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FINAL PROJECT REPORT

Demonstration and Assessment of Residential Gas Heat Pump Water Heaters in the Los Angeles Basin

Gavin Newsom, Governor

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PREFACE

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

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

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

Demonstration and Assessment of Residential Gas Heat Pump water Heaters in the Los Angeles Basin is the final report for Contract Number PIR-16-003 conducted by GTI. The information from this project contributes to the Energy Research and Development Division's Natural Gas Research and Development Program.

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

ABSTRACT

This project included the demonstration, measurement, and verification of a gas heat pump water heater prototype in five single-family homes in the Los Angeles Basin. Developing a simulation model helped assess the energy, emissions, and cost savings of this technology compared to other commercially available water heating options across the 16 California climate zones. Laboratory-based extended life and reliability testing was performed to assess the market opportunities and barriers to introducing this new technology. The researchers undertook outreach to stakeholders such as utilities, plumbing heating, ventilation, and air conditioning, and home energy improvement contractors, consumers, manufacturers, and other researchers to facilitate knowledge and technology transfer through presentations, papers, and online workshops.

The project included commissioning and shipping six precommercial gas heat pump water heater units to California and installing at five home sites and a research laboratory. After testing for more than three months, average annual savings were 110 therms or 54 percent compared to baseline using with CO_2 emissions reductions of 49 percent. Individual site savings ranged from 23 percent to 67 percent, from varied consumption and baseline equipment. The technology developer Stone Mountain Technologies is conducting additional demonstrations outside California and plans to have a series of different models be in commercial production starting in 2023 to early 2024. The company was able to raise an additional $15 million in new investment.

Keywords: Gas heat pump, gas absorption heat pump, residential water heating, California

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Background

With improved residential building envelopes and the increase of advanced (or "smart") thermostats, home energy use for space conditioning is declining. Water heating is similarly impacted, such as more low-flow water fixtures and the slight reduction in per-household occupancy, however water heating energy use still remains an important issue.

Unlike heating, ventilation, and air conditioning (HVAC) where more than half of installed gas-fired furnaces and boilers are high-efficiency (greater than 90 percent), the water heating market has proven more challenging to transform. In California, 9 million natural gas units heat water in approximately 75 percent of homes, representing one in four gas-fired water heaters in the U.S. Of this 75 percent natural gas water heating in the state, 95 percent of these units are minimum allowable efficiency (0.62 uniform efficiency factor [UEF]). Though there are higher efficiency options available (0.88 UEF and 0.97 UEF), there has been a historic challenge to broadly deploy high-efficiency water heating products. The combination of lower cost natural gas and higher equipment and installation costs have limited uptake, leaving a large potential for energy efficiency and emissions reductions.

Consumption of natural gas for space and water heating, which are the primary end uses of delivered gas to homes, is responsible for approximately 4 percent of United States greenhouse gas (GHG) emissions [U.S. EPA, 2019]. California's mild climate and aggressive building efficiency codes mean that water heater represents the largest residential gas load in the state. Supporting more efficient technologies for natural gas water heaters is expected to provide a significant impact to California's GHG reduction goals outlined in Assembly Bill 32 (AB 32, Nunez. Air pollution: greenhouse gases: California Global Warming Solutions Act of 2006).

Project Purpose

This project focused on a field and market evaluation of a "fourth generation" pre-commercial gas heat pump water heater in five single family homes in the Los Angeles Basin and laboratory-simulated extended lifetime testing. Gas heat pump water heaters are a hybrid water heater that moves heat from one place to another instead of generating heat directly like a typical gas water heater. The gas heat pump water heater is two to three times more energy efficient, emits fewer greenhouse gas emissions than other gas-fired options and uses natural refrigerant/absorbents (ammonia and water), which have zero ozone depletion potential and zero global warming potential.

The results from these efforts were evaluated to consider adding into efficiency codes. The goals of this project were to:

- Demonstrate a new class of high efficiency gas heat pump water heaters.
- Assess improvements made to this generation of gas heat pump water heater, in field and laboratory evaluations.
- Through analysis and evaluation, develop analytical tools to prepare this new technology class to be included in agendas such as utility incentive programs, energy efficiency codes, and building energy models.

- Share findings broadly to introduce the technology and solicit feedback from consumers, installation contractors, code officials, and other stakeholders.

This research provides the opportunity for ratepayers to benefit from lower energy costs and reduced GHG emissions across California and beyond. Consumers who purchase a gas heat pump water heater could expect 50 percent or more energy savings with the lowest 10-year cost of ownership for any water heating technology over the current baseline, code-minimum storage water heaters.

There is a range of audiences that will use the results of this research including consumers, plumbing contractors, gas and electric utilities, manufacturers, and other researchers.

Project Approach

This research effort was led by GTI and a variety of supporting partners and sought to advance this technology towards commercialization by:

- *Field Demonstration:* Demonstrate that the projected efficiencies of 130 percent or greater are valid, robust, and are not achieved through a loss of user comfort or performance. Estimate annual energy, operating cost, and emissions savings and solicit feedback from host end users and installation contractors through pre/post surveying.
- *Performance and Extended Life Testing:* Through laboratory testing at the Southern California Gas (SCG) Engineering Analysis Center, quantify energy efficiency with standard and simulated use testing comparing to "as-installed" measurements, demonstrate compliance with Ultra-low oxides of nitrogen (NOx) emission limits (10 ng NOx/J output), and perform extended-life on one prototype gas heat pump water heater to demonstrate reliability.
- *Model Development and Analysis:* Since the natural gas heat pump water heater represents a new product category, develop tools and guidance to prepare stakeholders and code officials. Develop a user-friendly gas heat pump water heater modeling tool to estimate annual operating efficiency and energy savings based on installation type, hot water use, and California Climate Zone. Perform a California building efficiency code analysis, evaluating the relative cost effectiveness of the gas heat pump water heater to exceed the 2016 Title 24 performance level compared to other water heater measures and develop a framework to integrate gas heat pump water heaters in the Residential Alternative Calculation Method.
- *Understand Market Barriers:* Survey and quantify market barriers to prevent adopting gas heat pump water heater in the Los Angeles Basin. Challenges considered include real and perceived barriers to consumer adoption and contractor recommendation (home performance contractors, HVAC, and plumbing contractors included).
- *Stakeholder Outreach:* Educate prospective gas heat pump water heater consumers, installation contractors, and other affected stakeholders through a series of workshops to introduce this technology and summarize project findings. Additionally, develop educational content and materials for contractors and utility ratepayers.

