 50%) compared to currently widespread employed surface combustion burner technology.

The use of low-cost formed sheet metal components without the additional aid of metal fiber coating could provide a path for lower-cost burner designs with improved lifetimes before replacement.

While the burner design currently being utilized for high-efficiency boiler applications may have multiple other applications, the primary target most would likely be small-diameter combustion-chamber applications.

Benefits / Market Implications

Advanced low-cost burner designs are essential for the continued development of a wide range of commercial and industrial gas-fired equipment for applications such as fluid or material heating.

Increases to the output modulation of available burner technology will improve efficiencies by:

- Enabling a wider burner operating range to better follow actual heating load
- Reducing cycling through burner shutdown and re-start, thus eliminating reheating losses
- Allowing for the use of advanced control technology (e.g., auto-adaptive controls), and
- Enabling continued progress in the design of new gas-fired equipment with improved energy efficiency and performance.
Development and use of higher turndown gas-fired burner designs provides a path for increased development of efficient and higher performance natural gas equipment. Utilization of advanced burner controls coupled to high turndown burners provide improved load matching, resulting in increased efficiency and reduced emissions.

**Technical Concept & Approach**

The project seeks to substantiate the performance claims of this surface burner technology through laboratory testing and evaluation. This is expected to help identify product-focused development and technology demonstration, opportunities, and best applications for ratepayers.

The project team will design and develop a test cell for evaluation and verification of burner operating performance. A boiler that uses the subject burner will be installed into the test cell. Operation of the boiler and test cell will be verified to ensure proper operation prior to performance testing.

The project team will develop and implement a test plan capable of accurately assessing the burner performance. Testing of the burner will include evaluation of the modulation ratio, sheet metal temperature, and emissions.

A Final Report will be issued upon project completion summarizing the key findings and testing results.

**Results**

In 2018, the project team procured a water tube boiler and completed construction of the test cell.

Configuration of the emission measurement instrumentation was completed.

Researchers also received an additional burner assembly for benchtop testing and evaluation.

In 2019, technicians completed baseline emission testing on the boiler at multiple firing rates.

**Status**

Modifications to the current boiler are being made to allow burner operation at higher excess air flow.

Emission testing continues at multiple firing rates and excess air ratios of the burner system.

Benchtop burner testing and evaluation was initiated.

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DISTRIBUTED GENERATION
Reliability Assessment of Natural Gas for Standby Power Generation

Researchers are developing data, technical support for standards updates, and supporting a website in an effort to provide credible, scientifically-sound information on the value of using natural gas for standby generation. End users benefit from more choices and information to leverage the 10X higher reliability of gas vs. electric supply.

Project Description

Although the market for emergency power supply systems (EPSS) is dominated by diesel-fueled generators, natural gas systems are gaining market share in the U.S. due to recent technical advances, low fuel costs, notable severe weather events, and regulations. For voluntary non-code-driven EPSS installations (typical of residential or small commercial applications) the natural gas market share is about 70%. In the EPSS commercial market, where volume is driven by code requirements, the natural gas share is only 20%-30%.

Research conducted under this project found that regulatory requirements were a significant barrier for natural gas EPSS. A traditional perception is that diesel engines with on-site fuel storage are the most reliable equipment for all backup power applications. Despite their widespread use, diesel generators (gen-sets) are not without reliability concerns. Power outages associated with major weather events have highlighted diesel gen-set vulnerability to inadequate fuel-maintenance practices and to the difficulty or impossibility of fuel replenishment in the midst of extended major outage events. On the other hand, the natural gas infrastructure is highly reliable. Underground supply pipelines are less likely than diesel fuel delivery systems to be compromised during major disasters – especially when passable roadways and available and tanker trucks are needed for subsequent delivery. Reliability of the natural gas supply has been the focus of several recent studies due to the growing dependency of power generation on natural gas.

The overall goal of this project is to reduce market and regulatory barriers for natural gas backup power generation. In the near-term, the project objective is to gather technical information showing that standby generation using natural gas by pipeline can be as or more reliable than on-site diesel fuel storage. Broad dissemination of data on the reliability of the natural gas supply, especially during simultaneous power outages, can support code officials in permitting natural gas utility supply for emergency power generators.

The initial phase of this project focused on identifying the market potential for a representative 50kW natural-gas-fueled distributed generation (DG) system. This study found regulatory barriers were a significant hurdle for natural gas code-driven EPSS due to the precedent use of on-site diesel storage and perceptions regarding the reliability of utility natural gas supply.

In the current phase of the project, the research team is developing technical information on natural gas reliability and the benefits of natural gas EPSS, and supporting proposed changes to applicable standards.

Benefits / Market Implications

Natural gas DG and EPSS provide cost-effective options that increase energy resilience while providing environmental benefits. These advantages, coupled with historically low natural gas prices, provide significant benefits to end users, the environment, and infrastructure reliability.

Supportive research on natural gas reliability will aid consumers, the gas industry, and regulators in understanding the benefits of natural gas as compared to diesel for backup generators. This collected research will also lay the groundwork for a change in industry perception and a potential update in regulations for backup generation.

The project team is supporting the development of a public Natural Gas Knowledge Center website with information that includes White Papers, significant data, and tools to compare natural gas to diesel in terms of costs, emissions, and infrastructure.
Technical Concept & Approach

In early phases of this project, researchers evaluated natural gas DG applications using various criteria, including: capital cost, system efficiency, reliability, serviceability, maintenance cycles, product life, exhaust emissions, noise emissions, systems integration, and modes of operation supported.

In the current phase of the project, the activities focus on the dissemination of data on the reliability of the natural gas supply to address regulatory barriers for the natural gas EPSS market.

Generac Power Systems, Inc., is partnering with the project team to provide industry insight on barriers regarding the natural gas generator market and to disseminate information.

Results

The project team is developing a collection of technical content on natural gas standby generation, and providing technical support for code revisions proposed by Generac as a member of the NEC/NFPA 70 technical committee. Similar efforts by Canadian utilities led to the acceptance of “off-site fuel sources” for emergency generators in Canadian Standards Association’s CSA C282 (“Emergency Electrical Power Supply for Buildings”) in 2007.

The project team partnered with Generac by providing technical content for Generac’s public website, (www.reliablenatgasgen.com), the Natural Gas Knowledge Center. The goal of the website is to disseminate technical content on natural gas reliability and other data to help the gas industry, authorities having jurisdiction, engineers, and customers make well-informed decisions. This public website provides the groundwork for a change in industry perception and potential revision in regulations on fuel supply for backup generation.

The Natural Gas Knowledge Center can be considered a work-in-progress as researchers continue to enhance tools and add content. The website includes condensed, readily-available, supporting data on reliability and other advantages of natural gas-fueled EPSS. The website also offers online tools, performance data, information on applicable codes, and case studies.

As part of this effort, researchers collected aggregate historical natural gas outage data from several utilities to quantify the reliability of the natural gas supply. These results show that natural gas distribution reliability is an order of magnitude greater than the reliability of the electric distribution service. This assessment was publicly distributed in July 2018 as a Gas Technology Institute (GTI) topical report, Assessment of Natural Gas vs. Electric Distribution Service Reliability, to substantiate the high level of reliability of natural gas service and to support its use for standby and emergency generators. The site also includes GTI’s white paper Reliability Assessment of Diesel vs. Natural Gas for Standby Generation, an overview of natural gas EPSS and a comparison of natural gas vs. diesel systems.

The website also offers an online tool, the Total Cost of Ownership calculator, that compares natural gas standby generation to diesel in terms of economics and full-fuel-cycle emissions.

Status

The project team continues to provide technical content for the Natural Gas Knowledge Center website and gather and document additional data regarding natural gas reliability.

Researchers are continuing to update the Total Cost of Ownership tool based on actual installed costs and regional factors.

Economic case studies are being developed for new non-emergency certified EPSS installations that can utilize demand response, including potential life-cycle cost benefits relative to natural gas and diesel emergency-only EPSS.

The project team is documenting case studies where utility champions were successful in petitioning local code officials for natural gas standby systems.

Other results were summarized in a Final Report for a recent project phase issued in October 2018.

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“Stored-fuel-fed emergency and backup generators, such as diesels, are a less-than-perfect solution to situations that involve wide-scale, frequent, and/or prolonged power outages. Natural-gas-fired generators, on the other hand, such as the Generac DG50, have the advantage of overcoming this challenge because they are fed from the gas utilities whose service remains unaffected by power outages.”

- Tim Short
Manager, Distributed Energy
Enbridge Inc.
Researchers evaluated a new M-Trigen micro-CHP system to confirm performance and develop information to help building owners and stakeholders identify the most impactful initial applications. The system provides space heating and cooling, hot water, and power, and has the potential to provide substantial energy savings.

Project Description

Micro-CHP systems (mCHP - combined heat and power) still represent a niche product in the U.S., partially due to historically high initial costs, poor matching of thermal and electrical loads, and the complexity of distribution and installation. For many mCHP applications, producing only hot water and electricity is not enough to make these products viable in the marketplace. However, if the mCHP system can also produce cooling, it provides opportunity in more applications and for longer runtimes, thus improving economics. While there are dozens of mCHP systems available, only two have integrated cooling. One of these is a technology from M-Trigen, Inc.

M-Trigen is working to introduce two mCHP systems under the PowerAire product line that produce about 6 kW and 10 kW of power. The smaller unit is based on a three-cylinder Toyota engine and can produce up to about 70 MBH of heat or five tons of cooling. The larger unit can produce more than 100 MBH of heat and 10 tons of cooling. The M-Trigen system is the only system in the North American market that can generate power, space heating, air conditioning, and hot water; but it is the cooling attribute that makes the M-Trigen system stand out for greater mCHP potential in North America as well as abroad.

The objective of this project was to test a new M-Trigen mCHP system to confirm performance and develop information to support market entry. This information is critical to increased understanding of this new micro-CHP system for building owners and national account stakeholders. Data will confirm lifetime cost and revenue streams needed for consumers to make informed decisions.

This project is cofunded by NYSERDA (the New York State Energy Research and Development Authority), New Jersey Natural Gas, the Propane Council, and M-Trigen.
Benefits / Market Implications

Potential benefits to end users and the environment are significant. In 2013, a mCHP manufacturer commissioned a study to determine the current and potential market for mCHP. It determined that the total number of mCHP units installed in North America at the time was no more than 200, and these were typically smaller units (<5 kWe) in high-end homes and multifamily apartments. The report also stated more than 370,000 light-commercial buildings could benefit from use of an mCHP system with a potential 1% compound annual growth rate. This translated into a potential annual volume of 5,300 units for new and replacement markets 10 years after introduction, at a total market value of $164 million. If retrofit opportunities are included, these numbers increase significantly.

The PowerAire 65 system is a packaged CCHP system manufactured by M-Trigen with planned distribution throughout North America. It is a certified pre-production demonstration-ready unit that could operate grid-parallel or islanded (when grid power is lost). The unit is powered by a three-cylinder 952cc natural-gas-fired Toyota internal combustion engine with an onboard 120/240 VAC Split Phase, 60Hz generator and inverter, refrigerant compressor, heat exchangers, radiator, and batteries. The system produces uninterruptible power, air conditioning, space heating, and hot water. For laboratory evaluations, the unit was coupled with a separate five-ton air handler unit and a five-ton split system air-source heat pump for a complete self-powered HVAC system on or off grid.

Technical Concept & Approach

The M-Trigen is a synchronous system with an inverter that can serve the dual function of stand-alone power (black-start capable) and grid parallel operation. Heat is scavenged from the internal combustion engine and sent to an external heat exchanger connected to a buffer tank for hot water storage. Stored hot water can then be used for domestic hot water, or space heating via an air handler unit with a hydronic coil. A refrigerant compressor is used in a vapor-expansion cycle for space cooling. Refrigerant can then be used together with a standard outdoor condenser, expansion valve, and an air handler A-coil for cooling. A generator coupled to the engine produces electricity, which is used on site and for battery charging.

Laboratory testing verified performance targets and subsequent field testing is under way with NY-SEERDA to further confirm performance of a fully-integrated system. Test activities were coordinated with an ASHRAE sub-committee (SPC204) to further develop a standard method of test for micro-CHP.

Results

Researchers evaluated a certified preproduction unit to characterize and validate system performance. Tests were conducted under controlled conditions to evaluate the sensitivities of the unit’s power, heating/cooling, and domestic hot water outputs and efficiencies at various loads, ambient temperatures, and other conditions. All tests were completed with only minor adjustments to internal system settings.

Supplemented by grid power, the unit was able to provide 6 kW of gross power (over and above its internal power for HVAC). It was limited to 5 kW of net power output when islanded in heating mode at 40°F ambient, and 3.5 kW of net power output when islanded in cooling mode at 95°F. Its maximum cooling capacity at 95°F was about five tons, and maximum space heating capacity was about 52 MBH at 40°F ambient. During heat pump operation, the PowerAire 65 produced over 60 MBH of hot water at 40°F ambient, and up to 75 MBH at 95°F ambient with onboard radiator operation. System energy inputs and outputs in heating and cooling modes.

Total system efficiencies were better than 85% to nearly 100%.

Status

This project is complete. A Final Report was issued in October 2018.

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Long-Term Performance and Reliability Assessment of CHP and DG Systems

Researchers are analyzing the long-term reliability and performance of high-efficiency gas-fueled combined heat and power (CHP) or distributed generation (DG) technologies. The goal is to identify typical CHP/DG failure modes and potential research and development opportunities to improve the performance of CHP/DG systems.

Project Description

Combined heat-and-power (CHP) applications typically improve energy efficiency, reduce operating costs, and enhance energy resilience for both individual customers as well as the regional power grid. CHP resilience was demonstrated during Hurricane Sandy, when New York schools, hospitals, and apartment buildings with natural-gas-fueled CHP systems were able to generate power and provide places of refuge during the storm and the weeks that followed.

Likewise, natural gas distributed generation (DG) or micro-grids have the potential to generate power during widespread outages or to be dispatched by electric utilities during periods of high electric demand to relieve local grid stress and prevent brownouts.

The configuration of CHP systems vary widely in capacity, efficiency, fuel type, and prime mover. In this project, researchers are analyzing the performance of existing natural-gas-fueled power CHP or DG technologies based on available data from select sources. The ultimate goal is to identify typical CHP/DG failure modes and develop potential R&D opportunities to improve the performance of CHP/DG systems for facility managers and other end users. This project builds on earlier studies which developed a methodology for recording and analyzing data to establish baseline operating reliability for DG/CHP systems.

Benefits / Market Implications

CHP is recognized as a proven technology for improving energy efficiency. Twenty-three states include CHP in one form or another as part of their Renewable Portfolio Standards or Energy Efficiency Resource Standards. A number of states – including California, New York, Massachusetts, New Jersey, and North Carolina – have initiated specific incentive programs for CHP.

This project is analyzing the baseline operational reliability of CHP/DG systems, ranging from micro-CHP systems under 50 kW to industrial CHP applications. Facility managers, researchers, manufacturers, and utilities can use this information to identify potential improvements in the operational reliability of CHP/DG systems. An established baseline will also allow current and potential users to benchmark the reliability of natural gas CHP systems.

Technical Concept & Approach

For this project, researchers are reviewing and summarizing available reliability data on current operational CHP or DG systems. The team is also exploring how performance can be used to infer traditional operational reliability parameters. CHP operation reliability data is being collected from multiple sources, such as DOE's CHP Technical Assistance Partnerships, DOE CHP Installation Database, and others.
This analysis will quantify the reliability of a wide range of CHP technologies and identify typical failure modes. This study will allow current and potential users to benchmark the reliability of natural gas CHP, and identify any potential research needed to improve the long-term performance of CHP systems.

Data is being grouped into technology categories for comparison based on key parameters, such as prime mover type, capacity, and application (e.g., continuous, thermal lead, and peak shaving).

Examples of key parameters included are:

- Period of Demand: Time the unit was planned to operate
- Availability Factor: Percent of the unit’s potential runtime, impacted by planned and unplanned maintenance
- Service Factor: Percent of total period hours the unit is on-line (varies due to site-related or economic factors)
- Mean Time Between Forced Outages: Nominal time between unscheduled forced outage and
- Mean Down Time: Nominal duration the unit is down during maintenance events.

Results

The project team developed methodologies to determine an operating strategy based on existing CHP data and a statistical approach to predict planned vs. unplanned downtime as an indicator of system reliability. This approach includes the development of custom software algorithms to compare the time of outages to the same time of day within a given time period. The project team also developed an approach to account for scheduled maintenance based on prime mover type.

Algorithms were modified to improve the handling of missing data. Algorithms were further refining by analyzing a subset of 40 systems with known operating strategies to validate algorithm results.

The detailed database includes multi-year performance data from installed CHP systems at 275 sites.

The CHP database is grouped into technology categories for comparison based on key parameters, such as prime mover type, capacity, and application (e.g. electric lead, thermal lead, peak shaving, etc.). The algorithm is then used to analyze CHP performance data within each category to identify the equipment types, applications, operating modes, or other parameters that impact CHP reliability.

The project team identified key metrics based on the IEEE Guide for Electric Power Distribution. These metrics will be used to quantify reliability and identify key parameters that influence reliability, such as prime mover type, size, building application, and operational strategy.

Several prime mover types (including reciprocating engines, microturbines, fuel cells, and gas/steam turbines) were analyzed with capacities ranging from under 50 kW to large commercial applications of more than 2,000 kW.

A Task 1 report was issued in December 2018.

Status

Efforts are under way quantify CHP reliability for the database of installed CHP systems.

In the second half of the project, researchers are assessing the validity and robustness of the methodology using power data to identify and classify outages or unexpected equipment failures. Results will be compared to manufacturer data, operation and maintenance logs, and known parameters to continue refining the algorithm to identify unplanned outages and quantify long-term operational reliability.

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CHP System with Integrated Particle Thermal Energy Storage

In this project, researchers advanced the development of a high-efficiency micro-CHP system with an integrated heat storage that is economical and expand the integration of highly-efficient CHP with renewable solar energy.

Project Description

The industrial sector in the U.S. has applied combined heat-and-power (CHP) systems for a long time, generally using a gas turbine or an internal combustion engine to generate electricity, and using the thermal energy in the exhaust gases to generate hot water, steam, or cooling. Smaller turbines used in micro-CHP systems generally operate with very high excess air levels, which reduces their efficiency. Although providing a greater amount of available heat in their exhaust gases, these gases are at lower temperatures and often require supplemental firing for effective capture of available heat. This increases equipment size, costs, and complexity.

One of the key technical issues is the mismatch between the amount of heat available in turbine exhaust gases and the demand for this heat at any given time. There are limited options for exhaust heat utilization during periods of low heat demand.

Currently under development is a solar technology with integrated thermal storage. The project, funded primarily by the U.S. Department of Energy (DOE), is demonstrating two nominal 5kW field prototype solar collector systems that include thermal storage. The system addresses the limitations of micro-CHP systems by allowing low-cost storage for on-demand utilization of waste heat.

The concept was tested at a 5 kW scale for capture, storage, and regeneration of solar energy. The system demonstrated no clogging, particle degradation, or heat transfer and pressure drop changes over the tested 4,000 heating-cooling cycles (100°C to 650°C), which represents many years of operation.

The objective of this project was to prove the ability of capturing and storing at least 50% of the thermal energy available in micro-turbine exhaust gas for on-demand reuse.

Benefits / Market Implications

CHP systems have the potential to significantly reduce carbon and air pollutant emissions while converting 80% or more of fuel input into useful energy.
Technical Concept & Approach

A key component of the system is an innovative particlegas thermal fluid. The fluid allows capture, transport, storage, and reuse of thermal energy over a wide range of temperatures at low pressures and low cost. The particle-gas fluid has very high heat-transfer rates, reducing the size of heat exchangers. The mixture allows the system to operate at 5-10 psig, as opposed to organic thermal liquids that reach over 100 psig operating pressures at temperatures higher than 350°C. The low-pressure capability significantly simplifies and reduces the cost of system components.

The project involved the use of a flow-characterization loop to select appropriate particles and the development of a heat exchanger that effectively captures the available waste heat in turbine exhaust gases.

A prototype heat exchanger was tested in the laboratory using simulated turbine exhaust gases at different temperatures and flow rates to characterize its performance and develop design data. The team also developed a preliminary techno-economic assessment of integrating particle thermal storage with micro-CHP.

Results

This project developed and demonstrated the concept of recovering and storing available micro-turbine exhaust gas energy in solid refractory particles.

The team envisions that the integrated thermal storage technology would be applicable to micro-CHP as well as MW-scale CHP applications.

Dense-phase transport was found to be more suitable because of its significantly higher particle-to-carrier air-loading ratios, and the resulting lower carrier air flow rates and particle-air mixture velocities. The lower velocities exponentially reduce the potential for particle attrition and flow-path erosion. The dense-phase tests were carried out by designing and building a high-temperature particle flow and storage loop and showed no flow path abrasion, particle degradation, or problematic accumulation of particles. Additionally, there were no changes in heat transfer rates and system pressure drops over numerous charge-discharge cycles during the 580°C tests as well as during tests at lower temperatures.

In 2017, calculations were refined for the heat exchanger and a baseline scenario was established. The heat exchanger was modified to include a finned stainless-steel tube, with particles flowing within the tube and hot exhaust gases flowing across the tube through the fins. The heat exchanger inlet and outlet transitions incorporate features to spread the flow uniformly across the entire finned tube for more effective heat transfer.

In 2018, the project team completed hot testing. The results of heat-exchanger tests successfully demonstrated the ability to transport particles in dense phase through a flow loop containing complex flow paths, including multiple bends and multiple full circles, and the ability to transfer heat in exhaust gas to refractory particles using a shell-and-tube heat-exchanger design. The test system achieved the desired process air (simulates turbine exhaust gas) flow rate, temperature, and heat-exchanger pressure-drop values. The particle flow rates, pressure drops, and particle-to-carrier air loading ratios, however, were significantly lower than desired for effective heat-exchanger operation. Even with a heat-exchanger coil length that was about 40% shorter than the design specification (to reduce particle side pressure drop), the particle flow rate values were only one-fifth of the desired values.

Test results clearly show the need for redesigning the heat exchanger and modifying the particle flow loop to significantly reduce flow path resistance and increase particle flow and heat transfer rates.

Status

This project was completed with a Final Report issued in January 2019. It is recommended that researchers use the current test setup to test a direct contact cyclone exhaust gas-to particle heat exchanger. The cyclone heat-exchanger design was shown to rapidly heat the particles in a fraction of a second to reach close to equilibrium conditions with less than 0.2 in wc pressure drop.

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Cost Optimization of 3D Printing of Advanced Burners for CHP and Distributed Generation

Research is being conducted to provide manufacturers a low-first-cost, high-efficiency, low-emissions advanced nozzle burner with improved performance and economy by using new 3D printing techniques and optimizing the design, material selection, processing and other factors.

Project Description

Manufacturers and the natural gas industry are looking at methods to reduce first costs for end users and rate-payers, improve system efficiency, reduce emissions, and provide products and services with greater market acceptance and improved customer satisfaction.

Additive manufacturing (AM) or 3D printing provides key benefits to offset these challenges and is making manufacturing more competitive and attractive. In addition, using AM opens up new design opportunities with on-demand components and can significantly improve efficiency and reduce emissions, while reducing spare parts inventories.

Three-dimensional printing has gained traction in multiple industries. However, it is important to manufacture the product by Designing for Additive Manufacturing (DfAM). Increasing part value through intelligent optimization helps significantly lower the part cost. Effective DfAM can result in a reduction of support structures, material, part weight, inventory, maintenance, and assembly labor, leading to considerable cost savings and a product that performs better and is more competitive.

Researchers designed, developed, and tested a 3D-printed advanced nozzle in a previous UTD project. This design incorporates beneficial complex, unique features that are impossible or very difficult to manufacture using traditional methods.

Low-volume costs, reduced lead-time, complex designs, and customizable parts are the key benefits of 3D printing. However, for larger-volume production, the cost is not yet competitive to traditional manufacturing. In this project, researchers are evaluating large-volume manufacturing costs using 3D printing and other techniques to reduce this cost significantly.

Installed CHP system from Solar Turbines Incorporated illustrates one type of CHP system that is targeted to benefit from a 3D-printed burner.
Specific project goals are to:

- Design and develop a 200kW ultra-low-emissions 3D-printed burner capable of achieving the performance metrics (\(< 5\) ppm NO\(_x\), \(< 10\) ppm CO, and turndown of \(> 6\) to \(1\)) for combined heat and power (CHP) applications
- 3D print the burner with the key complex features
- Test the scaled-up burner at atmospheric pressure to demonstrate the performance, operability, and discuss test results with partners and develop a plan to perform pre-commercial testing in a single-burner test rig.

The insights gained from this research are expected to benefit other gas-fueled equipment that can use the advanced nozzle burner.

Benefits / Market Implications

Current 3D-printing costs already show nearly a potential 25%–50% reduction to the cost of current commercial water-heater burners, while achieving superior efficiency, operation, and emissions reductions. This cost can be further reduced by 90% and can lead to a path for large-scale production. In addition, as the technology progresses and better and faster 3D-printing machines are introduced, the economies of scale will have a significant impact on the final cost of the burner. Considering the weight of the current advanced nozzle, the burner is projected to cost only about $14 to 3D print, which is much lower than currently stamped parts.

All these cost benefits will directly or indirectly help the customers and natural gas users. Improved efficiency with low first-cost, reduced lead-time, and reduced emissions can have a positive affect of safety, reliability, and revenues.

Technical Concept & Approach

The project will evaluate techniques to improve performance while lowering first costs for the advanced nozzle 3D-printed burner design for combustion turbines such as can be used in CHP and distributed generation.

Key parameters that affect the cost and performance of the burner will be evaluated and methods to eliminate certain processes to reduce the cost will be reviewed and implemented.

Specific tasks include:

- **Design and Process Improvements to the Advanced Nozzle Burner**

Researchers will identify and adapt the design and process changes. One of the key aspects is to lower the build time that will lower the cost of the component. Other key parameters are 3D-printing machine selection (i.e., binder jetting). Also, machines that can produce the parts at the lowest energy input will be evaluated. Researchers will also review different low-cost materials available for this design.

- **3D Print Design and Evaluation Performance**

After selecting the 3D-printing machine, along with the design and process parameters, the project team will 3D print the advanced nozzle burner. Researchers will evaluate and document the cost. Further, burner testing will be performed with a scaled-up burner at atmospheric pressure to evaluate efficiency, emissions, turndown, and overall performance.

- **Review, Report, and Discuss 3D-Printing Costs with Manufacturers**

Researchers will showcase the benefits and challenges of the technology with respect to cost parameters. This will enable a dialogue with end-use equipment manufacturers that will provide key inputs to further the advanced nozzle as a design for multiple applications and 3D printing as a manufacturing method.

Results / Status

Initially, researchers reviewed the design and investigated methods and techniques to lower the build time and other aspects of the design without sacrificing performance using 3D printing. The project team is examining methods to conventionally manufacture the advanced nozzle for comparison, trade-off analysis, and impact on performance.

Researchers are also reviewing a design for air-heating applications, which can be extended to CHP and distributed generation applications as well.

In 2019, researchers designed a burner and an individual nozzle was fabricated to evaluate the burner features. In discussions with partners, researchers identified test rig for performing the burner testing.

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Project Description

Combined heat and power (CHP) systems must achieve high efficiency and low emissions in a cost-competitive package that is capable of broad deployment throughout existing market segments. The FlexCHP technology developed with support from UTD satisfies these needs for those installations that need 65 kW demand and 80 boiler-horsepower (BHP). The technology has the potential to be widely adopted within commercial and industrial steam-generation markets because of its ability to achieve high steam-production rates and efficiencies that are unmatched by any other competing turbine-based CHP approach.

The success of the FlexCHP technology thus far is evident by 1) the many customers with interest in purchasing FlexCHP units, 2) a pending license agreement for the technology, and 3) support from the U.S. Department of Energy and state-level agencies. However, end users are requesting larger-capacity CHP systems. In response, the FlexCHP manufacturer has requested to participate in a new demonstration in order to move the technology forward. The development of an integrated turbine/burner/boiler product that offers the additional advantage of grid-independence for reliable operation of industrial plants will advance the adoption of CHP solutions only if the team is able to transition from 65 kW to larger units.

The FlexCHP technology is at a critical point in the technology development/deployment path. While the FlexCHP systems has been successfully developed and field demonstrated at a capacity of 80 BHP and 65 kW electricity (kWe), by being integrated with a Capstone C65 microturbine, the economics of the technology favors larger-capacity installations, and, thus, there is need to develop and demonstrate a scaled-up version.

The potential customer base for the Capstone C200S far exceeds that of the C65, and customers with even higher load demands can be satisfied by coupling multiple C200S units to achieve the required output.

Successful commercialization and deployment of the FlexCHP technology will have a transformative impact on commercial and industrial steam markets. Rather than purchasing a standard boiler with a conventional burner, end users will have the option of investing in a FlexCHP unit to generate on-demand steam and electricity. Customers will realize significant cost savings through reductions in electricity purchased from the grid. Ultimately, greenhouse gas and criteria pollutant emissions will be reduced, while at the same time yielding significant increases in gas consumption.

The FlexCHP technology uses exhaust from a turbine generator as an oxidant for downstream combustion with supplemental natural gas to generate steam in a firetube boiler. While some competing CHP technologies recover heat from the high-temperature turbine exhaust (~600°F) by delivering the exhaust through a Heat Recovery Steam Generator (HRSG), this approach fails to maximize the quantity of recoverable heat because the exhaust excess oxygen levels are not reduced. The FlexCHP maximizes efficiency by reducing the exhaust oxygen levels from 17.7% in the turbine exhaust to 3% in the boiler stack through supplemental combustion. In comparison to simply delivering the turbine exhaust through a HRSG, the FlexCHP technology provides an efficiency gain of more than 30 percentage points (~60% increase).
FlexCHP is the only CHP technology that demonstrated high steam output and efficiencies of 84% without post combustion clean-up (e.g., selective catalytic reduction or other expensive after-treatment). Further, it is the only technology capable of attaining compliance with air-quality regulations in key non-attainment regions.

Key performance indicators for this project will be:

- Power delivery with turndown ratios of 4:1
- System efficiencies over 80%
- Reliable delivery of power over variable load conditions, and
- Emissions of NOₓ less than 9 ppmv and CO less than 50 ppmv.

Benefits / Market Implications

For steam boiler customers for whom the price differential between electricity and natural gas rates exceeds a ratio of 4 to 1 on a per-unit-energy basis, the economics will likely be such that customers can anticipate payback of less than three years by purchasing a FlexCHP unit, with significant long-term benefit (assuming operation five days a week, 48 weeks per year). For customers paying electricity rates that are six times that of their gas rates (as is the case in key markets including California and the Northeast), customers can achieve payback in less than 1.5 years. As the FlexCHP is deployed more widely and equipment prices are reduced, the economic benefits of the technology will increase further.

As an example, consider a customer with a steam demand of 200 BHP and electricity load of 200 kWe. This customer could install a standard 200 BHP boiler that consumes gas at a rate of 8.5 million Btu/h and purchase electricity from the grid. Alternatively, the customer could install a FlexCHP rated at 200 BHP/200 kWe to generate the required quantity of steam and self-generate 200 kWe of electricity, consuming gas at a rate of 9.3 million Btu/h. If the customer rates for electricity are four times that of their rates for natural gas, on a per-unit-energy basis, the customer could reduce its energy costs by 18% annually by installing a FlexCHP unit. At the same time, greenhouse gas emissions would be reduced by more than 16%.

Technical Concept & Approach

Activities in this project fit within a broader research program to develop and demonstrate an advanced FlexCHP technology at larger capacities which is 1) capable of operating on both turbine exhaust gas and air (as this will greatly expand the market potential for the technology) and 2) is packaged as a fully-integrated commercial product across load scales for deployment by the manufacturing partner.

Project efforts will focus on logistics, procurement, installation, and testing of the C200S microturbine. A test plan will be developed to characterize system performance across a broad operating range, and data will be compared to the manufacturer claims. This will provide insight and knowledge for determining the optimal burner configuration to be used for scaling the technology to larger capacities.

The burner design will be validated and tested within a subsequent project phase. A Final Report will be prepared outlining activities, test results, and future plans.

Results / Status

Early in the project, Capstone distributors were contacted and other microturbine manufacturers were also contacted. Discussion also occurred with a major university that has four 200kW engines operating, which are designed to burn low Btu (600 Btu/scf) landfill gas. Discussions were also held at a site where two model C200 turbines are in place. Additional end-user sites are being contacted to identify a location with a C200S unit available for characterization.

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Ultra-High-Efficiency Natural-Gas-Fired Combustion Systems for mCHP

Research is under way to develop and validate an optimized thermochemical heat-recovery hybrid recuperator and burner with ultra-high combustion efficiency (90%) and ultra-low emissions for a highly-advanced residential micro-combined-heat-and-power appliance.

Project Description
This project is developing a prototype combustion system for an ultra-high-efficiency, ultra-low-emission natural gas micro-combined-heat-and-power (mCHP) appliance for the home.

The primary target markets are:
- Homes (detached/semi-detached), and
- High-value, high up-time, small-demand users (e.g., remote power, telecommunication infrastructure, and grid-constrained markets).

During testing, the mCHP system was able to achieve 77% combustion efficiency. In comparison, combustion systems with sophisticated heat recovery operate at about 65% combustion efficiency.

The objective for this project is to develop and validate an optimized thermochemical heat-recovery (TCHR) hybrid recuperator and burner – key components of a combustion system – with ultra-high combustion efficiency (90%) and ultra-low emissions.

Key performance indicators and goals to measure the success of this project will be to:
- Achieve up to an 11% boost in combustion efficiency by reforming humidified natural gas into synthetic gas at >600°C.
- Successfully pre-heat combustion air to ~560°C.
- Confirm ultra-low emissions, and
- Develop a burner with recuperation for a tubular heater-head.

The project team seeks to meet a goal of 65% combustion efficiency and 20% fuel-to-electric efficiency for a near-term product, and complete the design of an advanced combustion system TCHR hybrid recuperator to achieve a targeted 90% combustion efficiency for a 2020 system.

Benefits / Market Implications
The U.S. Department of Energy’s Advanced Research Projects Agency - Energy (ARPA-E) conducted an extensive analysis on the potential benefit of an ARPA-E strategy to site mCHP in U.S. residences to achieve energy and environmental savings.

The prototype near-term burner being tested under high fire. The inconsistent color in the metal foam sections under fire are indicative of poor manufacturing quality control in pore size and density.
These benefits include: 1) energy savings (~ five quads, 2) four- to five-year payback, 3) reduction of CO$_2$ (200 million tons), and 4) reduction of freshwater withdrawal (~8% of U.S. total).

The TCHR hybrid recuperator allows the Stirling engine to achieve high efficiencies at lower operating temperatures, which provides for the use of lower-cost alloys. The lower temperatures also improve system life and reliability.

**Technical Concept & Approach**

**Design and Construct a Recuperative Burner and Optimized Non-Catalytic TCHR Hybrid Recuperator Design**

- Modify the existing TCHR hybrid recuperator and burner computational modes based on alpha test data supplied by the manufacturer
- Run parametric analysis to converge size, geometry, operating, and performance conditions
- Design and engineer the optimized TCHR hybrid recuperator using non-catalytic steam-methane reforming and natural gas humidifier components, and
- Design, engineer, and fabricate the recuperative burner, and validate design and performance specifications through testing.

**Testing, Integration, and Validation**

- Conduct TCHR hybrid recuperator and burner testing in accordance with an approved test plan
- Integrate components into a full Stirling engine type and conduct testing, and
- Provide an integrated unit to for testing and evaluation.

Results will include a laboratory-tested pre-commercial Stirling engine with an integrated advanced combustion system.

**Results**

Initially, the project team provided a single-cell heat exchanger for baseline testing on recuperation.

In 2018, researchers initiated an analysis of an existing 1-2.5kW Stirling combustion system, experimenting with different heat-head designs for cost reduction. The project team evaluated two different burner designs for the Stirling engine.

In 2019, structural components of a near-term burner were fabricated, assembled, and tested at two firing levels. Under a high fire of 12.3 kW, the pressure drop across the burner was 0.75 in W.C. and NO$_x$ emissions measured 8 ppm @ 3% O$_2$. Under low fire of 5.2 kW, the pressure drop across the burner was 0.05 in W.C. and NO$_x$ emissions measured 5 ppm @ 3% O$_2$.

**Status**

The burner was shipped to for testing in a 1-2.5kW remote power system with off-the-shelf recuperation. It is expected that the prototype should be able to achieve a system efficiency >20% and be CARB 2007 compliant, thereby achieving ARPA-E’s goals.