A technical advisory committee was formed, comprising representatives from Consortium for Energy Efficiency, Northwest Energy Efficiency Alliance, Rinnai Corporation, San Diego Gas & Electric, Southern California Gas, Gary Klein & Associates, and Jim Lutz from Hot Water

Research. These individuals served as a sounding board as project progress was reported and provided assurance that a rigorous test design was implemented.

Challenges related to host site recruitment were addressed through several rounds of recruitment and on-site inspection. Issues related to unexpected performance were investigated and technical design issues resolved (for example, solution pump changeout). The COVID-19 global pandemic in the final year created some difficulties with in-person work at the host sites, but with creative use of video calls and robust communication, the project team was able to resolve these in a timely and safe manner. Through a detailed and robust research plan, this project was able to characterize the technology performance, costs, market barriers/drivers, and savings potential for homeowners.

Project Results

From early March to early June 2018 the team established the existing baseline water heating systems at the five residential host sites. This baseline showed an average measured delivered efficiency of 0.49, for average daily draws of 50 gallons with peaks of up to 163 gallons and with an average delivered temperature of 137°Fahrenheit (F). Six fourth-generation gas heat pump water heater prototype units were installed at five home sites and a research laboratory. The prototype gas heat pump water heaters were then removed and five condensing tankless or high-efficiency storage-type were installed at the host sites. This provided a second baseline. Where the first baseline is discussed, it is referred to as 'baseline' while the second baseline is always noted as 'second baseline'. Energy, cost and emissions savings were determined comparing the gas heat pump water heaters and a commercially available high efficiency unit.

While all sites had the gas heat pump water heaters installed for a year or more, unit up-time varied widely and was due primarily to operational and maintenance issues with the units.

Despite some challenges with prototype up-time, the gas heat pump water heaters units showed strong savings. The estimated annual average total energy savings are 110 therms or 54 percent compared to baseline and carbon dioxide (CO_2) emissions reductions of 49 percent, when including electricity inputs. At $1.10 per therm, this is a cost savings of $121 per year. When compared against the second baseline of high efficiency tankless water heaters, the gas heat pump water heaters showed a 57 percent reduction in energy use and a 56 percent reduction in CO_2 emissions.

In the laboratory testing task, a GHPWH unit identical to the field prototypes was commissioned at the Southern California Gas (SCG) Company's *Engineering Analysis Center* (EAC) to perform an efficiency, emissions, and reliability assessment. Heat pump time-averaged COP_{Gas} over the complete test was 10 percent below the performance target in pre-shipment testing, standby heat loss factors ranged from 5.0 to 10.0 Btu/hr-°F, and power consumption was up to 58 gallons delivered/kWh consumed. Other GHPWH design features remained in line for the UEF performance targets concerning delivered temperature, combustion efficiency, emissions, and the heat pump COP_{Gas} (as observed with field GHPWH units). Ultra-low NO_x emissions were verified in independent testing and certification. On durability testing, extenuating circumstances prevented the EAC from carrying out the longer-term test program. With future GHPWH production units, the three key areas identified to meet these UEF targets were improvements in 1) storage tank insulation, 2) low-power components, and 3) minor changes to the immersed HHX, all readily achievable per manufacturer guidance.

As assessment of the market barriers to the successful commercialization and adoption of a high efficiency gas heat pump water heaters yielded interesting results. Two national surveys were conducted – one for home contractors (371 respondents) and one for homeowners (1,131 respondents). Based on the data gathered through these surveys, the majority of contractors thought they were very likely to sell this new product (57 percent), while 37 percent would be somewhat likely to sell to some customers. Overall, surveyed contractors estimated they could sell an average of 55 gas heat pump water heaters per year, with a "worse case" being identified as 33 units/year. The implication is that plumbing and HVAC contractors think that in a mature market, gas heat pump water heaters could account for one-fifth to one-third of their annual water heater sales. The most cited strength of the gas heat pump water heaters technology is the improved efficiency (28 percent) and the most cited weakness is the initial cost (21 percent). Based on 27 in-depth interviews with plumbing, HVAC, or home energy improvement contractors or both, the key opportunities and deterrents for this new technology class are summarized in Table ES-1.

Table ES-1: Gas Heat Pump Water Heater Market Opportunities and Deterrents

Opportunities	Deterrents
• Installation price of tankless is much higher than most customers expect, thus curtailing sales and providing an opening for a mid-priced, higher efficiency product • Leading with long-term cost savings of a GHPWH overcomes some of the barrier of the upfront cost increases.	• Physical size is perceived as "big" unlike tankless which is perceived as "space saving" and "aesthetically pleasing" • Tankless units have dominated some markets with the perception of "endless hot water", appealing to customers. • Recharge time perceived less favorably than tankless

Source: GTI

This project yielded considerable information to enable next steps for product refinement and market preparation activities ahead of commercialization. The technology developer Stone Mountain Technologies is conducting additional demonstrations outside California and plans to have a series of different models be in commercial production starting in 2023 to early 2024. The company was able to raise an additional $15 million in new investment.

Technology/Knowledge Transfer and Supporting Market Adoption

Effective knowledge transfer is critical to the ability for research to build on previous work. As such, as part of this project it was intended that the project team would pursue opportunities to educate prospective gas heat pump water heaters consumers, installation contractors, and other affected stakeholders.

Educational Outreach

The team originally intended to partner with SCG to host an in-person public gas heat pump water heaters workshop at the Engineering Analysis Center. Unfortunately, because of COVID-19, hosting an in-person event was not possible. The project team transitioned this effort to a moderated virtual session focusing exclusively on residential water heating technologies, including gas heat pumps, at the 2020 ACEEE Hot Water Forum in July. GTI presented the findings with other residential gas heat pump research and facilitated group discussions on this topic with other key stakeholders. The advantages of using the Hot Water Forum as the outreach event are that a broader, larger stakeholder group was reached. The project team is also developing gas heat pump water heater educational and training materials targeted for installation contractors and a gas heat pump water heater Technology Snapshot that is targeted at prospective consumers. The Final Project Fact Sheet will be available for online distribution through the California Energy Commission and other websites. Subsequent to this study, SMTI continues to pursue pathways to bring low-cost thermally-driven heat pumps to the North American market, including products for residential space heating and water heating, targeting a 2023 launch.

Simulation Modeling Development and ACM Implementation

Two models were developed: 1) an easy-to-use tool that could provide a high level comparison of energy use, operating costs, and carbon emission estimates (for project managers and planners to use), and 2) a more detailed model that would provide detailed and flexible tools to engineers, designers, and researchers provide assessments of the energy impacts of the technology. To complement the estimates of gas heat pump water heater performance, the simple model combines the annual summary results with results from the 2019 Title 24 compliance software (California Building Energy Compliance Calculator for Residential Buildings, or CBECC-Res) and allows for modeling a range of water heating system types in all 16 California climate zones, as well as for a range of water heating load magnitudes.

Papers and Presentations

GTI developed and gave several presentations across the U.S. about this project to a wide variety of stakeholders including the 2019 ACEE Hot Water Forum in Nashville, 2020 ASHRAE Winter Conference, and 2020 North American Gas Heat Pump Collaborative (On-line).

Benefits to California

This research supports the opportunity to bring significant energy and cost savings to California ratepayers as well as environmental improvements by reducing GHG and NOx emissions. Although high efficiency water heating products are available, their market acceptance has been limited by high upfront costs and low natural gas prices. The gas heat pump water heater prototype offers the potential for a high efficiency system with comparable installation costs to minimum-efficiency storage water heaters and the lowest lifetime operation cost of any natural gas water heating system currently available. This new technology class has the potential of increasing the adoption of higher efficiency water heating options in California.

The commercialization and adoption of a high efficiency gas heat pump water heater in California would provide several notable benefits to ratepayers including an average energy savings of 54 percent and a proportional estimated reduction in GHG emissions. This equates to 195 therms saved and 2,276 pounds of carbon dioxide equivalent (CO2e) saved per year. Assuming a natural gas price of $1/therm, these savings total $2,235 over 10 years for an individual home. This would yield an estimated payback of about 7 years assuming high-volume equipment pricing of $1,600 for the GHPWH.

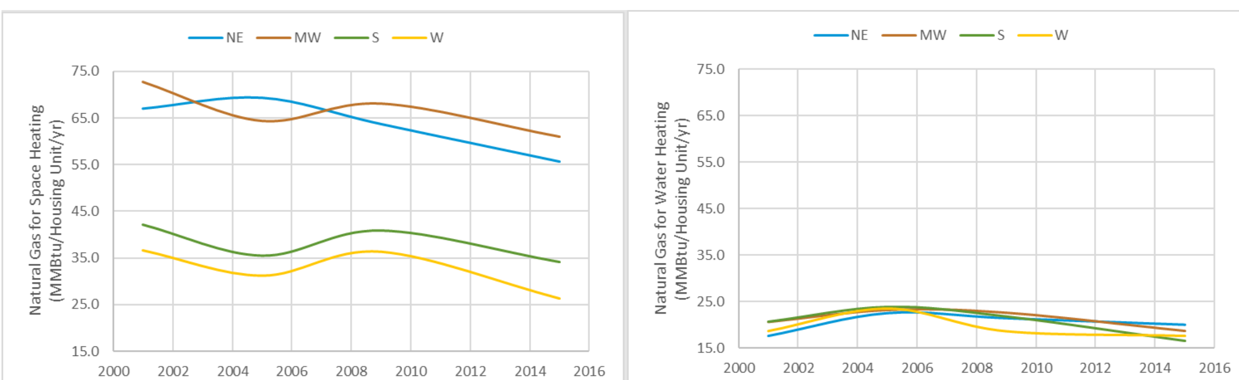
Based on the current distribution of gas water heating product types in California and their respective efficiencies, a 10 percent market share could yield annual natural gas savings of 90.9 million therms and a reduction of 482,000 metric tonnes of CO2e. In a more aggressive scenario of 50 percent market saturation, annual natural gas savings and GHG emissions reductions rise to 454.4 million therms and 2.4 million metric tonnes (MMT) of CO2e, respectively. California’s residential sector emitted 33.5 MMTCO2e in 2019, so the aggressive adoption of GHPWHs could reduce sector emissions by 7% (CARB 2021).

CHAPTER 1: Introduction

Background

With improving residential building envelopes and the proliferation of advanced (or “smart”) thermostats, home energy use for space conditioning is declining. This also holds true for homes that consume natural gas for space and water heating, which are the primary end uses of delivered gas to homes and are responsible for approximately 4 percent of U.S. greenhouse gas (GHG) emissions [U.S. EPA, 2019]. Natural gas consumption for home space heating has declined in all census regions from 2001-2015 (Figure 1) [EIA RECS, 2015]. This reflects the aforementioned improvements in the thermal envelope and also the increased market penetration of high-efficiency heating equipment. While it is a smaller residential load, generally 1.5-3 times lower on average, water heating becomes more significant in these circumstances. Water heating is being impacted by similar forces, such as the proliferation of low-flow water fixtures and slight reduction in per-household occupancy [U.S. Census, 2017]. As such the relative importance of water heating energy use is increasing with time. For mild-climate regions with aggressive building efficiency codes, such as California, it represents the largest gas load.

Figure 1: Average U.S. Residential Natural Gas Consumption for Space Heating (Left) and Water Heating (Right) per Housing Unit



For Northeast (NE), Midwest (MW), South (S), and West (W) Census Divisions

Source: GTI

Unlike heating, ventilation, and air conditioning (HVAC) where more than half of installed gas-fired furnaces and boilers are high-efficiency (> 90 percent AFUE), the water heating market has proven more challenging to transform. Within the past 15 years, residential water heating has seen a significant push in both policy and product innovation, including:

- 2006: introducing Ultra-Low NOx performance criteria in California,
- 2009: efficiency criteria through ENERGY STAR for the first time followed by the introduction of multiple electrically-driven heat pump water heaters, and
- 2015: raising the allowable minimum product efficiencies while implementing a significant change in the product rating and method of test.