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Integrating Micro-CHP and PV in Advanced Gas/Renewable Homes

Research is under way to expand the micro-combined-heat-and-power and photovoltaic capabilities in a virtual test home in a laboratory in order to more rapidly develop, test, and optimize system-based solutions that increase energy efficiency and reliability, reduce energy costs, and better integrate natural gas with renewable energy in homes in all climates.

Project Description

Micro-combined heat and power (mCHP) remains under-utilized in the western hemisphere, while well-established overseas in Japan and Europe. The primary barrier to widespread adoption is cost.

While a downward trend in cost is expected as new technologies penetrate the market, significant declines in cost are generally only seen after high-volume production and competition among manufacturers are realized. With consistently low gas prices and rising electricity prices, there are now dozens of manufacturers positioning for the residential mCHP market. In the meantime, the residential rooftop photovoltaic (PV) market continues to outpace expectations, with installed cost of solar PV declining from about $8-$9/W to <$3/W in the past ten years. In that timeframe, about 29GW of PV capacity was added with steep ramp ups as costs came down.

The growth in PV provides an opportunity for the gas industry to demonstrate its strengths for end users in all climates to integrate PV with clean, efficient, cost-effective, and reliable on-demand gas-fired equipment.

Aisin Seiki Co., Ltd., recently started offering its “COREMO” natural-gas-fired mCHP system in the U.S. The COREMO is an engine-based residential-scale system that can produce 1.5kW of power and 12.7 MBH of heat for space heating or domestic hot water (DHW). In response to a carbon levy implemented by the Canadian government in 2017, some Canadian gas utilities embarked on hybrid natural-gas/renewable research efforts. With Aisin, at least one utility supported development of a hybrid house pilot project. This new UTD project will leverage the lessons learned from the pilot project to gain a better understanding of the integration opportunities and challenges in terms of equipment and controls.

In this project, laboratory research is complemented by building energy modeling techniques to provide an opportunity to properly quantify potential energy savings from different types of gas-fired systems in various building types and climate conditions.
This project is part of a three-pronged approach to economically develop and evaluate superior system-based solutions to integrate natural gas and renewable energy in residences by:

1. Develop sizing guidance and system controls to balance on-site mCHP with available renewable resources and thermal energy needs
2. Evaluate solutions and design practices to assure that high-efficiency, low-impact gas-fired heating technologies (e.g., gas heat pumps and low-capacity condensing equipment) are able to maintain thermal comfort in all-climates, and
3. Develop solutions to deploy and store thermal energy, the primary connective tissue from efficient gas-fired heating to the home’s other systems.

Benefits / Market Implications
Zero Net Energy (ZNE) homes are attracting increasing market interest, and many homebuilders are opting for an all-electric approach. However, there are principle drivers for including gas in mixed-fuel ZNE and other high-efficiency homes. In terms of cost-effectiveness, gas enables lower-cost ZNE implementations by allowing smaller PV arrays to offset source energy use, and also provides key resiliency benefits.

Peer-reviewed analyses indicate mixed-fuel homes can reach similar levels of emission reductions and renewable energy utilization as all-electric ZNE homes.

In this project, the research team aims to develop system integration and control strategies with a portfolio of near- or market-ready equipment to demonstrate the effectiveness of integrating onsite gas and renewable generation with efficient gas-fired heating equipment and energy storage.

Technical Concept & Approach
Specific tasks include:

- **Micro-CHP Pilot House Assessment and Experimental Plan**
  Researchers will initiate a dialogue with pilot house project participants (including utilities, homebuilders, and manufacturers) to understand the opportunities and challenges related to equipment designs, controls, and system integration architectures.
  The project team will develop a test plan for the experimental integration of PV generation, mCHP, ultra-high-efficiency gas heating, and thermal energy storage in the virtual test home.

- **Design and Construct the Virtual Test Home**
  The project team will design and construct the power-equipment components of the test home, including a PV array, Aisin mCHP system, breakers, inverter, battery bank, and load distribution. Algorithms will be developed to simulate power loads against characteristically repeatable real-world space-heating loads.

- **Evaluation of Integrated System**
  Experimental tests will be conducted to evaluate the integrated system performance.

Results
As part of the current research, researchers teamed with manufacturers to develop a combination system that dynamically monitors air and water temperatures and modulates water flow to maximize efficiency and comfort. In addition, researchers are evaluating high-efficiency two-stage electric heat pumps, and initial tests show good performance at warm ambient temperatures, but significant de-ratings at low ambient temperatures. Furthermore, researchers and manufacturers are developing residential-scale mCHP systems.

Modeling indicates an integration of these systems would result in a more efficient and reliable system than traditional gas equipment or all-electric equipment. The current model would use a small 1.5 kW mCHP system isolated from the grid, an electric heat pump, a tank-type water heater, and a hydronic air handler unit.

In the winter, the heat pump would be off and the mCHP system would supply heat to the tank water heater for space heating and DHW. The mCHP power would be used for the air handler, water pump, and small water-heater power demands. In the summer, the heat pump is used for air conditioning. Off-grid PV is supplemented by the mCHP system to supply power to the heat pump, air handler, water pump, and tank.

Status
Activities are focused on the design and initial build-out of the virtual test home in the laboratory.

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Research is being conducted to characterize key mCHP technologies and increase market adoption of highly-efficient mCHP by providing the market with qualified, well-established, and cost-effective systems.

Project Description

The primary barrier to widespread adoption of micro-combined heat and power (mCHP) systems is cost. While a downward trend in cost is expected as new technologies penetrate the market, significant declines in cost are generally only seen after high-volume production and competition among manufacturers are realized.

A good example is the decline in installed cost of solar photovoltaic (PV) systems from about $8-$9/W to <$3/W in the past 10 years. In that timeframe, about 29 GW of PV capacity was added, with steep ramp-ups as costs came down.

Competition among mCHP manufacturers is inevitable. With consistently low gas prices and rising electricity prices, there are now many manufacturers positioning for the small-scale CHP market. However, high-volume production has yet to be seen. Qualified technology supported by a major manufacturer in an influential market such as California could help to spark the American market and expand the global market.

Industry experts recognize the energy efficiency and end-user benefits for mCHP. However, with dozens of mCHP technologies coming into play, it is difficult to determine the technologies that are best to pursue.

To gain a comprehensive understanding of the technical and economic viability of mCHP, many factors need to be considered, including thermal-electric ratio of the technology, regional- and application-specific coincidental power and thermal loads, quantitative and qualitative value of standby power, time-of-use energy rates, net-metering legislation, and the incremental costs of mCHP relative to traditional costs for retrofit and new construction equipment.

There are two components to this project:

1. Updating UTD’s 2012 Technical & Market Analysis for Residential and Commercial Micro-CHP. The Final Report for that project provided the industry with a snapshot of emerging mCHP technologies and a detailed, practical assessment of the market potential for them.

2. Laboratory testing in support of a much larger California Energy Commission (CEC)-funded project. The CEC project is funding the development and demonstration of two mCHP systems.
The objectives for this project are:

- To characterize key mCHP technologies and determine regional, technical, and economic viabilities of those technologies in residential and commercial applications. To do so, researchers will conduct a next-generation analysis of micro-CHP.

- To increase market adoption of mCHP by providing the California market with qualified, well-established, and cost-effective systems. The project team will perform laboratory tests to evaluate performance of mCHP systems. Emission rates of those systems will be evaluated to test compliance with the California Air Resources Board (CARB) regulations.

**Benefits / Market Implications**

The mCHP landscape has changed significantly in five years, and the long-term projected price of natural gas in North America has substantially declined. There are now at least six new 10kW-50kW engine-based mCHP products suited for the commercial sector, and a wide assortment of new technologies less than 10kW for the residential and light commercial sector.

Laboratory testing and demonstration of two mCHP systems will address the Distributed Certification Regulation (DG-Cert) requirements under the CARB Distributed Generation Program. The DG-Cert sets the bar for exceptionally clean and efficient distributed generation, and would position these manufacturers for expanded market offerings elsewhere.

**Technical Concept & Approach**

The first component of this project is to identify the best opportunities for end users to widely adopt mCHP by first characterizing the technologies and then putting them through a battery of energy and economic analyses. The objective is to identify and characterize existing and emerging mCHP technologies, and determine the viabilities of those technologies to single- and multi-family residential and light commercial building sectors. Economic analyses will be conducted for at least seven climate regions and will include:

- **Commercial:** Near-grid-efficiency mCHP applied to the U.S. Department of Energy commercial reference building models, including full-service restaurants, small hotels, outpatient healthcare, and midrise apartments.

- **Residential:** Above-, near-, and below-grid-efficiency mCHP applied to a residential homes based on the National Renewable Energy Laboratory housing stock characteristics database.

The second component of this project partially cofunds the CEC project to 1) perform systems tests to verify electric and thermal efficiencies and 2) facilitate third-party stack emissions testing to collect emission test data in compliance with CARB testing procedures.

Results will provide first costs and overall annual system efficiencies needed for desirable payback periods.

**Results / Status**

Researchers are in the process of identifying the best opportunities for widespread adoption of mCHP by characterizing the different technologies.

The initial list of technologies to conduct economic evaluations include:

- 6kW gas-engine-driven heat pump mCHP system (because of its space cooling capability)
- A 25kW micro-chiller (because of its refrigeration capability for convenience stores, restaurants, and other applications)
- A 1.5kW fuel cell, and
- A 3kW boiler-to-mCHP conversion system, and
- A 25kW mCHP system.

In 2018, a laboratory setup was created to performance test the 25kW Lochinvar mCHP system and facilitate third-party stack emissions testing to collect emission test data in compliance with CARB testing procedures. These data will support steady-state emissions performance for CARB DG certification application. The emissions testing will be performed with a new and aged catalyst to prove long-term emissions control. The long-term emission control data will support CARB certification requirements that the system can maintain emissions control for at least 15,000 hours.

In 2019, 25kW the Lochinvar mCHP system was commissioned. Preliminary results indicate emissions were controlled well below CARB limits with the new and aged catalyst.

The development of the Marathon Engine Systems 4.5kW system is under way with the CEC. The system is scheduled to be tested in the laboratory after the 25kW Lochinvar system.

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INDUSTRIAL APPLICATIONS
Ribbon Burner Improvements

The objective of this project is to develop and demonstrate an innovative cost-effective, low-NOx ribbon burner combustion system that can be used for a wide variety of industrial processes. Results of a prototype unit in a full-production field test demonstrated 50% NOx reduction and 5% energy savings.

Project Description

The gas-fired heating, drying, and baking of food products is accomplished extensively by conventional ribbon burners, which are also widely used in other industrial food-processing and surface-treatment applications. These natural gas burners/systems are coming under stricter emissions regulations in many regions of the United States, especially in California. Reducing NOx emissions is critical for the continued use of ribbon burners combustion systems throughout the state.

In response, researchers developed an advanced low NOx (ALN) ribbon burners combustion system directly applicable to the business and environmental concerns of the California bakery industry. Considering the broad application of ribbon burners, the ALN combustion system has the potential to support the wholesale baking industry in meeting and exceeding more stringent emission requirements while increasing efficiency and maintaining product quality.

The overall objective of this effort was to develop and demonstrate a new NOx-mitigation technology to cost effectively enhance to the traditional ribbon burners combustion systems, and included laboratory-scale demonstration followed by technology demonstration and monitoring of an industrial baking oven in the field. UTD’s project partners included the California Energy Commission and SoCalGas.

Benefits / Market Implications

According to the American Bakers Association, there are more than 700 baking facilities and baking suppliers nationwide. A typical mid-size bakery might have three production lines and consume about 7 million cubic feet of natural gas per month, resulting in approximately 0.6 Tcf of annual natural gas consumption by the U.S. baking industry.

Reaching the target of 50% reduction in NOx production (< 15 vppm at 3% O2) could lead to significant reductions of pollutant emissions from ribbon burner installations. Considering the broad application of ribbon burners for industrial processes, the ALN ribbon-burner concept has the potential to help end users meet more stringent emission requirements without sacrificing efficiency, major design, or process control.

Assuming a 30% market penetration in the baking industry, California-wide emissions reductions are estimated as follows (spreading the technology across the nation will offer much higher benefits):

- Natural gas reductions of 1.3 million to 1.5 million therms per year
- Carbon emission reductions of 7,500 to 10,000 tons per year, and
- NOx emission reductions of 200 to 300 tons per year.

Ribbon burner (left) and flame pattern of the burner at the average firing rate (right).
Technical Concept & Approach

This project involved the following completed tasks:

- Qualified Host Site Selection and Baseline Performance Quantification
- Demonstration System Specification, Design, and Engineering
- Technology Installation and Shakedown at the Host Site
- Data Collection and Analysis
- Post-Demonstration Monitoring, and
- Technology Outreach and Initiation of Commercialization Activities.

Results

The ALN ribbon burners combustion system demonstrated a 50% NO\textsubscript{x} reduction in a full production environment, with potential for even greater reductions. This brings emission levels well below the new air quality regulation emissions in southern California that are the most stringent across the United States.

The demonstrated approach assumes a portion of exhaust gas (which is laden with CO\textsubscript{2}) is mixed with the combustion air to reduce the O\textsubscript{2} content in it and, therefore, to reduce the NO\textsubscript{x} emissions produced by industrial ribbon burners or other types of burners with partially premixed flames. This approach was demonstrated in a full-scale wholesale bakery, confirming that it can meet new regulations limiting NO\textsubscript{x} emissions without the need for expensive modification to the burner systems. For situations when the NO\textsubscript{x} reduction is critical and replacing the conventional ribbon burner is not possible or is cost-prohibitive, the demonstrated approach can become a viable option, especially in light of the strengthening of federal and state environmental regulations.

Results of conducted experiments and computational fluid dynamics modeling demonstrated that the dilution of the combustion air with CO\textsubscript{2} can result in significant reductions in NO\textsubscript{x} formation.

Quantifiable fuel savings of approximately 5% compared to the baseline run were demonstrated during the project. Emissions and fuel consumption data was determined by an independent third party as part of a measurement and validation report. Bagel production was successfully accomplished with the modified system with no loss of production.

The technology was presented at the Baking Industry Equipment Manufacturers meeting in 2018. It will be promoted at the IBIE (major International Baking Industry Expo) in Fall 2019 via marketing and outreach to end users and qualified OEMs.

A U.S. Patent for the technology was granted and officially released in April 2019. Licensing discussions are in progress with a potential commercialization partner.

Status

A Final Report that summarized the results of the completed project phases was issued in April 2019.

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Gas-Fired Rotary Dryer with Heat Pump for Food-Processing Applications

In this project, researchers demonstrated at a host production site an innovative technology that integrates a gas-fired thermal-vacuum process with a heat pumping system to dry agricultural products. Energy savings of 61% to 65% were achieved.

Benefits / Market Implications
Integrating a heat pump into the higher-efficiency GFTD provides significant energy savings and carbon footprint reductions. Applying GFTD technology to commercial and industrial gas-fired drying processes would achieve energy savings of more than 60%, reduced pollutant emissions (at least 10%), and offers the strong potential for moisture recovery and reuse.

The successful implementation of GFTD technology with integrated heat pumping across industrial food processing and agricultural drying offers significant energy savings and environmental benefits for end users and dryer operators worldwide.

Technical Concept & Approach
For this project, a research team designed, fabricated, and assembled the approximately 100-tons-a-day GFTD system and demonstrated its performance potential in a full-scale production environment. The demonstration system was commissioned at the participating host site in late 2018, followed by the system startup, shakedown, performance-data collection, data processing, and final reporting.

In this project, researchers demonstrated the advanced high-efficiency drying technology that integrates a gas-fired thermal-vacuum drying (GFTD) process with an innovative ejector-based heat pumping technology, to further improve efficiency and production of drying operations. Technology performance was evaluated at a California food-processing plant.

Feed of the product being dried.
Employing commercially available off-the-shelf equipment and key components provides the opportunity to reduce combustion emissions and increase cost effectiveness in industrial and commercial drying operations. The advanced, ejector-based heat pumping approach was employed to further enhance a performance efficiency of GFTD technology.

This UTD project cofunds a research project funded by the California Energy Commission, with additional co-funding provided by SoCalGas and cost sharing from Wilson Engineering, and Martin Feed, LLC, a California cattle feed processing site that serves as the host facility for this technology demonstration.

Results

The effectiveness and efficiency of industrial drying is characterized by the length of drying time, energy consumption, capital and operating costs, product quality, and environmental compliance. The primary achievement of this commercial-scale demonstration was the system design and ejector manufacturing. These are key components of the technology, and in this field demonstration they consistently met the required calculated parameters. The thermo-vacuum process used in this technology significantly improved the drying time and energy consumption of the system, while reducing environmental impact.

In order to dry product from 35% to 12% of moisture content (demonstration unit original design specification), there was a need to remove 84 pounds of moisture per minute. A standard drying process would use 5.4 MMBtu/hr to directly heat the materials and an additional 10-15 MMBtu/hr to heat air circulated through the system to remove the moisture evaporated from the materials being dried. The technology demonstrated under this project requires only 6.7 MMBtu/hr (7,000-8,000 CFH) to provide both the heating and vacuum that deliver the airflow to remove the moisture evaporated from the materials. This results in natural gas savings of 61%-65% (12-13 MMBtu/hr) for the same drying product throughput. Based on the drying system design, it is estimated that capital costs could be reduced by 50% or more, taking into account the adequate replacement of recirculation pumps and air fans for the ejectors and heat exchangers.

The project demonstrated the designed performance of the ejector system for product throughput of 366 pounds of wet material per minute (10-11 ton/hr).

A U.S. patent application for the technology was filed. The demonstration system is being considered for follow-on engineering optimization, performance enhancement (including water recovery and utilization), and drying product nomenclature expansion beyond the food processing.

Status

A Final Report on the development and demonstration of the technology was issued in June 2019. Various recommendations were made to move the technology forward.

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Field Validation of Gas-Quality Sensor for Natural Gas

The objective of this project is to conduct field evaluations to demonstrate the abilities of a new reliable and low-cost gas-quality sensor that can detect changes in gas quality [heating value, hydrocarbon, and carbon-dioxide concentrations] in real time and provide valuable data to operators and end users.

Project Description
Natural gas is priced by total energy delivered (in Btus or therms). However, Btu content cannot be easily measured, so a common practice is to measure the volumetric flowrate at the point of use, and to determine total energy used by multiplying this number by the average energy content (Btu per standard cubic foot) measured at a central location. While this approach is typically adequate for billing residential, commercial, and most industrial customers, there are industrial combustion processes (e.g., processes for glass and fertilizer production) and power-generation equipment (e.g., dry low-NOx gas turbines and lean-burn internal combustion engines) that have stricter limits on gas quality and composition.