In the U.S., 62 percent of all housing units in the 50 largest metropolitan areas are served by gas-fired water heaters (67 percent, if Florida is excluded), and for the ~4 million gas-fired storage water heaters sold each year to serve these homes only 5 percent sold are at or above the ENERGY STAR level of 0.67 Uniform Energy Factor (UEF) [U.S. Census, 2017 and AHRI, 2019]. This is even more pronounced in California where natural gas fuels water heating in approximately 75 percent of homes with an installed base of 9 million units, representing one in four gas-fired water heaters in the U.S. Of the 75 percent of homes with natural gas water heating, 95 percent are served by minimum allowable efficiency products of 0.62 UEF. The availability of higher efficiency options is not the issue, with products available up to 0.88 UEF for storage products and 0.97 UEF for tankless products. Instead, this reflects a historic challenge to broadly deploy high-efficiency water heating products where the combination of lower cost natural gas and higher equipment and installation costs have limited uptake, leaving a large potential for energy efficiency and emissions reductions.

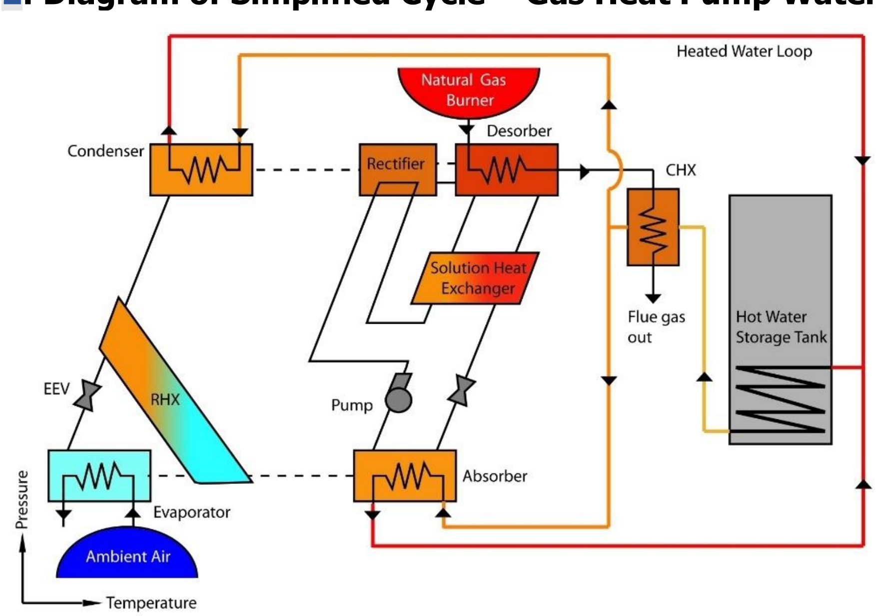
To address this potential, the project builds on prior efforts to develop and demonstrate an integrated gas-fired heat pump water heater (GHPWH) for residential applications, designed for a direct retrofit and to reduce energy consumption and emissions by 50 percent or greater over conventional baseline appliances (i.e., a standard efficiency gas-fired storage water heater). The GHPWH is based on a direct-fired single-effect vapor absorption cycle using the ammonia-water working pair and incorporates internal heat recovery to achieve a projected 1.2-1.3 UEF, depending on use patterns. While the design and development of this GHPWH is described in prior publications [Garrabrant, 2013 and Glanville, 2016], here the authors provide an overview of results from an expanded demonstration in Southern California, including as-installed efficiencies versus measured baseline, installation and operating challenges, and qualitative input from installers and the host sites. Additionally, the authors report on the development of a model simulation to support technology adoption and an assessment of applicable the market strengths and barriers.

Technology Overview

The GHPWH is based on the vapor absorption refrigeration cycle, using the ammonia-water working fluid pair, where an absorbent (water) is used as a carrier for the refrigerant (ammonia). Though the refrigerant is still compressed by an electromechanical pump like electric HPWHs, unlike a more typical vapor compression cycle, the refrigerant (ammonia) is compressed as a liquid in solution with the absorbent (water), requiring significantly less energy. For example, comparing a 1.3 $COP_{heating}$ ammonia-water heat pump to an 8.2 HSPF vapor compression heat pump, the absorption cycle solution pump requires less than 1.0 percent of the total energy input to the electric compressor [Herold, 1996]. While only a small fraction of the energy is required to lift the pressure of the refrigerant in the absorption cycle's "thermal compressor" by comparison, the bulk of the energy input to the heat pump overall is the thermal energy needed to boil off the refrigerant into a vapor state from this absorbent/refrigerant solution.

Like vapor compression based HPWHs, a refrigeration effect moves heat from ambient air, at the evaporator, to the stored water (via a hydronic loop), at the condenser. While compression of the liquid refrigerant/absorbent solution is performed by the solution pump, thermal energy from the very small, single-stage, 6,300 Btu/hr (1.8 kW) gas burner is required to drive the refrigerant vapor from its absorbed state in the desorber (or "generator"). This desorption process occurs at an elevated temperature, 250-300°F (121-149°C), thus exiting flue gases still have useful heat, which is recovered in a separate condensing heat exchanger (CHX), prior to flue gas exhaust. As the ammonia/water pair has a significant heat of absorption, this is recovered at the absorber as well, by the same hydronic loop as the condenser. Thus, the GHPWH heats the stored water via three inputs: condenser heat from the heat pump, recovered heat of absorption in the absorber, and heat recovery of the flue gases via the CHX (Figure 2). Because only a fraction of the heat delivered to the tank is from the evaporator, roughly 30 percent, the GHPWH performance is less sensitive to ambient conditions than electric HPWHs and with less of a "cooling effect". As such, the GHPWH does not provide cool exhaust air to the space and any cooling impact is unlikely to be substantial. Additionally, because heat pumps pump additional heat from a heat source to where heat is required instead of converting work to heat, the coefficient of performance can be greater than 1.

Figure 2: Diagram of Simplified Cycle – Gas Heat Pump Water Heater



Source: Stone Mountain Technologies, Inc.