For major customers, some gas companies have installed equipment to continuously monitor gas quality to obtain measurements that can be readily converted to heating value, methane number, or Wobbe Index. The introduction of shale gas and upgraded biogas from anaerobic digesters into the gas-transmission network is increasing the importance to more accurately and more regularly measure the natural-gas heating value for many of these large-volume customers.

There is also increased opportunity for gas companies to use renewable natural gas (RNG) supplies that can be obtained from upgrading biogas from wastewater digesters and landfills to satisfy growing markets for compressed and liquefied natural gas (LNG) use for transportation applications.

The most common equipment used today for continuously measuring natural gas heating value is the gas chromatograph (GC). Although GCs provide accurate Btu values based on direct measurements and compositional data, they have several drawbacks, including:

- Long response times (often four minutes or more)
- High capital costs (in excess of $20,000), and
- Regular calibration required (a recurring operating cost).

To address the issue, researchers developed and extensively laboratory tested a heating-value sensor on natural gas, biogas, and producer gas. Testing in the field was also conducted for biogas applications. The sensor is expected to be significantly lower in cost (under $5,000) than gas chromatographs and will address other limitations of the GC.

The objective of this project is to continue to develop and then demonstrate a practical, reliable, and low-cost gas-quality sensor (GQS) that can detect changes in gas quality (e.g., heating value, hydrocarbons, and carbon-dioxide concentrations) in real time and provide this data to natural gas pipeline operators and end users of natural gas.

Benefits / Market Implications
Gas distribution companies and large-volume gas consumers that are sensitive to variations in gas quality will benefit from the faster, lower-cost new Btu sensor. Industrial customers can operate equipment more efficiently with lower emissions when real-time fuel heating-value data are available. Operators of natural-gas-fueled turbines and internal combustion engines can have enhanced control of equipment performance and protection.
Specific advantages of the GQS include:

- The sensor needs to be calibrated just once for the application. User calibration isn't required.
- Simple to use; no special training is needed.
- Measurements can be taken at high gas pressures.
- Measurements can be taken continuously, allowing trending and controls operation.
- In-line configurations are possible.

Technical Concept & Approach

The GQS uses the infrared light-absorption properties of hydrocarbon gases to measure the Btu content and composition of a natural gas mixture. It has been shown that this sensor technology can be used to measure the air/fuel ratio in air/hydrocarbon gas mixtures delivered to combustion equipment. The accuracy of heating-value measurements made by this new instrument can closely match those of a GC, but at a much lower cost.

Technicians will prepare, calibrate, and install a GQS prototype at a utility site to monitor the heating value and composition of natural gas for 12 months.

GQS measurements will be conducted side-by-side with a gas chromatograph to verify accuracy of the GQS measurements. The gas-quality data will be provided to the pipeline operators and/or end users in real time.

The project team will provide support to the GQS licen-see as the project moves pre-production gas quality sensors through customer testing. UTD members will have the opportunity to be in the first group of pre-production field testers.

Results

This project was initiated in 2014 with the procurement of a new GQS spectrometer which was integrated with the GQS hardware. The GQS software was modified to allow the GQS controls to communicate with the new spectrometer. The extended-range spectrometer enables higher accuracy and repeatability of natural gas monitoring.

An experimental apparatus was used to calibrate and test the GQS after upgrades and modifications. The experimental setup consists of a blending station and a certified mixture of methane, ethane, propane, butane, and carbon dioxide. The composition of the blend supplied to the GQS was varied by diluting the certified blend with nitrogen.

In 2017, testing of beta prototypes was performed using 12 gas mixtures with compositions covering the range of anticipated real-world biogas and natural gas.

GQS developments include:

- Software integration was conducted. The new spectrometer can read high wavelength data and, therefore, collect carbon dioxide data directly. Software was modified to collect and process this data.
- Details of the dimensions, utility requirements, and other aspects of the box (inlet and outlet ports, temperature range, etc.) to hold the GQS for demonstration testing were made.
- The enclosure was received, and the team completed assembling the GQS inside the enclosure. Two sensors were installed. One sensor followed a prototype design using a spectrometer and the other sensor is a commercial prototype built by the commercializing partner and using an interferometer.
- Filed demonstrations were arranged for a site in Tulsa, OK, and at an LNG facility in North Carolina. All sensors were installed in enclosures and prepared for testing per safety requirements of the two host sites. Data was collected in Tulsa in early 2019 and in North Carolina during the summer of 2019 from two versions of the gas quality sensor connected in series in both enclosures.

In 2019, project team provided support for the GQS demonstration in Oklahoma while idling a demonstration unit in North Carolina while waiting for the facility to be in operation in the summer of 2019.

Status

The project team will analyze data from the field demonstrations, including results of calibration tests of 10 next-stage GQS units.

Efforts in this project also supported technology development valuable for the licensor, CMR Group, to commercially introduce an initial version of the GQS device in summer 2019.

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On-Site Electrical Generation

Research in this project is focused on photovoltaic technologies suitable for converting thermal radiation into electricity. The goal is to design, build, and test an innovative thermal photovoltaic concept for combined heat-and-power generation at a 1-2 kW scale, to economically maximize energy efficiency of homes, small businesses, and similar users.

Project Description

Small-scale on-site electricity generation is an attractive option for natural gas consumers. However, current-generation technologies are often inefficient and relatively expensive, and involve high temperatures and moving parts.

In this project, research focused on thermal photovoltaic (TPV) technology as a potential solution. Recent advances in gallium-based cells offer the potential for achieving significantly higher conversion rates for high-efficiency TPV-based combined heat-and-power (CHP) systems. While TPV is ideal for CHP applications, the technology is also applicable for power generation alone.

For this project, researchers designed, built, and tested an advanced TPV concept for CHP generation. The results were used to develop a performance model for the selection of appropriate TPV cells and a conceptual design for a TPV-based power generator with the potential for 70% power-generation efficiency.

Benefits / Market Implications

TPV CHP systems offer several advantages over conventional technologies:

- The systems have almost no moving parts, are practically noise free, and have low maintenance and long life
- The TPV power-generation component can be directly integrated into a variety of thermal equipment to maximize performance, which is a distinct advantage over separate power-generation systems, and
- Significantly fewer pieces of equipment are required, resulting in a reduced footprint and weight.

Technical Concept & Approach

Similar to conventional solar cells, TPV cells can convert radiant energy into electricity via photons, offering an opportunity to directly generate electricity using radiant burners and TPV cells. Both approaches involve a thermal emitter (sun or radiant burner) and a PV diode cell designed to match the wavelength of the emitter. The key differences are the emitter temperature and its distance from the cells.

In recent years, partly because of accelerated investments in high-temperature concentrated PV solar technologies, this research area is attracting more interest for both stand-alone power-generation systems for remote applications as well as for CHP. However, current approaches do not adequately address the key efficiency and cost challenges, making near-term prospects for commercial products unlikely.

This project builds on other research currently under way to develop a high-temperature/high-efficiency solar heat-storage and power-generation system. One of the core technologies being developed is a low-cost, gallium-based high-temperature and high-efficiency solar diode, which provides an excellent match for a natural-gas-fired infrared emitter.

Researchers conceptualized an innovative approach to address both the efficiency and cost issues of current
Technologies to significantly boost power conversion efficiency to more than 30% and system efficiency over 80%, while keeping costs within the range of alternative CHP technologies to more than 80%, while keeping costs within the range of alternative CHP technologies.

Key features of the concept are:

- Use of high-efficiency, low-cost, standard-size, and mass-producible gallium-based TPV cells to reduce costs and increase conversion rate.
- Use of economical backing material on the cells to maximize heat transfer and facilitate adhesion to heat-exchanger surfaces.
- Integration of TPV cells directly into the heat-transfer interface to minimize heat losses and maximize cooling (keeping cells cool increases conversion efficiency and cell-adhesive life.)
- Use of mirrors with oxide coating for selective transmission of desired wavelengths and reflection back to the radiant surface of undesired wavelengths to maximize conversion rate and keep cells cool, maximize efficiency, and extend life.
- Use of radiant emitter with integrated heat recovery to maximize system thermal efficiency and prevent contamination of TPV surfaces.
- Use of high levels of internal recirculation to increase temperature uniformity, eliminate hot spots, and minimize NOx generation.

Results

In this project, researchers demonstrated the viability of the concept of using back-reflective TPV cells to achieve high-efficiency conversion of natural gas energy to power. The results of benchscale experiments show potential for designing a compact natural-gas-fired TPV CHP system that provides >55% power-generation efficiency and allows wide variations in the ratio of power and thermal energy (hot water) generated.

The project team designed and built a test facility consisting of a one-inch-diameter gas-fired radiant tube with burners and heat-recovery devices on both ends. The tube was surrounded by a cylindrical reflector to simulate back reflecting TPV cells. The experimental effort focused on developing the gas-fired infrared (IR) emitter surrounded by a highly-reflective enclosure, since the integrated performance of various TPV cells could then be modeled relatively easily to estimate heat and power generation.

Tests were conducted at different conditions, while making step modifications to overcome challenges encountered. The results of experiments demonstrated the viability of achieving 1) regenerative self-sustained combustion with low exhaust-gas temperatures within a small-diameter tube, and 2) high tube-surface temperatures by enclosing the tube in an un-insulated reflective enclosure.

The results show the possibility of achieving radiant tube emitter temperatures in the range of 2,400°F by increasing the firing rate, reducing the excess air levels, and increasing the regenerative bed volume. The NOx emissions during the tests were high; however, these can be reduced to acceptable levels by additional equipment modifications.

Further adjustments were made to the test system and additional performance testing was conducted. The team was able to demonstrate stable combustion up to 5 kWth input and also demonstrate the potential for using back-reflecting PV cells to increase TPV CHP efficiency.

The project team was able to:

- Achieve stable flames over a range of air/fuel ratios and firing rates, when firing from either end of the radiant tube
- Achieve self-sustained reversing operation without the need for an external ignition source, and
- Acquire proof-of-performance data (air and fuel flow rates, system pressure drop, air and exhaust gas temperatures, reflector temperature, etc.).

The project team explored design concepts for a 2kW TPV CHP system to facilitate test planning, and initiated development of the test plan for evaluating its performance. As opposed to the previous design, the regenerators or recuperator, the burner nozzles, and the combustion air and the exhaust gas piping and valves will be located on the same end of the tube to minimize piping and reduce the size of the system.

Status

Complete fabrication of the system in the current project phase is under way.

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Next-Generation Infrared Burner

In this project, researchers evaluated gas-fired infrared burners that use advanced metal foam material to offer end users new high-efficiency products. The project team is collaborating with material and burner manufacturers to advance the technology.

Project Description

Using gas-fired infrared (IR) heaters instead of electric-driven IR heaters can significantly reduce both source energy emissions and end users' operating costs. The goal of this project is to build on earlier developments to advance a gas IR burner for commercial and industrial use.

Unlike conduction or convection, IR heating uses radiative heat transfer, which transfers heat through electromagnetic radiation (light). As IR light is absorbed by the load material, its surface is heated. This surface heating phenomenon can be highly efficient by avoiding the unnecessary thermal load of heating surrounding air.

The IR-heating industry divides IR heaters into short-, medium-, and long-wave products. The associated emitter temperatures as well as its radiant portion increase significantly at shorter wavelengths, while the response time decreases. While electric heaters are available across the IR spectrum, gas-IR is available primarily in the medium wavelength range. Catalytic gas-fired heaters are also available in the long-wavelength range. The short response times allow precise control of work-zone temperatures with the short wavelength electric heaters. Electric IR also typically offers significantly greater turndown range compared to gas-IR and shorter response times for heating and cooling.

In this project, researchers investigated advanced metal foam IR burners, with better material properties.

The technology evaluation testing provided baseline performance data for key performance indicators for these burners. It also allowed manufacturers to review key issues and identify technical areas that need to be resolved to make the product commercially successful.

Benefits / Market Implications

Currently, nearly 75% of the IR heater market in commercial and industrial applications is occupied by electric units. Development of an advanced gas-fired advanced IR burner that can meet market specifications will save energy on a source basis by increasing the direct use of clean, affordable natural gas.
Technical Concept & Approach

Specific tasks included:

- **Burner Design**
  
  The project team designed a laboratory-sized 35,000 Btu/hr burner with sensors, control, and valves with advanced material. This unit has broad flexibility and is well instrumented so a wide range of parametric tests can be conducted and data used to optimize design and operating conditions.

- **Laboratory Testing**
  
  A range of IR burner tests were conducted to demonstrate safe and stable operation, collect valuable data for burner optimization, and investigate the effect of all independent variables on the performance of the advance IR burner.

Results

Researchers selected and tested multiple commercial IR burners to evaluate operational and emissions performance. Different materials and original equipment manufacturers (OEMs) were chosen for the testing to provide a spectrum of performance data. The key performance indicators for the burner testing were turndown, emissions, start-up and shutdown characteristics, and temperature uniformity.

Test showed the advantages and key limitations of these burners. The high-throughput burners could provide high output; however, these led to high emissions and potential material degradation. Burner materials such as ceramics led to cracking due to thermal cycling and were difficult to form into different shapes. Other materials such as metal fibers lead to non-uniform mixing, non-uniform temperature profiles, and loss of fiber material due to high-temperature zones.

Metal foam materials testing showed promise in certain aspects, such as adapting to different shapes and layouts, more robust design, and improved thermal cycling characteristics. This material showed the potential to replace a majority of the materials and be able to provide a long-term solution to gas-fired IR.

Emissions and performance testing showed that the non-uniform mixing and high local temperatures led to increased NOx emissions (>20 ppm @ 3% O2). In addition, the start-up time for a gas-fired IR was high (>7 seconds) with burner material choice making a significant impact.

Based on the testing of all the burners and in discussion with OEMs, some materials show great promise but the challenges that need to be considered include:

- Low backpressure can make air/fuel distribution difficult across a large burner face
- Life expectancy may need to be demonstrated
- Semi-rigid – material can tear or fracture if bends are too sharp
- Safe mode of failure if subjected to extreme temperature must be demonstrated
- Eliminate or reduce potential for backlighting
- Material can be subject to oxidation, and
- Material may trap particulates.

Status

A Final Report was issued in July 2019.

Researchers have teamed with a burner manufacturer and an advanced material manufacturer to resolve key issues to move the technology to the market.

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On-Demand Heat-and-Power System

In this project, researchers demonstrated an innovative, compact, gas-fired closed-loop heat-and-power generation system that uses a unique new particle-gas heat-transfer fluid. The system is designed for use in commercial/industrial processes to integrate and maximize renewable solar energy.

Project Description

This project advanced the development of a gas-assisted particle/thermal transport and storage system.

The system uses novel secondary optics in a solar receiver to achieve high efficiency at high temperature; collect heat in particles instead of silicone oil for high temperature and low fire danger; store heat in particles instead of molten salt for low cost; and use reflective lift-off cooled photovoltaic (PV) cells on the secondary reflector to raise efficiency.

The particle-gas thermal fluid allows transport and storage of thermal energy over a wide range of temperatures at low pressures and low cost. Its very high heat-transfer rates enables the design of compact heat exchangers, and the low pressure significantly simplifies and reduces the costs of the system components.

The use of supplemental natural gas with this novel technology makes renewable solar energy more attractive to the end-user by enabling round-the-clock on-demand electricity generation and optimum sizing and utilization of the more expensive energy storage and power block components.

In this project, researchers further demonstrated the system and identified new opportunities the technology. Following successful tests, the particle flow loop with storage was integrated with the prototype collector system.

Benefits / Market Implications

The technology under development in this project has the potential to provide a robust, cost-effective, high-efficiency, solar-energy-driven process-heating and power-generation option to industrial, institutional, commercial, and power-generation sectors. The many beneficial characteristics of the particle-gas heat-transfer and storage fluid (e.g., the very wide temperature range; inert, high heat-transfer rates; low pressures; and very low pumping power) make it attractive for various other applications in commercial/industrial applications.
Particles were successfully operated up to 685°C peak temperatures. The use of internally-flowing particle HTF was demonstrated for the first time in an actual prototype collector system, which involved several meters of pipe and flex hoses.

Prototypes demonstrated:
- The ability of a two-stage linear trough system to generate high concentration ratios on the absorber and enabling efficient high temperature operation
- The use of back-reflecting solar cells to provide spectrally selective secondary concentration, and
- The potential of particle HTF for increasing the operating temperature in solar thermal systems above the 400°C limit of thermal oils and the 580°C limit of current molten salts.

To facilitate assessment/commercialization of the technology, the team developed a system-performance model, a technology-to-market plan, a detailed techno-economic analysis with bottom-up costing, a value-chain mapping with market analysis, and a technology transition plan.

The team also assessed the potential for applying the particle transport and storage system developed in this project to other industrial and commercial processes. The most attractive opportunity appears to be in heat recovery and storage from high-temperature industrial and commercial systems, both continuous and batch type, for immediate or on-demand use.

Status
This project was completed with a Final Report released in September 2018.

Following successful completion of the current project, the research team has secured significant governmental funding for a project to scale-up and demonstrate the integrated system.

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Energy-Recovery Heat Exchanger

This project involves designing and demonstrating in North America an advanced recuperator technology to preheat combustion air that has been proven in Europe to increase overall system efficiency for commercial and industrial gas furnaces.

Project Description

A common way to increase the efficiency of commercial and industrial furnaces is to use a heat exchanger to transfer heat from hot exhaust gas to combustion air. While preheating combustion air can lower natural gas demand by 10%-40%, many furnaces do not employ this simple means of energy savings because the higher equipment costs make payback times too long to justify the investment.

This project addresses this issue by demonstrating a technology known as the Radiative Recuperator with Secondary Emitters (RRSE) – a technology that has been found to be more compact, less expensive, and more efficient than heat exchangers currently available in North America. The RRSE’s shorter payback time will enable this technology to be installed on many commercial and industrial furnaces that currently have no cost-effective means to recoup exhaust-gas heat to save energy and reduce emissions.

The objective of this project is to demonstrate the capabilities of the RRSE in a real-world setting in North America.

The RRSE was developed at the Center for Energy Efficient Technologies (CEET) of the National Academy of Sciences, Ukraine. The RRSE has undergone significant development, modeling, laboratory testing, and initial industrial testing. But despite extensive testing and impressive performance results, the RRSE has never been deployed outside Eastern Europe. The demonstration supported through this project provides an opportunity to introduce this advanced heat-recovery device to a wide industrial audience.

The RRSE is supplied with flexible inserts known as secondary emitters inside the tubes along the full length of the system. The arrangement has been demonstrated to be superior to existing recuperator designs equipped with spiral inserts (turbolators). Compared to conventional heat exchangers, the RRSE has:

- Increased heat transfer from flue gas to combustion air
- Higher combustion-air preheat temperature
- Decreased heat-transfer surface area
- Lower total weight of recuperator metal, and
- Lower wall-surface temperatures (leading to longer service life).
Results
Researchers are using a recuperator design with a stacker for scrap preheating to maximize heat recovery. Researchers found that potential energy savings of 19% can be obtained with air preheating alone. When scrap preheating is combined with air preheating, energy savings as high as 34% can potentially be achieved.

Benefits / Market Implications
This project addresses a large potential market for furnaces that are not yet using combustion-air preheating. These furnaces are found in industry (such as die casting, foundries, minerals and ore processing, various chemical processes), agriculture (drying, roasting), and commercial cooking (bakeries, general cooking, chips, brewing). Scales differ from one industry segment to another, but the RRSE is highly adaptable and can easily be sized for commercial and industrial applications.

The RRSE can provide cost-effective energy savings on a wide range of furnaces. To illustrate one large potential market for RRSE heat exchangers, the North American Die Casting Association estimates there are more than 400 die casters in the United States, and most do not presently use any exhaust-gas heat-recovery devices. Saving 30% energy on 30% of the die-casting furnaces alone would reduce gas demand nationwide by 60 million SCF per year.

Technical Concept & Approach
Specific tasks for this project include:

- **RRSE Design**
  The full-sized design serves as a template for design of various sizes and configurations

- **Fabrication**
  An industrial configuration of the RRSE will be fabricated specific to the field test demonstration site furnace capacity.

- **Industrial Installation**
  The RRSE will be installed on the exhaust duct of an aluminum-melting furnace at a die-casting company in California. This will be part of a larger installation of equipment designed to demonstrate energy savings on this furnace.

- **Demonstration Testing**
  Independent variables to be evaluated include number of secondary inserts, temperature of preheated air, velocity of exhaust gas and air through the RRSE unit, and volume of exhaust gas processed. Results will be used to optimize the system design and to validate the technology in preparation for commercial development of the technology.

Status
Final modifications are being made to the furnace and brickwork in preparation for installation of the burners and recuperator.

The refractory work is now mostly complete. The new control panel will also be assembled while final furnace modifications are made.

Full system installation is planned for 2019 with operation beginning immediately after installation.

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Recovery of Water from Humid Exhaust Gas to Save Water and Energy

Researchers are investigating a novel new thermal ejector technology to recover useful process water from humid exhaust gas, which in turn can increase overall efficiency. The project involves a field demonstration at a large industrial facility in California.

Project Description

Industries that use large volumes of water to cool natural-gas-fired furnaces could save money if water from hot exhaust gases can be economically recovered and returned to the plant for cooling and other uses.

Toward this end, this project is focused on thermal ejector technology that uses the low-level heat in exhaust gas to recover usable, room-temperature water.

In this project, a research team is demonstrating an innovative self-regulated ejector cooling system that generates colder water at a manufacturing plant. This project is being conducted in collaboration with the California Energy Commission.

The thermal ejector technology to be demonstrated in this project is the first practical technology that can recover room-temperature water that can immediately be returned to a plant and used for process cooling.

Benefits / Market Implications

Drying, curing, commercial cooking, and other agricultural and industrial processes with humid exhaust gases are strongly positioned to realize large benefits from utilizing thermal ejector technology. This technology offers the opportunity to reduce the huge water demand at power plants. Overall, freshwater savings are estimated at one billion gallons per year in California when deployed on only 50% of applicable industrial and commercial furnaces.

The technology has the potential to provide additional service and economic benefit for the same amount of gas combustion.

Some sites can also save significant amounts of natural gas when warm water produced by a unit displaces ambient temperature water supplies. Carbon dioxide emissions would also decrease at sites where recovered warm water reduces natural gas demand.

Water recovery and reuse can enable plant expansions while also improving plant efficiencies and reducing greenhouse-gas emissions per unit of plant production.

Technical Concept & Approach

For this project, a demonstration of thermal ejector technology will be conducted at a major industrial host site in California. The project team will attach a demonstration scale unit to the humid exhaust gas of equipment at the facility, and recover water from a portion of that exhaust gas. The demonstration system will be based on the laboratory-tested prototype, but will have production capacity of one ton of water per hour (~241 gallons/hour).

Using the remaining thermal energy in the humid exhaust gas from the facility’s drying kiln will help to conserve water (a very valuable resource in California) and enable the plant to receive an added benefit from the same natural gas already being burned in the kiln, thereby also conserving natural gas.
Project work began with modeling and design of the demonstration unit. Plant information was used to model and design the demonstration unit. The unit is expected to recover more than one ton/hour of water from 10% of the kiln exhaust gas (10,000 cubic feet/minute).

After modeling and design calculations, a skid-mounted system was designed.

Demonstration testing will be carried out over a period of at least six months. A full set of performance data will be collected. When the demonstration testing data is available, the project team will develop a technology transfer strategy, including a product-readiness plan.

Results

Initially, project representatives visited the demonstration site to meet the project team, initiate the air quality permit modification process, and address developments for the water-recovery unit. Information from the visit was sufficient to plan the positioning and size of the skid-mounted demonstration unit. A preliminary layout was completed to serve as a starting point for a complete design.

The site host provided exhaust gas data for a furnace similar to the one to be used for the demonstration. This furnace is located at a different plant. This data confirmed the anticipated range of exhaust gas compositions, including water content, to be expected. The water content in the 256°F exhaust gas is high at 43 volume percent (32 weight percent). The amount of water recovered will depend on ambient air temperature which changes from day to night and around the year.

The final system design has one quarter the footprint of the first system and is much more reasonable for scale-up. Assembly of the demonstration unit will begin when all heat exchangers and other components are received.

In the final system design, no external water is required and the power demand was greatly reduced. Water and refrigerant are recirculated in closed loops to cool the flue gas. Ambient air is moved by low-pressure drop fans in order to extract heat from the refrigerant into the environment. External power is needed only for two water pumps, two ambient air fans, the flue gas blower, valves, and controls. Components are expected to be reasonable in size because there are no gas to gas heat exchangers in the system.

Status

The project team is coordinating efforts with the host site, host site company combustion engineers, the heat exchanger fabricator, and the assembly contractor. Assembly and start-up is scheduled for the fourth quarter of 2019.

Data on exhaust gases confirmed the anticipated range of exhaust gas compositions, including water content, to be expected. The water content in the 256°F exhaust gas is high at 43 volume percent (32 weight percent). The amount of water recovered will depend on ambient air temperature which changes from day to night and around the year.

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Project Description

Current state-of-the-art burners can achieve <9 vppm NO\textsubscript{x}, but with high levels of excess air, which reduces boiler efficiency. Options for achieving low emissions for burners in the commercial sector are either to install Selective Catalytic Reduction (SCR) or Flue Gas Recirculation (FGR). However, SCR systems are expensive and require additional permitting for ammonia slip and added maintenance costs, floor space, and expendable costs (urea and aqueous ammonia). The FGR systems also require additional equipment (e.g., a hot fan, insulated ducting, and controls). In addition, a high level of recirculated gases may present challenges to achieve single-digit emissions. However, a cost-effective, high-efficiency low-emission burner would eliminate the need for SCR and FGR.

Through previous UTD studies, a method was developed for improving flame stability and mitigating combustion noise, a major issue with low-emission burners. In this project, the technique is being incorporated into the burner design.

A pre-commercial prototype burner was designed in collaboration with Power Flame, Inc., a major U.S. burner manufacturer. The burner demonstrated the ability to achieve <9 vppm NO\textsubscript{x} emissions with 4:1 turndown. NO\textsubscript{x} emission requirements of 9, 12, or 20 vppm are satisfied through adjustment of excess oxygen, allowing the same burner to operate across a wide spectrum of U.S. boiler markets.

In comparison to conventional ultra-low-NO\textsubscript{x} (ULN) burner technologies operating at <9 vppm NO\textsubscript{x}, the prototype burner provides a 2.3 percentage point gain in efficiency for operation at <9 vppm NO\textsubscript{x} (83.6% versus 81.3% efficiency).

The objective for this project is to field test and deploy a commercial prototype high-efficiency, low-emission, natural-gas-fired burner to meet current requirements in California as well as expected future requirements in non-attainment areas throughout the world. The ultimate goal is to commercialize a high-efficiency commercial burner that is economically and operationally more attractive to end users than current boiler systems.

The project team secured a clear path to market through its partnership with Power Flame. This project is being cofounded by the California Energy Commission and SoCalGas.
Benefits / Market Implications

The burner offers a cost-competitive alternative – in an easy-to-operate and simple design – to currently available equipment for the commercial hot-water/steam-generation market, and a means for achieving compliance in several major markets. Monitoring the performance of a commercially-integrated low-emissions boiler/burner system, complete with controls package, will provide critical data needed to facilitate its commercialization.

Technical Concept & Approach

This project specifically focuses on incorporating advanced control systems and combustion stability techniques into a burner design. The project team is addressing the remaining technical requirements for the pre-commercial burner technology through support and monitoring of a field demonstration at a linen supply company in California.

The technology is unique in its ability to achieve ultra-low emission levels and increase boiler efficiency compared to conventional burners. The burner incorporates dynamic flow geometry to achieve induced entrainment of cooled products of combustion, providing greater spatial uniformity in the distribution of the reacting species, heat release rates, and temperatures. Also, the technology allows for staging of combustion reactants within the combustion chamber, providing further thermal distribution within the boiler chamber. These features minimize localized high-temperatures regions within the flame, limiting the production of thermal NOx in a simple and robust design.

In the demonstration, a 125HP burner/boiler system supplies steam to the commercial laundry facility.

The goal is to evaluate the boiler/burner system performance over an extended monitoring period at the demonstration host facility. Technicians will make necessary modifications to the burner design and facilitate demonstration of a first commercial deployment of the burner. Subsequent efforts expected to occur in a future project will scale up the firing capacity of the burner to an even larger commercial sizes (e.g., 150 to 250 HP).

Results

Initially, several discussions occurred with Power Flame related to data and the selection of burner design improvements. Discussion focused on features that would ultimately set the burner apart from others that are presently on the market. A list of improvements/refinements was compiled and included: shorter windbox, scanner sighting, refractory use/life, and pilot upgrades.

The monitoring system for the pre-commercial boiler/burner system was installed in early 2018 at the commercial laundry facility. The boiler/burner consistently achieved emissions <9 vppm NOx without the need for costly and complex SCR, external FGR, or operation at high-excess-air levels. Extensive evaluation of the technology for over 10,000 hours of real-world conditions proved the burner capable of meeting low-emission levels while operating with relatively low excess air and high efficiency levels.

The host site demonstration documented a 9% savings in fuel usage as compared to the baseline boiler.

In addition to the continuous year-long operation and the energy savings, the host site operations manager noted that: 1) The control panel display provides the operator with a clear, concise readout of the operating parameters, 2 Operating conditions are stable and stay consistent with set points, and 3) The data-logging system provides operator knowledge for troubleshooting issues that may arise.

Operating emissions are much below the regulatory threshold, with significant fuel savings when compared to the previous installation.

Successful completion of this demonstration project has built confidence and awareness of the technology, furthering commercialization efforts, and helping to advance to market a cost-competitive, efficient alternative for commercial boiler operators seeking to reduce operating costs and greenhouse gas emissions, while maintaining regulatory compliance.

Status

Researchers anticipate making continuous product refinements in cooperation with a revised drawing package from Power Flame, and advancing this technology toward commercialization.

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Advanced Immersion Tube Burner

For this project, a research team will design, build, and demonstrate a low-cost, high-efficiency immersion tube burner that is simple to control and has low emissions. The burner will be capable of meeting increasingly stringent environmental regulations for end users in the food-processing industry and many other applications.

Project Description

Gas and electric immersion heaters are common for heating liquids in a variety of applications, including food processing such as frying and pasteurizing.

There are an estimated 25,000 or more immersion tube burners in use in the U.S. This does not include a much larger number of these tubes used in the oil and gas industry. For comparison, oil and gas operations in Alberta, Canada, alone, use an estimated 20,000 to 40,000 immersion tubes.

Electric heaters have advantages in terms of ease of installation, turndown, compactness, and onsite efficiency, while gas-fired heaters have lower fuel costs. Electric heater controls are also generally simpler and easier to operate. In gas-fired designs, the bath liquid achieves elevated temperatures by firing natural gas through a metal tube immersed in liquid. The tube could be of a variety of configurations (straight through, U-shaped, W-shaped, circular etc.). Because of large variations in tube configurations and the very high cross sectional firing intensities required, combustion improvements are difficult and current burners continue to have limitations with combustion stability, turndown, emissions, and controls.

Immersion tubes are generally 1-1/2 inches to eight inches in internal diameter, with firing capacities of 24,000 to 8 million Btu/hr. Assuming an average size of 1.5 million Btu/hr, and a 50% duty cycle, the total natural gas used is estimated at 4.4 billion Btus annually.

The focus of this project is on a low-emission, high-efficiency advanced immersion tube technology that promises to be competitive with electric heaters. Besides immersion tubes, the technology may have applications in water heaters, firetube boilers, steam generators, duct heaters, gas turbines, air heaters, absorption chillers, thermal oxidizers, synthetic gas combustion, and combined heat and power systems.

The burner will be capable of meeting increasingly stringent environmental regulations and be an easy-to-operate natural-gas-fired technology.

Benefits / Market Implications

The technology being developed in this project would be applicable to immersion tubes over a wide size range and offers a number of benefits, including:

Different immersion tube configurations for fluid heating.
• Reduced NO\textsubscript{x} emissions to <10 ppm, compared to current levels of 35-40 ppm. This would translate to 1,200 tons/year NO\textsubscript{x} reduction, assuming a 50% capacity factor. The state-of-the-art low-NO\textsubscript{x} burners suitable for this application all claim <25 ppm NO\textsubscript{x} at 3% O\textsubscript{2}, although no actual test data is provided.

• Increased efficiency to >80%.

• Enhanced customer retention, by offering significant environmental and operational improvements over current gas-fired technology.

• Increased manufacturing/production efficiency and reduced costs by using advanced 3D manufacturing techniques. Assuming 5% of the burners are retrofit annually with a 10% reduction in installed costs equates to an estimated $3 million in cost savings.

Technical Concept & Approach
Researchers recently tested a burner concept developed in part in a prior UTD project. The burner, manufactured by partner Oak Ridge National Laboratory, has the potential to provide a very high turndown ratio, uniform heat flux, and low NO\textsubscript{x} levels. It also has simple controls. Once set, it only needs to control combustion airflow to meet the demand.

The design inherently allows the air/natural gas ratio to self-regulate over the turndown without the need for external controls.

In laboratory tests, the burner achieved less than five ppm NO\textsubscript{x} (at 3% O\textsubscript{2}) with low CO on an un-insulated and un-cooled combustion chamber. In an immersion tube application, it could potentially generate comparable NO\textsubscript{x} levels at significantly lower excess air conditions. Key performance indicators for this project will be to further develop the concept to:

• Achieve 10:1 turndown, <5% excess air for high efficiency, and <10 ppm NO\textsubscript{x} and <50 ppm CO over the turndown range

• >80% efficiency over the entire turndown range

• Demonstrate stable combustion and reliability

• Secure a manufacturing partner and the first potential licensee of the new technology

• Successfully use existing UTD intellectual property developed for water heaters in a more demanding application, and

• Demonstrate cost-performance benefits versus electric heating.

Results
Researchers are designing a burner suitable for common entry-level products.

Preliminary designs for the multi-nozzle burner for sizes up to 8 million Btu/hr were developed to facilitate test planning. Based on these designs:

• A 3 million Btu/hr burner will have an approximately seven-inch inside diameter. The design incorporates flow-straightening vanes in the air inlet to improve distribution of combustion of the aspirated natural gas to the nozzles. This should improve combustion and heat transfer uniformity within the immersion tube.

• An 8 million Btu/hr burner will have an inside diameter of about 12 inches. The NO\textsubscript{x} emissions with the larger nozzles could be slightly higher at comparable excess air levels.

Researchers completed a plan for evaluating the burner performance over a range of operating conditions. This includes a test matrix, schedule, duration, and anticipated measurements.

In 2019, researchers initiated a detailed design of a 100,000 Btu/hr burner for laboratory testing in a simulated immersion-tube environment.

Status
Researchers are completing a simulation housing fabrication and laboratory prototype burner.

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“Advanced immersion tube heaters are deployed in a great variety of applications, including for indirect heating of process streams and liquid vaporizers for propane, oxygen, or other gases. The market today is differentiated, with some applications benefiting from high heat flux and others requiring lower heat fluxes. Simultaneous low NO\textsubscript{x} and CO performance with high efficiency at medium to high heat fluxes represents a commercial opportunity fitting between existing technologies.”

- John Clarke
Technical Director
Combustion Innovations, Inc.
TRANSPORTATION
Free-Piston Linear-Motor CNG Compressor Scale-Up

In this project, a research team is designing a large-scale free-piston linear-motor compressor for use as an inexpensive, energy-efficient, low-maintenance, and oil-free alternative to traditional reciprocating compressors used for natural gas vehicle fueling, in order to reduce operating costs for vehicle owners.

Project Description

While the natural gas vehicle (NGV) industry has been growing rapidly, there are still many issues challenging the industry, including station cost, maintenance, and gas contamination. These issues are heavily influenced by the compressor used at fueling stations.

Existing compressors for NGVs consist of multi-stage reciprocating compressors that use a rotating motor to drive a lubricated crank shaft that drives multiple pistons that may or may not be lubricated. These units suffer from high manufacturing costs, high mechanical parasitic losses, relatively high maintenance costs, and relatively short operational lifespans.

Previously, researchers successfully developed a small-scale Free-Piston Linear-Motor Compressor (FPLMC) for at-home NGV refueling that showed promise for reducing the cost of these appliances. This project builds on that work.

The team is using commercial motors to build a 50 standard cubic feet per minute (SCFM) compressed natural gas (CNG) compressor. The project has demonstrated the control of the commercial motors using off-the-shelf pistons compressing air. The team is now redesigning the fluid end and motor housing to operate with natural gas.