The first and second generation GHPWH prototypes were designed and demonstrated through laboratory testing through 2013 [Garrabrant, 2013], by a team including the authors with academic and manufacturing partners. Following a successful proof-of-concept development program, including laboratory demonstration of target operating efficiency ($COP_{Gas} > 1.50$) and projected compliance with Ultra-low NOx limits (10 ng NOx/J output), the team shifted to early-stage field trials, including placing second and third generation GHPWHs in single-family homes in Tennessee, Washington, Idaho, and Oregon (Figure 3). This paper concerns the "4th Generation" GHPWH designs, which incorporate improvements to the reliability of key

Figure 3: First through Third Generation Gas Heat Pump Water Heaters

Source: GTI

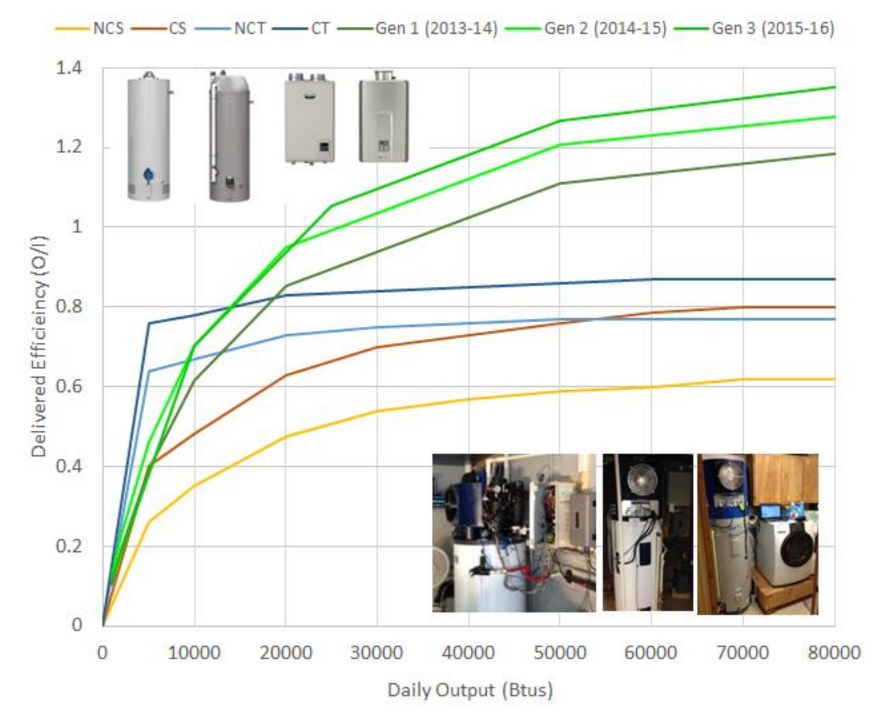
components (expansion valve, solution pump), the cost-effectiveness of the design, and the controls for better performance during high demand, based on prior field and laboratory testing of the previous generation designs. The newest generation unit shares the following characteristics with prior generations unless otherwise noted:

- Sizing: Similar to electric HPWHs, the absorption heat pump has a heating rate of approximately 10,000 Btu/hr (2.9 kW) and is integrated with a nominal 65-gallon storage tank (prior generations used 80-gallon tanks). It has a footprint comparable to the electric HPWH models. In rare occurrences when the demand is high, the GHPWH heats the upper tank with a 1.25 kW heating element simultaneously with gas heat pump operation. This element is sized so the GHPWH can operate on a standard 15 A, 120 VAC circuit and does not operate in isolation.
- Infrastructure: The GHPWH has an estimated 35 percent-50 percent lower retrofit installation cost than other efficient gas water heaters, such as tankless systems or condensing storage systems, due in large part to its very small combustion system. The GHPWH can retrofit directly with ½″ gas piping, common for the majority of existing gas storage water heaters, as opposed to ¾″ gas piping for some high-efficiency tankless installations. Also, the GHPWH’s high-efficiency burner is vented with ¾″-1″ diameter PVC. Combustion and evaporator condensate are handled using common methods as with other condensing appliances.
- Siting: As an air-source heat pump, the GHPWH must have adequate air flow across the evaporator, just like electric HPWHs. The sealed ammonia charge is less than 1/5 the limit for safe operation recommended by ASHRAE Standard 15/IIAR-2, commonly used as a mechanical safety code, permitting indoor installations of the GHPWH within occupied residential spaces.
- Cost: The residential GHPWHs have a target consumer cost of no more than $1,800, with a high-volume target of $1,600. While the equipment cost is higher than baseline (non-condensing gas storage) and other, less efficient, alternatives, the GHPWH installation cost is close to a direct retrofit with baseline, without the need for a larger diameter gas piping, large diameter venting, nor higher voltage electrical service. As a result, the GHPWH total installed cost is comparable to or less than alternatives and, with projected gas and electricity consumption over 10 years, the GHPWH has the lowest estimated total cost of ownership [Glanville, 2016]. Assuming a natural gas price

of $1.00/therm and high-volume equipment pricing, and applying a 3% price escalation rate, the estimated payback is approximately 7 years.

- Performance: Prior generations were evaluated in laboratory conditions and then prototypes were monitored from 6 to 12 months, gathering more than 7,200 operating hours collectively during field operation. A summary of operating efficiency relative to conventional gas-fired water heating equipment is shown in Figure 4, indicating increases in GHPWH performance relative to conventional storage and tankless water heating options as measured in prior field assessments [Kosar, 2013]. Generally, the "3rd Generation" GHPWHs operated near or at operating efficiencies demonstrated in prior lab testing, with COP_{gas} ranging from 1.4 to 1.8 on a site basis. From these results, with an "Input Output" methodology to estimate the delivered efficiency as a function of daily hot water output frequently used in field studies of this nature [Bohac, 2010], the GHPWHs demonstrated an estimated delivered efficiency of 1.25 for the indoor installation and 1.18 for the garage installation for a high usage home, consistent with per-site gas consumption reductions of 50 percent or greater [Glanville, 2016]. In the development of the "Fourth Generation" design, improvements were made concerning operating controls and key components, most notably the two critical moving parts within the absorption heat pump: the solution pump and the electronic expansion valve (EEV). As this GHPWH technology is based on a novel, small-sized absorption heat pump, several necessary components did not exist off-the-shelf and required either a custom design (solution pump) or for existing components to operate at the low end of their design range (EEV), which in both cases were revised for improved reliability and robustness through a focused development program. Additionally, the aforementioned CHX was shifted from a submerged design within the tank to an external heat exchanger within the 'heat pump' module, reducing equipment cost and complexity but slightly reducing overall combustion efficiency and UEF.