Benefits / Market Implications

The FPLMC design was developed to improve compressor durability and system efficiency, while significantly decreasing costs of the overall system, including installation and maintenance of compressors.

The FPLMC design eliminates all but one moving part of the compressor and has the potential to significantly reduce capital and maintenance expenses associated with refueling stations, as well as eliminating issues associated with gas contamination and oil carryover (the FPLMC is completely oil free).

The FPLMC can also be used as a two-in-one compressor and booster to increase storage utilization and fill rates.

Technical Concept & Approach

The FPLMC concept consists of a compression piston or pistons directly driven by a linear motor. This approach uniquely combines the functions of the compressor and motor into one device with a single major moving part, thus eliminating the inefficiencies inherent in converting rotary motion into linear motion, and eliminating the risk of oil carryover that is inherent with any lubricated crankcase.
The design has fewer wearing components, reduced parasitic friction, and, consequently, increased compressor durability, improved reliability, and reduced maintenance for end users.

The project team will develop and test a 50 SCFM gas compressor to demonstrate the commercial feasibility of using the linear motor compressor concept for larger-scale CNG station applications, such as to serve a fleet of Class 5-7 delivery trucks. This compressor will be a laboratory tested to demonstrate the performance, efficiency, and durability of the linear motor design under continuous, long-term operation.

Results

In Phase 1 of this project, researchers confirmed the feasibility of a scaled-up linear motor compressor by validating that it was possible to design and build a high-power reluctance or permanent magnet linear motor. Theoretical designs were developed for both motor types in excess of 100 kW. To make progress in the selection process, the project team evaluated commercial motor options to determine if there were any cost-effective designs that could drive the development forward, identifying several commercial motor variants.

Researchers investigated the performance of the scaled-up FPLMC by modifying the existing dynamic models that were developed and validated for the small-scale FPLMC. The performance of the compressor was analyzed over a range of operating conditions. This allowed the research team to optimize the design of the compressor for any performance target.

Researchers refined the dynamic compressor simulation into a parametric version that could be used to evaluate a range of compressor performance points. This simulation was used to evaluate how to best optimize the compressor and linear-motor combination.

An evaluation of the cost of commercial linear motors found that when optimized, commercial linear motors are comparable in price to standard rotary motors used to drive traditional reciprocating compressors.

In 2017, the project team identified components for the compressor, including servo drives, controllers, and software to control the commercial linear motors.

In 2018, researchers conducted a detailed engineering analysis of the commercial motor and controller performance to determine their limits within the linear compressor application. The project team made progress towards validating that commercial motors and controllers can be used for compression. This involved testing the response of the commercial controllers and correlating their performance to a dynamic simulation of the motors and controller operation.

In 2019, the project team validated air compression using commercial motors and validated the accuracy of the simulation. The project team is now working to modify the motor and compressor design to be suitable for natural gas compression.

Status

The project team is developing final CAD models of a prototype gas compressor and motor housing.

Future activities involve an effort to demonstrate multiple commercial motors used in parallel to drive a higher-power gas compressor to demonstrate real-world performance over time.

The project team has been in regular dialogue with compressor-component manufacturers for design input, quotes for compression stages, and exploratory commercialization discussion.

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CNG Fuel Station Best Practices

The objectives of this project was to collect assessment tools and assemble them into a user-friendly software webpage application to help CNG fueling-station operators achieve best practices and meet the requirements of applicable codes and standards.

Project Description

Natural gas has gained more use in the transportation sector in the past decade than ever before, due largely to the low cost of compressed natural gas (CNG) versus traditional fuels. There has also been an increased number of state incentive programs to supplement incremental costs for natural gas vehicles (NGVs) and stations, as well as increased focus on the environmental benefits of NGV fleets.

Because of the rapid growth, there are many new companies that are investing in CNG infrastructure. While new investments expand the cumulative benefits of the NGV industry, less-experienced companies that enter the market may be unaware of industry best practices and have limited technical capabilities to verify station performance.

Many CNG-station operators seek, or could benefit from, a technical review of their station operations to optimize the performance and safety. In addition, there are times when unsatisfactory performance of a station cannot be corrected until root cause(s) are determined. This can require specialized tools, collection and/or measurement devices, and instruments that are not commonly available or may not exist. Examples of tests that could assist station operators include: dispenser flow rates, fuel-quality testing (moisture, compressor oil, heavy hydrocarbons, odorant level, etc.), assessment of the "fullness" of fills, leak detection, thermal imaging, and noise emissions.

This project involves collecting and comparing operating practices to support the universal adoption of best practices and help ensure longevity, reliability, and safe operation of fueling stations.

The project team will also create a software webpage application to recommend and record maintenance activities for CNG fueling stations. The application will provide best practice information.

Benefits / Market Implications

The transportation market is by far the most concentrated energy sector in the United States, with more than 27 quads of energy use coming almost entirely from petroleum. This represents an enormous potential for beneficial use of natural gas as a transportation fuel and opportunities for consumers to save money and reduce greenhouse gas emissions.

Fast-Fill Station

CNG station fuel flow schematic and choke points.
The U.S. Department of Energy forecasts growth in natural gas use in the transportation industry from approximately 40 Bcf in 2011 to 84 Bcf in 2020 – levels that can possibly be exceeded given strong customer interest.

The most important impact of this project will be to ensure customer and public safety and maintain CNG’s reputation as a “safe fuel.” Another important value of this project is to improve customer satisfaction with the fueling experience. The development and distribution of performance-assessment tools will greatly relieve some of the burden that is placed on the fleets when developing fueling requirements.

**Technical Concept & Approach**

Phase 1 of this project involved collecting and collating information relating to safety, performance, and best practices of CNG fueling stations. The product of this investigation is roughly 80 pages of material which can provide great value to CNG fueling station operators. However, the quantity of information presented poses problems with effectively distributing this information. Therefore, Phase 2 develop a website application to effectively place this vast source of information at the fingertips of the station maintenance team.

In Phase 2, the project team created software in three main stages:

1. Software architecture and content
2. Programming, and
3. Software beta testing at a fueling station four weeks.

**Results**

In Phase 1 of this project, information was developed on the following areas:

- **Safety**
  This included information from applicable codes and standards as well as details on conducting safety reviews.

- **Station Performance**
  A series of tools and troubleshooting guides were developed to evaluate station performance.

- **Station Best Practices**
  Items surrounding a station that require regular maintenance are included in this area. Periodic maintenance checklists were created based on best practices found around the industry. A software tool integrating maintenance checklists with troubleshooting guides was included in the software. It can be the basis to allow notifications to be issued when some maintenance data deviates from trends. This can provide an early-warning system to maintenance personnel.

In Phase 2, the above information was incorporated into a mobile webpage application which includes a data entry interface for the compressor, dryer, and dispenser. The application also includes troubleshooting guides to provide ready access to the information necessary to ensure safe and reliable CNG station operation. This application was beta tested and is now ready for release to anyone who is interested. Since it is a web page, a different page will need to be created for each site. If interest merits, the system can be upgraded to improve the ability to add stations.

**Status**

The project is essentially complete. A web-based application was developed with the ability to operate over almost any device and not limit the storage of information to that specific device. The application allows data entry, storage and display of data in tables, notification of upcoming maintenance, and storage of troubleshooting guidelines developed in Phase 1 of this project. The Phase 2 Final Report is pending.

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CNG Composition Impacts on Engines and Fuel-Delivery Systems

Researchers developed a test protocol to collect and analyze natural gas and liquid contaminants found at NGV fueling stations, and are developing test methods to evaluate the efficiency of different liquid-contaminant removal systems and assessing mitigation solutions. The overall objective is to further enhance NGV engine reliability for end users.

Project Description

Some engine and vehicle operating issues reported by large natural gas vehicle (NGV) fleets are suspected to be a result of heavy hydrocarbon contamination (usually as a result of compressor oil carryover). However, heavier hydrocarbons and oils are some of the most difficult substances to accurately measure because they often drop out of test samples when improper procedures or equipment are used, leading to misleading or misinterpreted results. To address the issue, this project is focused on developing appropriate protocols for fuel-quality sampling and testing in order to quickly obtain solutions when operational issues arise.

Investigations in Phase 1 of this project found that a significant portion of reliability issues in compressed natural gas (CNG) vehicles can be traced to the contamination of the fuel with heavy hydrocarbons, either from compressor oil or from compounds in pipeline natural gas. These hydrocarbons are present either as a vapor or an aerosol in the CNG as it is transported onto the vehicle.

Phase 1 was successful in demonstrating a test protocol, but it also highlighted the lack of available filter testing at CNG pressures. Phase 2 addresses this need by:

1. Developing a test protocol to evaluate and rate the performance of coalescing filters or any other components designed to remove aerosols from high-pressure natural gas streams, and

2. Developing guidelines to design and apply methods to remove aerosol contamination from CNG downstream of the compressor in a natural gas fueling station.

Benefits / Market Implications

The protocols developed through this project will provide industry stakeholders (fleets and other end users, station owners, utilities, etc.) with consistent, accurate procedures that can be widely applied.
Generation of performance data for coalescing filters and adsorbents will enable design improvements to enhance the user experience with NGVs. Guidelines will provide station designers with the ability to confidently design stations which include components based on testing done with high-pressure CNG instead of low-pressure compressed air. These guidelines will include critical information to assist in the selection of adsorbent material, in particular their capacity to remove heavy hydrocarbons and odorant from the gas stream, which are currently poorly understood.

Ultimately, results from this research will allow end users to further reduce the capital cost of building CNG fueling infrastructure and generate more satisfied NGV user experiences.

**Technical Concept & Approach**

In Phase 1, researchers investigated the root causes of some reported vehicle issues (clogged injectors, regulators “freezing,” liquids in filter housings and storage containers, etc.). The investigation involved a literature search as well as discussion with vehicle and engine OEMs and fleets. Liquid samples were collected from nine different sites which were experiencing vehicle operational issues suspected to be due to CNG quality. When possible, liquid samples were collected from the low- and/or high-pressure coalescing filters on the vehicle. Additionally, liquid samples were taken from fueling station filters or dryers whenever possible.

In Phase 2, the project team is designing, building, and commissioning a test system to evaluate the performance of coalescing filters. Design and application guidelines will be determined from the data obtained during the testing program. An economic analysis will also be conducted to determine the cost savings these solutions could provide to fleets and fueling-station operators.

In Phase 3, a similar program will be conducted with adsorbent filters instead of coalescing filters.

**Results**

The review of vehicle contamination issues and causes revealed that the most common cause of vehicle reliability issues was contamination of the gas with compressor oil. Several instances of natural gas liquids contamination at CNG fueling stations were found, but these were predominantly upstream of the compressor and not the direct cause of the vehicle reliability issues.

Two test methods to detect (and/or measure) the presence of these heavy hydrocarbons were developed and tested.

The first method (the cryogenic trap method) takes a small slipstream of gas, reduces the pressure to atmospheric and the temperature to -130°F to condense any heavy hydrocarbons which could be vaporized in the gas, then filters out the liquids. These liquids are then tested in a gas chromatograph for quantification.

The second test method is meant to provide a quick, qualitative check of the gas stream to see if oil is present. This method uses commercially-available indicator tubes to detect heavy hydrocarbon or oil mist. These indicator tubes are meant for use with compressed air, so the test method had to be slightly adjusted for natural gas. The testing was inconclusive partly due to a lack of a known sample to test. This led to the development of a way to test gas streams with a known quantity of oil present. This occurred in Phase 2 of this project.

In Phase 2, a test system was designed and built to dose a known amount of heavy hydrocarbon into a gas stream, which will allow accurate evaluation of filler efficiency and the quick-check testing method described above.

The test apparatus construction was completed in early 2019. The system was designed to provide flow rates up to 250 SCFM to accommodate larger filters. Commissioning and initial testing were completed. No conclusion has yet been drawn from the testing.

**Status**

Phase 1 identified a lack of a method for evaluating the performance of different filter devices design to remove heavy hydrocarbons (compressor oil) from CNG fuel streams and is complete. Phases 2 and 3 are in progress.

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Modular CNG Storage System Investigation

For this project, researchers are investigating the status, related codes, and certification needs for various conformable CNG storage systems which have the potential to provide a 40%-55% reduction in weight, 20%-30% reduction in space, and 20% reduction in cost.

Project Description

The current state-of-the-art vessel for storing compressed natural gas (CNG) is a cylinder with either a metallic or non-metallic liner reinforced by a carbon or glass fiber wrap. However, this type of storage can be an inefficient use of the space on a vehicle. In response, the U.S. Department of Energy Advanced Research Projects Agency - Energy (ARPA-E) created a program to investigate conformable storage for CNG in order to increase the on-board fuel capacity of CNG storage, while simultaneously reducing cost and weight.

In this ARPA-E program and with UTD cofounding support, researchers identified several candidate technologies, including two radically different techniques:

- **Gas Intestine**

  In this design, a continuous polymer tube is folded back and forth on itself, allowing it to be efficiently packed in a rectangular or trapezoidal space, increasing the overall conformability factor. This tank design is also estimated to significantly reduce the cost of production because a continuous mesh overwrap can be applied in such a way to allow for continuous-production techniques. Initial estimates of the benefits include a 40%-55% reduction in weight, 20%-30% reduction in space, and 20% reduction in cost compared to a similar cylinder with the same storage volume.

- **Squeeze-Cast Tank**

  The second design is a squeeze casting that uses a continuous internal structure to form a pressure-bearing rectangular box while minimizing internal stress by creating a continuous minimal surface. The approach employs two novel aspects: 1) a mathematically optimal, internally structured tank and 2) a unique fabrication process based on squeeze casting over three-dimensional core structures. The resulting structure can evenly distribute stresses throughout the entire structure and will allow for a variety of outer dimensional shapes.

This UTD project leverages related research funding from ARPA-E and is investigating the status, related codes, and certification needs for various conformable storage systems being developed.
Benefits / Market Implications

Conformable storage for CNG vehicles has the potential to significantly reduce the storage volume, weight, and cost of high-pressure onboard CNG storage for natural gas vehicles (NGVs). These improvements could allow greater end-user adoption of CNG as a transportation fuel (e.g., longer range, lower cost, and lighter weight of CNG storage).

Transformative improvements not only positively impact the light-duty NGV market, but can also open up the long-haul market that has been historically slow to adopt CNG. By storing more fuel in a lighter configuration, Class 8 trucks can easily travel from station to station while still maximizing the amount of material they can carry.

Technical Concept & Approach

This project includes an evaluation of various conformable and modular storage designs to determine the market potential, status, barriers, and needs for the technologies. The project team will help to determine the best way to accelerate field testing and the commercialization of these technologies for end users.

Specific tasks include:

- **Product Evaluation**
  
  This evaluation will compare and select designs with the best potential for success as a transformative solution for CNG storage on vehicles. The evaluations will include a review of test results, validation of theoretical design calculations, a review of design assumptions and safety code compliance, and an assessment of the manufacturer’s capabilities to advance its product to market. Meetings with each technology provider and subject matter expert(s) will either validate the approach as sound or eliminate it from consideration for support.

- **Barrier Reduction**

  After selecting the most promising technology or technologies, the project team will meet with the manufacturer(s) to identify any technical or industry barriers currently preventing commercialization. Depending on the results, researchers will develop a strategy to reduce the barriers.

- **Search for Additional Funding**

  The project team will assist manufacturers in securing additional funding from various state, federal, and private industry sources. This additional funding can be used for technical development, testing, or barrier-reduction activities.

Results

Contacts were made with manufacturers and the research team has been receiving input about the status of each technology. The largest barrier identified through these discussions was the inability to certify an alternative storage design. As a result, a joint development proposal between Gas Technology Institute (GTI) and CSA Group was accepted by ARPA-E to refine the ANSI NGV2 standard to accommodate conformable storage. The contract was finalized, and GTI and CSA are reaching out to companies to participate in the code development process.

In 2017, the project team supported the release of a draft copy of NGV2 that includes the proposed language and test methods that will be used to certify conformable storage tank designs. Public comments are in the process of being reviewed by the NGV2 technical committee before the standard can be published.

In 2018, gunfire test methods were under debate for conformable cylinders as the caliber bullet recommended for standard cylinders is considered excessive for conformable designs that may have a small cross-section. A decision is not yet final; however, there may be similar codes that can be referenced regarding relevant test methods for small-diameter cylinders.

The project team received status updates from all known conformable storage manufacturers. Manufacturers also provided design and code guidance.

In 2019, the project team supported the development of final changes to NGV2, to make it possible to certify conformable storage designs.

Manufacturers of conformable vessels are developing manufacturing test pieces for testing and certification.

Status

The project team is waiting for test samples from several tank manufacturers. These tanks will primarily be used to verify both the design’s performance as well as the language that was added to NGV 2. These unique tank designs have never been tested, so the design and tests must be developed and fully evaluated to determine whether the tanks are suitable for CNG service.

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CNG Dispenser Full Fills

The goal of this project was to demonstrate an advanced control technology and a simple method for conditioning gas as it is dispensed into a natural gas vehicle in order to effectively manage the temperature and density changes and achieve a full fill, in order to reduce tank size and end-user costs.

Project Description

One of the largest issues facing the natural gas vehicle (NGV) industry and end users is under-filling, or failing to fill the tank to a settled 3,600 psi at 70°F. To address this challenge, the goal of this project was to demonstrate an advanced control technology and a simple method for conditioning gas as it is dispensed into an NGV.

Benefits / Market Implications

Under-filling directly impacts the cost and range of NGVs. The actual amount a vehicle is under-filled is dependent on a number of factors; however, about 20% under-filling is frequently cited as the deficit.

This project has the potential to significantly improve the fueling experience, lower the cost (due to decreased vehicle storage requirements), and enhance system efficiency for fleets that are most critical to the rapid adoption of NGVs. By improving the full-fill process, the cost of owning a CNG vehicle is reduced because smaller tanks can provide better range; while also improving the experience of the driver, who expects vehicles to be consistently filled. Improved full fills may also help to draw additional users (such as long-haul fleets) who are often concerned with maximizing their range without compromising their payload capacity.

Technical Concept & Approach

- Characterization Technique

The goal of this task was to advance the characterization technique for determining the initial conditions of a vehicle’s storage system. This task was expected to improve the current techniques used to determine the proper ending pressure and temperature given the starting pressure, temperature, and volume of the vehicle’s storage system.

- Fueling Simulation Tool

The goal of this task was to optimize a transient thermodynamic fueling simulation tool to improve industry understanding of the fueling process. Analysis of the fueling simulations identified critical system characteristics and advanced methods for operating a pre-commercial dispensing system.

- Testing and Validation

The goal of this task was to perform real-world testing to validate the transient thermodynamic fueling simulation tool, pre-commercial dispensing system, and advanced fueling method. This task involved the design and fabrication of the pre-commercial dispensing system as well as validation testing and data collection to verify benefits.

- Technology/Knowledge Transfer Activities

The goal of this task was to develop a plan to make the knowledge gained, experimental results, and lessons learned available to the public and key decision makers.
Results
Under-filling has seen little improvement because the solution is complicated, requiring changes to both vehicles and dispensers, as well as the need for cost-effective pre-cooling at the CNG station. This project explored these barriers, seeking to develop and demonstrate short-term solutions where possible, or make recommendations about long-term solutions to achieve consistent full fills.

Project highlights:
- Tested and verified that commercial dispensers significantly under-fill vehicles
- Developed and validated a CNG station simulation tool capable of testing dispenser algorithms across a wide range of ambient temperatures, starting tank conditions, and gas compositions
- Tested many existing and newly developed dispenser algorithms using the simulation tool
- Determined that vehicle-to-dispenser communications are necessary to improve fills
- Developed an advanced, high-accuracy dispenser algorithm that uses communicated information about the tank to achieve an accurate full fill
- Verified the improved algorithm performance by conducting CNG fills at laboratory facilities
- Verified that gas cooling was also necessary to achieve a full fill on days warmer than about 20ºF.

There are several root causes for the inability of current NGVs to receive a full fill: 1) inaccuracies in determining when a vehicle has reached a full fill condition, 2) uncertainty about the gas composition, and 3) heat of compression. Researchers addressed these issues by developing an advanced full-fill algorithm. The algorithm leverages communication between the vehicle and dispenser to accurately measure the real time temperature and pressure on the vehicle, then plugs that information into a polynomial that accounts of variations in gas composition to deliver an accurate and safe full fill. The algorithm takes the real-time data and calculates the fill status of the vehicle as a percent full that is used to control the fill and inform the driver of the amount of gas they are receiving.

The algorithm was tested across a range of conditions. Fill results to date have all been within 1% of an actual full fill. Using this algorithm, CNG dispensers can maximize the amount of gas a vehicle receives under any starting tank conditions or ambient temperature. The algorithm should also be compatible with any gas conditioning method used in the future to improve full fills on hot days.

The project team evaluated a number of gas cooling methods, coming to the conclusion that chillers are the only commercial means of guaranteeing a full fill currently available; however, expanders show significant potential for achieving full fills at a reduced capital and operating cost.

In 2018, researchers conducted a series of tests to validate that direct temperature measurements could be accurately used during a CNG fill to reliably determine when the tank was full. The communication protocol can positively identify a vehicle that is attached to the dispenser, establish a secure connection, and then communicate a wide array of data between the dispenser and the vehicle.

In 2019, analysis of the algorithm indicated that it can also adapt for uncertainty across a wide range of gas compositions without risking overfilling the vehicle. The communication protocol was integrated into a test system to validate that the Bluetooth system had accurately communicated sensor data between the vehicle and dispenser during an actual CNG fill.

Status
This project was completed with a Final Report issued in April 2019.

The project successfully demonstrated an improved full-fill algorithm that can help to immediately improve fills for fleets and stations that choose to adopt the technology. However, the algorithm alone is not a complete solution, and must be paired with a cost effective pre-cooling design to guarantee full fills year round. Accomplishing this long-term goal will provide significant benefits to the NGV industry, including consistent range and performance of NGVs, as well as cost and weight savings as the size of existing fuel systems can be significantly reduced.

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Through this project, researchers are monitoring and participating in relevant natural gas vehicle codes and standards developments. Efforts are focused on helping create or modify important codes and standards by participating on select technical committees and working groups, or through review and formal comment.

Project Description

Over the past several decades, many important safety standards and codes were developed to guide the natural gas vehicle (NGV) industry. Today, there is a suite of component- and systems-level standards that allow for continuity of the systems and to ensure vehicle, infrastructure, and operator safety.

Continuous monitoring for improvement and keeping pace with changes in technology is a critical need and significant challenge.

This project addresses the need to respond to new technologies, clarify coverage between existing standards, and expand coverage to all necessary applications. Part of the focus is to also help ensure that antiquated standards do not create an obstacle to product advancements and commercialization.

In recent years, UTD has supported efforts to develop information and provide input into the consensus-building process under rules of standards development bodies such as the American National Standards Institute (ANSI).

Also, a safety concern arose of over-pressurization of vehicle fuel storage cylinders fueled with current compressed natural gas (CNG) dispensing technologies. The NFPA 52 Committee/Code is unable to require listing or approval of temperature compensation systems because there is no industry approved standard to list or approve systems. In light of the need for a temperature compensation standard for natural gas fueling, representatives from this UTD project led a separate CNG task force to develop the CNG fueling temperature compensation standard. The now published requirements for temperature compensation devices allow CNG dispensing systems to adjust for full fill of vehicle fuel storage containers under all surrounding outdoor ambient temperature conditions and variations in natural gas composition.

In summary, the objective of this UTD project is to monitor and participate in relevant NGV codes and standards developments and to support the creation or modification of important codes and standards through participation on select technical committees and working groups, or through review and formal comment.

Benefits / Market Implications

Knowledgeable and logical input into the consensus-building process under rules of standards development bodies is critical to ensuring proper coverage to protect users and the general public.

This project also aids end users by supporting the introduction of new residential and non-residential NGV...
Results / Status

Representatives for this project:

- Continue to chair the NGV4.3 Task Force on Temperature Compensation requirements.
- Participated on the Harmonization Committee to identify inconsistencies and recommend changes to CSA B108, the International Fuel Gas Code, and the International Fire Code to recognize CSA NGV 5.1 and 5.2.
- Participated in the ANSI/CSA NGV 5.2 Compressed Natural Gas Vehicle Fueling Appliance Standard development process.
- Participated in the CSA/NGV 6.1-CNG Fuel Storage and Delivery Systems for Road Vehicles committee. This standard was first published in September 2016. Proposed revisions to the standard were distributed for public review and comment in 2017.
- Participated on the CSA Technical Committee for ANSI/NGV 4.1 (CSA 12.5) NGV Dispensing Systems Standard. In 2018, researchers presented to the committee information on communications and fueling algorithms for CNG dispensing. The Technical Committee is forming a Working Group to initiate the development of standards for communications.
- Participated on a Common Issues Task Force comprised of the chairs of all Technical Committees and Task Forces related to natural gas vehicle based standards to reconcile any differences that may exist among standards.
- Monitored the research being conducted on a new adsorbed natural gas (ANG) storage container standard ANG-2, as well as a low-pressure version of NGV5.1 specific to use with ANG vehicle storage under the Interim Requirement IR 7-16.
- In 2019, NGV2 2019 (CNG Fuel Containers) was published that includes localized fire tests and conformable storage.

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NGVAmerica Technology Committee Participation & Representation

This project provides technical information and resources to advance the safety, economy, reliability, low emissions, and best practices for users of vehicles powered by compressed natural gas or renewable natural gas, in coordination with the NGVAmerica Technology Committee.

Project Description

NGVAmerica (NGVA) coordinates a broad base of support for identifying the technical needs of the natural gas vehicle (NGV) end users. Through NGVA, the NGV industry can mount a coordinated effort to set priorities and promote technology.

NGVA is dedicated to the development of a growing and sustainable market for vehicles powered by natural gas or biomethane to benefit consumers and the environment. The organization represents more than 230 companies, environmental groups, and government organizations interested in the promotion and use of natural gas and renewable natural gas as transportation fuels. Its members produce, distribute, and market natural gas and renewable natural gas across the country; manufacture and service natural gas vehicles, engines, and equipment; and operate fleets powered by gaseous fuels.

NGVA’s Technology & Development Committee was created in 2015 to interact with federal agencies and industry stakeholders on NGV technology development, codes and standards, best practices, and other industry issues. NGVA working groups were created to support critical issues and needs, and revised over time to keep pace with the changing priorities of the industry. The organization relies largely on the voluntary efforts of member companies and their representatives to address the issues of most importance and interest. NGVA acts as a coordinator and facilitator to unite interested stakeholders.

Support for this project is being used to provide UTD representation on the NGVA Technology & Development Committee.

Benefits / Market Implications

UTD’s representation on the NGVA Technology & Development Committee is critical to address the needs of end users and to further advance the benefits of NGV technologies. Each of NGVA’s working groups focus on topics identified by the industry as the top priorities to position the consumer and the industry for the future. Speaking with a single voice backed by the consensus of stakeholders is a more powerful way for NGVA to set technical priorities for research and development for the consumer and industry.
Technical Concept & Approach

Two project team members are participating part time on the NGVA Technology & Development Committee and working groups, and a project member is now the Co-Chair of the Committee. Participation includes attendance at all committee and select working group meetings. When required, input will be gathered from UTD members to feed into the planning and priority-setting processes.

Updates are being provided through conference calls for UTD members and their representatives to receive briefings on the activities and plans of the NGVA Committee. On an as-appropriate basis, staff representatives solicit periodic requests for input from UTD’s Transportation Working Group and designated representatives to ensure that a broad base of opinions and thoughts are brought into the NGV Technology Committee’s decision making.

Results

In 2018-2019, project representatives continued their involvement with various NGVA working groups. A new working group was added in 2018 to address issues unique to facilities involved in manufacturing NGVs and components.

Representatives participated with groups addressing:

- Incident Investigation and Root Cause Analysis
- Gas Quality
- CNG Fuel System Inspection
- Codes and Standards
- Maintenance Facility Modifications
- Emissions/Environmental
- LNG and Marine and Rail
- NGV Manufacturing Facility Best Practices/Training, and
- NGV R&D Priorities.

Representatives participated on the Alliance to Save Energy “50 By 50 Commission: Heavy Duty Transportation Technical Committee” by providing technical information for the gaseous fuels section of the report. Progress on the Commission’s report and federal policy recommendations were shared with members as they became available. The Emissions Working Group conducted conference calls to address issues surrounding methane slip/fugitive emissions and, secondly, the accuracy and treatment of NGVs in the most commonly used emissions impact modeling tools. The Working Group also developed a White Paper titled Understanding Global Warming Potential - and Other Greenhouse Gas Emission Metrics. In conjunction with the RNG Coalition, the group created an infographic to show the vast quantity of RNG that is being used as a transportation fuel. The infographic can be downloaded from the following link:


Project representatives provided a detailed natural gas R&D topic list to NGVA and governmental agencies as high-priority recommendations for upcoming natural gas research funding initiatives. The project team supported NGVA in the development of a Cold Weather Advisory Bulletin to ensure safe operations of NGVs in cold weather as well as released a CNG fuel system inspection guidance document that can be found at the following link:


Status

Through the support of this project, two technical staff members continue to participate, one as Co-Chair, on the NGVA Technology Committee and their working groups.

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Test and Validate Small-Scale CNG Compressor Fill Stations

A project team is evaluating novel, small-scale compressed natural gas (CNG) scroll and liquid piston-type compressors. The objectives are to validate the manufacturer’s claims of performance, perform a safety review, and assist manufacturers in introducing new products in order to expand customer choice.

Project Description

One of the major issues with achieving wider adoption of compressed natural gas (CNG) vehicles is the lack of a convenient and reliable infrastructure. While small-scale compressors for filling have been commercialized in the past, consumers may want greater reliability and lifespan. A reliable compressor with a long lifespan could have the potential to attract small businesses and homeowners who are interested in CNG as an alternative to gasoline or diesel.

The liquid-piston-type compressor has been successfully applied to hydrogen compression, and is particularly known for quiet, durable operation. A novel CNG liquid-piston compressor evaluated in this project is built on the same fundamental principles, but employs some critical design modifications that allows it to operate with natural gas mixtures. The primary benefit of the design is the elimination of wearing seals and piston rings, giving it the potential for reduced maintenance and durability improvement compared to conventional reciprocating compressors.

Designers of the compressor estimate that the system could have a lifespan of 20,000 hours with only periodic hydraulic-pump-seal changes required. This is significantly longer than any comparable commercial units currently available.

Although the unit uses a liquid directly in contact with the gas being compressed, the rate of compression, method of introduction, and post-compression filtration eliminates the risk of natural gas contamination.

The technology is being tested in Europe with a major automotive manufacturing group and could deliver the reliability required for a home or small-fleet refueling compressor and be cost effective. The objectives of this project are to validate the manufacturer’s claims of performance, perform a safety review, and assist the manufacturer in its product commercialization efforts.

In this project, a research team will also help refine the design, validate overall cost of ownership, and evaluate the system for any code compliance issues in North America.
Benefits / Market Implications
This project has the potential to bring a near-commercial compressor technology closer to market in North America.

This technology has the potential to be a good alternative to current small-scale compressor technologies, making it easier for small businesses and homeowners to consider CNG as an alternative to gasoline and diesel.

Technical Concept & Approach
A project team will evaluate the prototype of the compressor. Researchers will then analyze the economics, report on the results, and provide recommendations on commercialization support.

A thorough review of the current designs of technologies will be reviewed, including assessments for compliance with ANSI NGV 5.1 and other relevant codes and standards. This review will provide the manufacturers with a comprehensive list of issues and design changes that are required for entrance into the North American market. This task will conclude with the selection of a pre-commercial prototype device to have its performance evaluated and tested.

A pre-commercial prototype will be fabricated, assembled, and delivered for additional testing and validation. The flow, pressure, temperatures, and power during operation will be recorded and analyzed. Cost projections will be evaluated for reasonableness and then used in a full-cycle cost of ownership analysis.

The project results will be delivered in periodic status reports and a Final Report that includes final results, recommendations on the cost effectiveness of the unit, and key designs improvements completed under this project.

Results
In 2017, the developer of a scroll compressor tested earlier in this project exited the natural gas vehicle fueling market. Subsequently, interest grew in the evaluation of a new liquid-piston technology and so research transitioned away from the evaluation of the scroll compressor design, with funds redirected towards testing the liquid-piston compressor.

In 2018, the project team reached an agreement with the manufacturer on the testing of its unit in a controlled environment and a detailed test plan was developed.

A unit was received at the laboratory, installed, and commissioned into service. A data-acquisition system was adapted to the test plan and installed. Personnel from the manufacturer provided operational training and safety orientation on the use of the equipment.

Researchers completed a series of three consecutive fill events into a target vessel volume of approximately 7GGE. The unit was operated to replenish the gas used during each fill. Data was collected during the fill events as well as the compression periods.

Vapor-liquid equilibrium analysis was performed on the hydraulic fluid of the unit.

The design and fabrication of test stand for fast-fill oil carryover testing were completed. The oil carryover was lower than had been modeled; however, design modifications could greatly improve future units.

After the new unit was installed in the laboratory, the compression system was tested for approximately 85 hours. Between compression cycles, dispensing tests were conducted to validate vehicle fueling performance.

Status
Testing quantified and validated many beneficial characteristics of the unit and points to its commercial potential. Oil carryover concerns highlight the reasons for testing to identify issues in a controlled environment to ensure that initial deployments meet customer expectations and do not lead to unsatisfactory experiences.

A Final Report was issued in July 2019.

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US Hybrid ISL8.9 Charge-Sustaining Hybrid Truck Retrofit and Demonstration

Research was performed to develop and demonstrate a fully integrated and optimized natural gas hybrid-electric Class 8 vehicle to advance the performance, fuel efficiency, and competitiveness of natural-gas-engine hybrid-electric systems.

Project Description

Hybridization is a proven means for reducing fuel consumption for conventional vehicles; however, if not properly integrated, the hybrid-electric vehicle will exhibit performance difficulties. Problems include the inability of the engine to operate at its ideal efficiency by avoiding low-power operation and rapid-throttling events.

Several heavy-duty hybrid evaluations were performed that showed an increase in NOx emissions for the hybrid vehicle compared to the non-hybrid version, as well as some instances with no increase in fuel economy. To improve the competitiveness of natural-gas-engine hybrid-electric systems, hybrid functionality, engine integration, engine controls, and exhaust after-treatment need to be addressed.

The objective of this project was to develop and demonstrate a fully-integrated and optimized natural gas hybrid-electric Class 8 vehicle with advanced performance, improved overall system efficiency, and reduced emissions.

The optimization was applied to an existing plug-in hybrid Class 8 truck platform that includes an electric-drive system with 80kWhr lithium ion battery capacity and a 240kW electric-drive motor. A hybrid configuration was used for the vehicle that allows the Cummins Westport Inc. (CWI) ISL8.9 G engine to drive the truck during cruising for best efficiency and allows the electric motor to supplement the power to provide superior acceleration and energy recovery during regenerative braking. In hybrid mode, the total available power exceeds 500 HP, providing performance similar to that of a 15-liter diesel engine, while significantly reducing emissions and increasing fuel economy. The truck was designed to be able to operate in electric-only mode for zero-emission driving for short durations.

This project was cofounded by the California Energy Commission (CEC) in partnership with US Hybrid Corp. and the University of California, Riverside.

Benefits / Market Implications

This project has the potential to significantly advance hybridization technology towards a cost-effective, near-zero-emission commercial offering. The results from testing supported the hybrid technology and getting it ready for commercialization.
Commercial natural gas engines are currently available to fleet owners; however, the options are extremely limited. Commercialization of US Hybrid’s technology will build upon CWI’s ISL platform to bring a second near-zero option into the market, introducing a natural-gas/electric hybrid offering where none exists today. This advancement would allow for completely renewable operation using either renewable electricity or renewable gas.

Technical Concept & Approach

The project scope was based on the structure of the CEC agreement, which also includes technical tasks for UC Riverside and US Hybrid that include component design, analysis, and testing, as well as vehicle integration, optimization, and chassis dynamometer testing.

Specific tasks included:

- **Evaluation of Project Benefits**

  This task included estimating energy use, greenhouse gas and criteria pollutant emissions reductions, benefits to the targeted market sector, and implementation costs. This information was gathered during the course of the project.

- **Technology and Knowledge Transfer Activity**

  This task will result in the development of a Technology and Knowledge Transfer Plan that includes an explanation of how the knowledge gained will be made available to the public, a description of the intended use of the technology, a discussion of any relevant policy developments, and copies of any fact sheets, journal articles, or press releases prepared during the project.