Figure 4: Summary of Performance of Prior Gas Heat Pump Water Heater Generations as Compared to Conventional Gas Water Heating Equipment



N/CS = (Non-) Condensing Storage & N/CT = (Non-) Condensing Tankless

Source: GTI

CHAPTER 2:
Project Approach

This project team sought to advance this GHPWH technology towards commercialization:

- Field Demonstration: Deploy and monitor five GHPWHs for a 12-month period to demonstrate that the projected delivered efficiencies of 130 percent or greater are valid, robust, and are not achieved through a loss of user comfort or performance. Estimate annual energy, operating cost, and emissions savings and solicit feedback from host end users and installation contractors through pre/post surveying.
- Performance and Extended Life Testing: Through laboratory testing at the Southern California Gas (SCG) Engineering Analysis Center (EAC), quantify energy efficiency with standard and simulated use testing (comparing to "as-installed" measurements), demonstrate compliance with Ultra-low NOx emission limits, and perform extended-life on one prototype GHPWH to demonstrate reliability.
- Model Development and Analysis: Since the GHPWH represents a new product category, develop tools and guidance to prepare stakeholders and code officials. Develop a user-friendly GHPWH modeling tool to estimate annual operating efficiency and energy savings based on installation type, hot water usage, and California Climate Zone. Perform a "Title 24 Analysis," evaluating the relative cost effectiveness of the GHPWH in comparison to other competing water heater technologies measures used to exceed the 2016 Title 24 performance level and develop a framework for GHPWH integration in the Residential Alternative Calculation Method.
- Understand Market Barriers: Survey and quantify market barriers to broad GHPWH adoption in the Los Angeles Basin, once commercialized. Barriers considered include real and perceived barriers to consumer adoption and contractor recommendation (home performance contractors, HVAC, and plumbing contractors included).
- Stakeholder Outreach: Educate prospective GHPWH consumers, installation contractors, and other affected stakeholders through a series of workshops to introduce the GHPWH technology and summarize project findings. Additionally, develop educational content and materials for contractors and utility ratepayers.

Description of Host Sites

As a first step of the field demonstration, it was necessary to find qualified host sites that represent the projected GHPWH market, to better understand performance and installation barriers. Ultimately, five sites were selected for this demonstration task. The following qualifying criteria for identifying suitable host sites were used:

- At least three occupants.
- Existing gas-storage water heater.
- Single-family residential site.
- Space to accommodate current water heater and GHPWH.
- Simple installation and removal of equipment.

- "Friendly" Host Site, meaning willingness to cooperate fully with all aspects of the demonstration.

The five host sites selected were generally similar as outlined in Table 1. All sites have water heaters installed in garages, the majority of sites have four occupants, and have gas-fired storage-type water heaters. All but Site #5 have natural-draft, minimum efficiency water heaters with 40,000 Btu/hour (hr) input. All but Site #5 are detached single family homes. Figure 5 and Figure 6 include photos of each site's garages. Table 2 highlights the primary features of the hot water distribution system at each home, including piping material and layout, number and characteristics of bathrooms, and major end uses.

Table 1: Characteristics of Host Sites

Site	Home/Occupant Description	Heater Location	Existing Equipment
1	Single Family Detached Home, Four Occupants: (39, 36, 6, 3)	Garage	Gas Storage Type: Bradford White *M440T6FBN*, 40,000 Btu/hr input, 40 gallons, 0.62 EF
2	Single Family Attached Home, Four Occupants: (30, 30, 3, 1)	Garage	Gas Storage Type: Bradford White *U440T6FRN*, 40,000 Btu/hr input, 40 gallons, 0.62 EF
3	Single Family Detached Home, Four Occupants: (60, 57, 25, 20)	Garage	Gas Storage Type: Bradford White *MI40T6EN12*, 40,000 Btu/hr input, 40 gallons, 0.54 EF[A]
4	Single Family Detached Home, Four Occupants: (60, 49, 19, 14)	Garage	Gas Storage Type: Bradford White *U45036FRN*, 40,000 Btu/hr input, 50 gallons, 0.62 EF
5	Single Family Detached Home, Two Occupants: (61, 63)	Garage	Gas Storage Type: Rheem PowerVent *42VP40FN*, 36,000 Btu/hr input, 40 gallons, 0.67 EF

[A] **Estimate based on build-date of unit (2002)**

Source: GTI

Figure 5: Sites 1, 2, and 3

Source: GTI

Figure 6: Sites 4 and 5

Source: GTI

Table 2: Main Features of Host Site Hot Water Distribution

	Site 1	Site 2	Site 3	Site 4	Site 5
Primary Plumbing Material/Layout	Copper; Main/Branch Layout	Copper; Main/Branch Layout	Copper; Main/Branch Layout	Galvanized Steel; Main/Branch Layout	Copper; Main/Branch Layout
Recirculation? Insulated?	No	No	No	No	No
Number of Showers/Baths	Two: One Shower, One Shower/Bath	Two: One Shower, One Shower/Bath	Two: One Shower, One Shower/Bath	Two: One Shower, One Shower/Bath	Two: One Shower, One Shower/Bath
Number of Bathrooms	Two	Three	Two	Three	Two
Washing Machine	Yes, one	Yes, one	Yes, one	Yes, one	Yes, one
Dishwasher	Yes, one	Yes, one	Yes, one	Yes, one	Yes, one
Other DHW End Uses	N/A	N/A	N/A	N/A	N/A

Source: GTI

Field Data Acquisition System

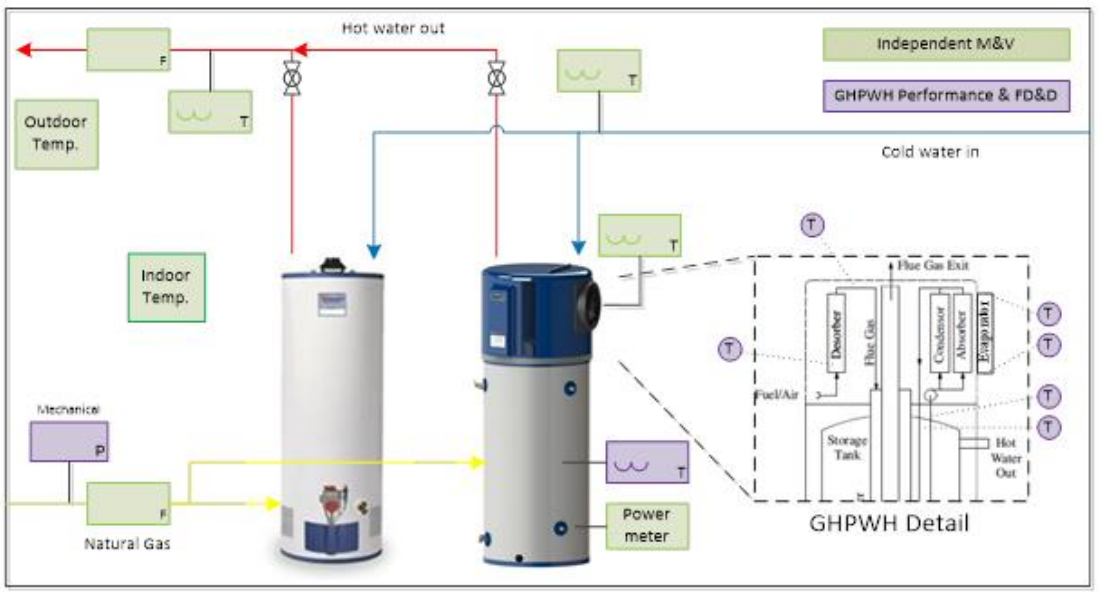
As outlined in the monitoring plan (Appendix A), data was collected using the Logic Beach Intelliogger IL-80 datalogger, connecting to project implementers and evaluators via a cellular modem on Verizon's network. All clocks were synchronized to the NIST clock available on the web. The IL-80 sent datasets to a secure website via FTP on a weekly basis, backing up data their respective servers, and also storing data onto its 128 MB onboard memory card. To prevent data loss due to power surge and/or temporary power loss, the datalogger was powered via surge protection and an Uninterrupted Power Supply (UPS) with provisions for remote power cycling. With this datalogging platform, to quantify the aforementioned performance metrics, the data in Table 3 will be collected on a continuous basis and Figure 7 shows a diagram of measurements used during these planned field evaluations of the GHPWH prototypes, distinguishing between those used for measurement and verification (M&V) (green) and added measurements for GHPWH performance monitoring and fault detection and diagnosis (FD&D) (purple). Table 4 summarizes the measurement points used during this and subsequent phases for measuring water heater energy input, energy output, and environmental conditions continuously using the remotely connected datalogger package.

Table 3: Independent Measurement and Verification Continuous Measurement Points

Measurement	First and Second Baselines	GHPWH	Method	Accuracy
Natural Gas Input	X	X	Positive displacement diaphragm meter with integrated pulser	±1%, Temperature Compensated
Electricity Input	X	X	True rms power transducer with split core current transformers (CT)	±0.5% (Meter), ±0.75% (CT)
Water Flow	X	X	In-line turbine flow meter with pulse output	Resolution of 0.0132 gallons
Water Temperature (Hot/Cold)	X	X	Type T Thermocouples	±1.5°F
Indoor Air Temperature	X	X	Type T Thermocouples	±1.5°F
Outside Air Temperature	X	X	Publicly Accessible Weather Station	N/A
Exhaust Air Temperature		X	Type T Thermocouples	±1.5°F

Source: GTI

Figure 7: Diagram of Instrumentation During Baseline and Gas Heat Pump Water Heater Monitoring



Source: GTI

Table 4: Measurement Points and Variables

Measurement Type	Measurement Point	Variable	Units
Continuous	Gas Valve State	N/A	
Continuous	Natural Gas Flow	V_{NG}	ft^3
Continuous	Water Flow	V_{HW}	gal.
Continuous	Power Consumption	Q_{elec}	Wh
Continuous	Indoor Temperature	$T_{ind,db}$	°F
Continuous	Exhaust Air Temperature	T_{EA}	°F
Continuous	Water Out Temperature	$T_{w,o}$	°F
Continuous	Water In Temperature	$T_{w,i}$	°F
Continuous	Evaporator In Temperature (NH_3)	$T_{evap,i}$	°F
Continuous	Evaporator Out Temperature (NH_3)	$T_{evap,o}$	°F
Continuous	Hydronic Supply Temperature	T_{sup}	°F
Continuous	Hydronic Return Temperature	T_{rtn}	°F
Continuous	Desorber Shell Temperature	T_{des}	°F
Continuous	Mid-tank Temperature	T_{tstat}	°F
Continuous	Flue Gas Outlet Temperature	T_{FG}	°F
Batch	Inlet Fuel Pressure	P_{NG}	in. WC
Batch	GHPWH Operating Noise	N/A	dB
Batch	Evaporator Air Flow (Velocity at Multiple Points)	v_{evap}	ft/min.
Batch	Hydronic Flow Rate	$\dot{V}_{hyd}$	gpm
Batch	Excess air level, as dry stack O_2	n_{O2}	%, dry
Batch	Flue Gas Outlet, Desorber Temperature	$T_{FG,Des}$	°F
Batch	Tank storage volume	V_{tank}	gal.

Measurement Type	Measurement Point	Variable	Units
Batch	Non-Condensable Formation (if needed)	Visual Confirmation	Visual Confirmation
3rd Party Data	Outdoor Temperature	$T_{OD,db}$	°F
3rd Party Data	Outdoor Humidity	RH_{OD}	%
3rd Party Data	Barometric Pressure	P_B	in. Hg
3rd Party Data	Natural Gas HHV	*HHV*	Btu/scf