- **Production Readiness Plan**

  This task will result in the development of a Production Readiness Plan that will include discussion of critical processes, equipment, facilities, personnel, or support systems needed for a commercially viable product. In addition, it will include the costs of production and the expected investment needed to launch the commercial product.

Results

In 2017, UC Riverside brought an ISL-G engine to its laboratory and instrumented the unit for rapid prototyping with an engine-control module. US Hybrid assembled the balance of the vehicle (without engine and engine-control module). US Hybrid completed an LNG hybrid truck and delivered it to UC Riverside for further testing on a chassis dynamometer. UC Riverside submitted the Dynamometer Demonstration Report, which was reviewed and submitted to CEC for review. The first round of optimizations resulted in vehicle power and torque in amounts that were comparable to a 12- or 13-liter engine; however, the test vehicle was only equipped with an 8.9-liter hybridized engine. Potential opportunities to improve the control of the vehicle systems, including fuel monitors and battery management system, were identified. The demonstration showed that there was a path to ultra-low emissions with some further optimization work to eliminate low-torque operational conditions via better control and anticipation of power needs.

In 2018, the project team explored multiple pathways to modify the engine-control system, vehicle components, or the hybrid module. The emissions benefits of the hybridization concept were simulated using engine dynamometer test data and models for battery use during the cold start period.

The project team integrated and demonstrated the hybrid truck on a chassis dynamometer at UC Riverside’s facility. The hybrid-electric truck was tested following five different drive cycles. Results showed the hybrid-electric truck could easily move twice the load of the non-hybrid truck with reduced emissions.

The project team continued to coordinate efforts for the next project that aims to optimize the hybrid system for improved emissions and zero-NOx emission capability. Findings from previous testing work will inform this effort.

Status

The chassis dynamometer testing is complete and the Final Report is being generated. Future deployment of hybrid technology should take advantage of this engineering success. This includes the commercial CWI NZ natural gas engines, which are superior to the engine used in this research project. It is recommended to develop a hybrid demonstration with the advanced ISL G 8.9 NZ engine utilizing the same chassis platform. This platform would demonstrate the best-available technology for hybrid integration.

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CNG Station Methane Measurement Investigations

Research in this project involves developing techniques to quantify the leaks and losses of natural gas when fueling vehicles with CNG, evaluating advanced compression technologies, and providing guidance on methods to monitor station leakage performance, maximize operational efficiency, and minimize leaks and losses.

Project Description

While natural gas vehicles (NGVs) have demonstrated significant reductions in many criteria pollutants and ozone-forming emissions, one component that was not included in most past regulations is methane. Although methane is not present in gasoline or diesel fuel, it is the predominant compound in natural gas and therefore even relatively small amounts of methane leakage at a compressed natural gas (CNG) fueling station can cause concern. New U.S. Environmental Protection Agency greenhouse gas (GHG) standards are expected to regulate total GHG emissions, including methane emissions.

Fortunately, some advanced compressor technologies have recently come on the market that are capable of reducing or eliminating methane emissions from compressors. These enhanced compressors are starting to be implemented, and evaluating their performance compared to some baseline compressor methane leakage rates would be extremely helpful in accelerating industry adoption.

An additional need that has been described by several CNG station owners is that there are frequently difficulties in reconciling the metered inlet gas to CNG stations with the gasoline gallon equivalent (GGEs) dispensed. A method to account for all sources of gas flows in and out of a station, along with explanations of how the precision and accuracy of various metering devices compare, would assist in properly characterizing vented gas, station economics, and the environmental impact from station operations.

The objectives of this project are to quantify the leaks and losses of natural gas in the CNG fueling process within a CNG fueling station, evaluate advanced compression technologies, and provide guidance on tracking methods to monitor station leakage performance.

Benefits / Market Implications

The U.S. Department of Energy (DOE) is investigating losses associated with high-horsepower gas compression facilities – one aspect of which is the increased energy consumption associated with leaks and venting of natural gas in midstream and downstream transmission.

The potential for increased regulations to minimize these losses, coupled with the environmental GHG consequences of methane releases from the same situations, prompts the need for data on state-of-the-art technologies and the potential impacts from CNG station operations. In addition, identifying and assessing new or upcoming technologies to reduce CNG fueling station emissions will be another important result.

Reducing the errors in measurement used to determine leakage and accounting discrepancies can advance station operations and the understanding of environmental impacts.

Technical Concept & Approach

This project is leveraging the activity under a separate research project funded by the California Energy Commission (CEC) that is quantifying full-value-chain emis-
sions to provide guidance specifically to CNG fueling stations. This guidance includes information on common sources of gas losses, methods to mitigate those losses, and a method to monitor stations for losses in an effort to quickly catch poor station performance.

The CEC project team plans to visit more than 30 CNG stations in California as well as the Gas Technology Institute (GTI) on-site fueling station in Des Plaines, IL.

Specific tasks include:

- **Assisting the CEC Project and Interpreting Results for CNG Fueling Stations**

  The project team will assist the CEC project to help ensure that the resulting data are relevant to the NGV industry and effectively collected. Data collection will not only measure the emissions, but also determine the specific sources and how to mitigate the emissions through operational process changes, material selections, improved maintenance procedures, and implementation of other best practices. This project also includes a review of advanced compressor technologies.

- **Literature Review and Reconciliation with Other Studies**

  Some recent efforts by others to quantify methane releases from CNG stations have been conducted, but without industry consensus on the methodology used or peer review of the results. Because the sample size was less than 10 stations, the project team will seek additional data points to use as a baseline. Researchers will also complete a literature review of documented emissions testing at CNG fueling stations. The goal of this task is to reconcile data gathered at stations and create a complete understanding of emissions issues and the mitigation methods that are most effective.

- **Developing a Method for Monitoring Station Gas Losses**

  Efforts will be made to develop a method of monitoring gas losses at a CNG fueling station by comparing corrected flow meter calculations from the inlet flow meter and dispenser (where available) to determine the potential gas losses when including consideration of flow meter accuracy, time lag, and other issues.

  In this project, technicians are using an infrared optical gas imaging (OGI) camera and a combustible gas indicator to quickly locate leaks at CNG stations. Both of these devices can be swept across individual components to determine whether a leak exists by detection of elevated methane concentrations. The infrared OGI camera is used to visualize the leaking methane by taking advantage of the unique physical and chemical properties of fugitive gas leaks. Utilizing a radiant contrast between the surrounding background and the gas leak plume, the camera will detect and display the leak as a black plume on the thermal image. The thermal image can be viewed on the camera viewfinder, allowing a properly trained operator to quickly locate methane emissions sources. Once all leaks have been located by either OGI or combustible gas indicator, follow up quantification of leakage rates is conducted via use of a high-flow-rate vacuum gas sampler.

Results

In 2018-2019, the project team collected a significant amount of leak data from about 15 stations, using the three separate well recognized leak detection and measuring techniques. A significant literature review was also conducted to support this study. Preliminary conclusions are beginning to emerge, but further data collection will be needed before the evaluation is complete. The largest potential methane emissions source appears to be the compressor vent, but the severity of piping joint leaks varies broadly between individual joints and individual stations.

Researchers also carried out tests to quantify the volume of gas contained in the gas lock between the CNG dispenser hose nozzle and NGV fueling port connection. The code requirements involving the volume of the dispenser nozzle and hose were also studied, helping to create an estimate of the volume of gas contained in the gas lock between the dispenser hose nozzle and car receptacle connection since this small volume of gas tends to escape each time the NGV is fueled.

Status

Researchers plan to take methane emissions measurements at least two more stations to obtain more data to support this project, and then finish the Final Report.

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Cost-Effective CNG Pre-Cooling Technologies

In this project, a research team is investigating and designing an innovative, cost-effective, compressed natural gas (CNG) pre-cooling system to condition CNG prior to being dispensed into a natural gas vehicle to achieve full fills.

Project Description

Pre-cooling compressed natural gas (CNG) before it enters a CNG vehicle is essential to achieving a full fill under most fueling and ambient conditions. This need is driven by the heat of compression occurring during a CNG fill that causes the tank to significantly gain heat, resulting in the pressure limit being reached prior to transferring the total mass that defines a full fill.

Under-filling of CNG vehicles directly impacts the cost and range of the vehicle, negatively impacting the perception and payback period for end users who operate natural gas vehicles (NGVs).

The largest capital-cost barrier for CNG adoption and the increased consumption of natural gas is the high cost of CNG storage cylinders onboard NGVs. Type 3 and 4 cylinders are typically used for North American markets to limit the weight penalty on many vehicles; however, these cylinders come with a high cost compared to steel tanks used in many other parts of the world. For example, the incremental price increase for a heavy-duty CNG class 6 or 7 truck requiring 150 diesel gallon equivalent or greater fuel storage is about $50k to $75k, depending on the total volume of the CNG storage system.

There are industry efforts under way to directly reduce the cost of composite storage vessels; however, the issue of under-filling directly impacts the volume of storage required on a vehicle. By providing consistent full fills, a vehicle requires a smaller fuel system, reducing the cost and weight of the vehicle’s CNG system. This improves the vehicle’s range, economics, and the user experience of operating a CNG vehicle.

Research has been ongoing to improve full fills by developing improved dispenser algorithms, investigating vehicle-to-dispenser communication, and analyzing pre-cooling systems. These activities have led to the conclusion that some form of pre-cooling is necessary to guarantee a full fill, as well as providing some direction towards the best method to use to achieve the pre-cooling.

The most obvious method for pre-cooling is to use a vapor-compression chiller to cool the CNG being delivered to the vehicle. This method is being used for some virtual pipeline filling stations, but is too expensive for most CNG vehicle stations. Research is currently determining whether the system design and operation can be optimized to bring down costs. Results to date indicate that there may be opportunities to reduce cost as these systems become more common; however, they also become disproportionately more expensive for smaller stations as the chiller must be sized to handle the full flow.

Alternatively, the existing CNG compressor could be used to drive a cooling loop that is used to store cooling capacity between vehicle fills, and then use that cooling capacity to pre-cool the CNG going into the vehicles during a fill. This strategy has the advantage of reduced capital cost as it uses existing CNG station equipment, but will add run time, complexity, and maintenance cost to the CNG compressor. A detailed analysis is being conducted to estimate the annual increase in compressor run time to accomplish the required pre-cooling. This analysis can be used to determine if the increased compressor run time is worth the reduced capital cost of the equipment.

It is also possible to improve a CNG fill by using a turbo-expander or similar device to pull energy out of the gas as it is flowing into the vehicle. The expander causes the gas to get colder than it would with Joule-

The graphic shows results from modeling current CNG dispenser fill algorithms and how it is nearly impossible to achieve a full fill once ambient and station gas temperatures rise above 50°F (10°C).

The graphic shows results from modeling current CNG dispenser fill algorithms and how it is nearly impossible to achieve a full fill once ambient and station gas temperatures rise above 50°F (10°C).
Thompson cooling, allowing more gas to enter the vehicle before the pressure limit is reached.

These devices show the most promise as they do not require any additional energy input to achieve the desired pre-cooling. The largest issue with these types of devices is that they are not commercially available for CNG's high pressures, requiring a device to be designed specifically for this application.

Overall, the expander development seems to be the most promising path forward due to the ideal thermodynamic performance and efficiency. Ideally, the expander would result in a lower capital cost, as well as a lower operating cost because it does not require additional power.

Benefits / Market Implications

The use of pre-cooling would improve the safety of the fueling procedure since gas temperature would be controlled by the station and less variable than in existing fueling procedures.

CNG pre-cooling can be accomplished using large, low-temperature chillers that cool the gas to around 20°F (-7°C) before it enters the vehicle. These chiller systems are used by virtual pipeline companies when transferring much larger quantities of CNG, but are not cost effective for most fleets and smaller CNG stations. The estimated cost of an existing pre-cooling system is about $100 per standard cubic foot per minute of CNG needing cooling. Therefore, a bus fleet might require a system that costs several hundred thousand in capital investment, in addition to the increased operating and maintenance costs of the chiller system.

A lower-cost option is necessary if pre-cooling is going achieve widespread adoption, making under-filling an issue of the past.

Technical Concept & Approach

In this project, a research team will investigate and design a CNG pre-cooling system to condition CNG prior to being dispensed into a NGV to achieve full fills.

Technologies being considered include a vapor-compression chiller with and without thermal storage, using the CNG compressor to serve as a refrigerant loop to leverage existing hardware for cooling, and a turbo-expander technology that can be used to remove excess energy from the CNG stream as it enters a vehicle.

The project will include a comparison of the available cooling strategies, a selection of the preferred strategy, and a preliminary design of the pre-cooling system and operation.

The project will start with a broad technical assessment and selection of a preferred pre-cooling design.

Currently, the likely preferred approach is to develop an expander, since that would be the highest impact option. The project will end with a pre-cooling system design that has the best chance for making a transformational impact on the CNG filling process.

Researchers will perform a final analysis of the pre-cooling strategies described above. These technologies will be evaluated for technical feasibility, cost, and market disruption potential. The most promising and/or disruptive technology will be selected as the preferred path forward.

The project team will perform a preliminary design analysis of the selected pre-cooling strategy. The design will include detailed models, simulation, and schematics of the selected technology that estimate the expected cooling performance and how much it impacts CNG full fills, as well as the estimated capital and operating cost of the technology in a simulated station. A design report will be issued under this task to fully define the performance and impact of the preferred precooling method on a simulated CNG station.

Results / Status

In 2018, the project team proposed the development of a free piston linear expander to the U.S. Department of Energy as the preferred approach to achieving isentropic expansion and pre-cooling of gaseous fuels, including CNG and hydrogen. Subsequently, the project was awarded and contracts finalized.

The project team is developing a design for the free piston expander. Researchers need to determine the best method for energy rejection from the gas being cooled. Options being considered are electricity generation and/or gas compression. The research team has also been focused on developing an understanding of the tradeoffs related to operating stroke vs. frequency, diameters, and other guiding characteristics.

Efforts are under way to enhance a simulation of the free piston expander to better estimate the performance of the system. The simulation will be used to optimize stroke, frequency, and other relevant design parameters.

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Virtual Pipeline Market Study and Technical Assessment

In this project, research quantified the potential benefits of over-the-road bulk fuel transfer of compressed natural gas or renewable natural gas. Researchers investigated solutions to overcome technology barriers (including full fills, odorization, and special permitting) to reduce effective costs for end users.

Project Description

Advances in virtual pipeline technology are rapidly changing the economics transmitting natural gas or renewable natural gas. However, specific aspects of market economics are not well defined, including filling costs, odorization requirements, dispensing costs, and credits for renewable production or sale. This contributes to a value proposition that can be perceived as risky.

A previous UTD project sought to identify high-volume, off-road applications for expanded use of compressed natural gas (CNG). One of the applications identified in that study was delivery of gas via virtual pipeline. Virtual pipelines transfer gas using purpose-built compression stations on existing pipelines and modular transport trailers that off-take gas at these stations. The trailers are then delivered to customers, who then depressurize the gas for use.

The industry really started growing in 2010-2011 and now there are at least 15 compression/delivery stations in the U.S. Northeast and planned expansions across the U.S. These compression stations and trailers are largely privately owned, but some operations have been developed with utility support.

These virtual pipeline operators are enabling natural gas use at off-pipeline hospitals, universities, paper and textile mills, dairy and food-processing centers, textile or glass manufacturing centers, mining operations, and other traditional gas users who desire to switch from heating oil or other energy sources, but the nearest natural gas utility cannot justify a pipeline extension to serve them.

New advances in storage technology and integration have brought new capabilities to the market. This trend will likely continue as the market continues to mature.

The objective for this project was to quantify the potential benefits of, and seek solutions to overcome technology barriers (including full fills, odorization, special permitting, etc.), for over-the-road bulk fuel transfer of CNG to serve temporary as well as long-term loads. This project also explored how these technologies may enable biogas production and transpor-

Benefits / Market Implications

This assessment of virtual pipeline technology has now enabled a clearer definition of the specific aspects of a virtual pipeline strategy. Identifying and quantifying distributed sources and users – as well as the economics associated with filling, dispensing, odorization, and permitting – provides utilities with a solid basis and justification for future project work. This same information will also aid evaluations of technology needs and potential research and development opportunities.
Improved understanding of the virtual pipeline value proposition may allow for expanded integration of renewable natural gas. Identification of key market drivers for renewable natural gas sources will provide improved guidance for how utilities can build their renewable portfolios.

Virtual pipelines enable end users to take advantage of a cheaper, more environmentally friendly fuel for their heating and power needs. They also offer another means of monetizing renewable natural gas from isolated sources such as landfills and digesters.

Virtual pipelines also require a significant labor force for their operations, resulting in correspondingly strong local job creation that cannot be outsourced.

Technical Concept & Approach

In this project, a research team researched and assessed virtual pipeline technology, studied market potential, identified barriers and needs, and performed a high-level economic analysis of the virtual pipeline potential and value proposition.

Specific tasks included:

- **Literature Review and Outreach**
  
  This review identified new technologies, new market entrants, and new business plans within the virtual pipeline market. It also identified and summarized technology advances that will affect the value proposition. The literature review also investigated the potential for renewable natural gas sale and transport via a virtual pipeline operation.

  This task also included outreach activities to technology providers, current operators, and potential operators.

- **Technical Assessment**
  
  A simple techno-economic assessment was conducted, utilizing the findings from the literature review and outreach. The capability of current technology and any near-term advancements identified during the literature review and outreach were reviewed and compared. Technological needs were uncovered and summarized and discussed in the Final Report.

- **Market Study**
  
  Findings were incorporated into a market analysis to explain how products interact on the market and form the value proposition, including capital and operational costs and market associated challenges.

Results

More than 50 companies that participate in some element of the virtual pipeline industry were identified and characterized.

Growth of the virtual pipeline industry is being encouraged by low natural gas prices, delays or cancellations of conventional pipeline projects, and ongoing technological advances in CNG cylinder technology. There is also serious interest in technologies for enabling complete and consistent filling of the vessels onboard virtual pipeline vehicles to improve their efficiency. Research that is currently under way to seek improved solutions for enabling full fills of CNG vessels (while at the same time minimizing equipment and operating expenses) was identified as advantageous for virtual pipelines.

A techno-economic assessment of a representative continuously-operated trucked CNG virtual pipeline was conducted and revealed a simple payback period that was quite favorable (1.7 years). Several pertinent alternative scenarios were also explored, revealing payback periods ranging from 1.0 to 6.1 years.

Status

The Final Report was completed in July 2019.

For more information:

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