Source: GTI

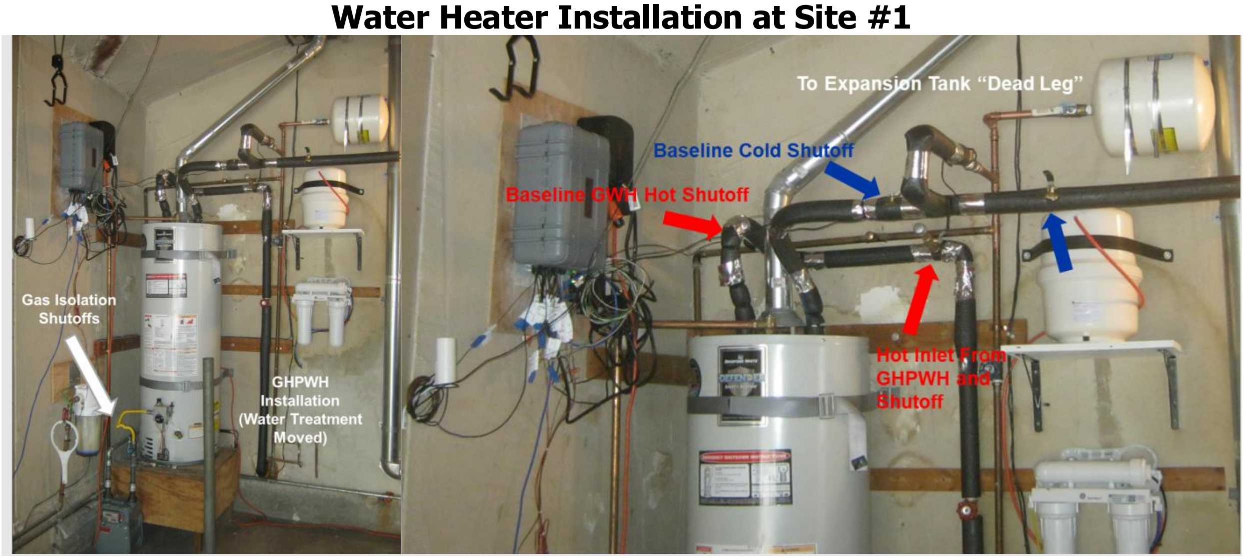
CHAPTER 3:
Project Field Evaluation Results

Field data was collected and categorized into three separate types: baseline (existing water heater at each home), the prototype GHPWH, and a second baseline period when a high efficiency, commercially available gas water heater was installed at the site. Where the first baseline is discussed, it is referred to as 'baseline' while the second baseline is always noted as 'second baseline', and savings reported refer to the original baseline unless otherwise specified. Two baselines allowed the project team to assess the magnitude of savings of the GHPWH compared to as-found, lower efficiency systems and a "best case" high efficiency system. Details concerning the baseline assessments and GHPWH assessment are both contained within the Appendices B and C.

Baseline Water Heating Systems and Performance

Data collection equipment per the monitoring plan (Appendix A) were installed at five sites, with additional preparations for future GHPWH installations (for example repositioning of plumbing), with an example in Figure 8. During these installations, the team initially identified potential barriers to GHPWH adoption, based on installation/infrastructure needs, initial host site feedback, and input from plumbing contractors. More than three months of baseline conventional gas water heater operational data was collected from the five homes, spanning from early March to early June 2018. The general goals in the initial Baseline Monitoring Phase were threefold.

Figure 8: Baseline Monitoring Equipment and Preparations for Gas Heat Pump Water Heater Installation at Site #1



Source: GTI

Establish Site-Specific Performance Baseline

The project team sought to establish a baseline of energy and water consumption to later compare to savings during GHPWH monitoring period and a second baseline period concerning retrofit of a standard high-efficiency gas water heating product, normalizing savings to site-specific characteristics. For the purposes of establishing this performance baseline via independent M&V, the data was processed in spreadsheets for each site and condensed into 5-minute interval data. During the data validation process, gaps in the data totaling approximately five site-days of data were identified, but do not cause any concern for the processed data. At the time of sampling, these customers gave information about their household size and information on the existing water heater was collected. This information along with measurement result summaries are shown in Table 5. This sample is predominantly four-person family households. The baseline water heaters are all conventional natural gas water heaters. The first four have pilot lights while Site #5 has electronic ignition. Summary results of the monitoring are also provided in this table. The average measured hot water temperature setpoint for the sites is 137ºF which falls between the typically recommended range of 120ºF to 140ºF. The average hot water use for the sites is 50 gallons per day with peaks of up to 163 gallons. The annual natural gas usage by the baseline water heater is projected from the three months of monitoring. The average field measured baseline water heater efficiency is 49 percent.

Table 5: Characteristics and Summary of Measured Original Baseline Results

Site #	Measured Setpoint Temp. (F)	Hot Water Use (Gallons/Day)	Annual Gas Use (therms)	Measured Efficiency
1	127	57.9	161.2	0.52
2	142	54.7	112.7	0.51
3	144	52.0	93.9	0.47
4	149	54.9	187.9	0.48
5	122	29.2	150.3	0.47
Average	**137**	**49.8**	**141.2**	**0.49**

Source: GTI

At the close of the GHPWH monitoring periods, each host site had its GHPWH removed and the original water heater was replaced with a high-efficiency gas-fired water heater, with some examples of retrofits shown in Figure 9. While the original water heating equipment, low-efficiency and typical of the majority of Los Angeles-area homes, serve as the as-installed site retrofit baseline, these high-efficiency water heaters installed post-GHPWH monitoring period can serve as a 'Second Baseline'. This represents an alternative scenario where a consumer would retrofit to a high-efficiency gas water heating product instead of the higher-efficiency GHPWH.

While the retrofits were staggered after the decommissioning of the GHPWH units, depending on scheduling with sites and any extensions of the GHPWH monitoring, second baseline water heaters were installed according to Table 6. As per site request and installation contractor recommendation, the tankless units installed (Sites #1 - #4) used a standard integrated recirculation pump, employing a 'cross-over tee' approach wherein a custom cross-over tee is installed tying the cold and hot lines together at the farthest fixture. An integrated recirculation pump, controlled on a timer or demand-based, will activate the tankless water heater to pre-heat this loop, assuring time delays to hot water at distant fixtures is minimized. As noted, while the hosts all requested the recirculation feature, they did not use it consistently with Site #1 and #4 using demand-based recirculation, Site #3 was timer-based, and for Site #2 recirculation was disabled all together.

Figure 9: High-Efficiency Tankless Water Heaters Installed as Retrofits at Host Sites #1, #3, and #4

Source: GTI

Table 6: Characteristics of 2nd Baseline Water Heaters for Each Host Site

Site #	Product Type	Make and Model	Max Input (Btu/h)	Max Output (FHR/GPM) and UEF	Recirc.	Install Month/year
1	Tankless	Rinnai / RU199iN	199,000	11 GPM / 0.93	Demand based	9/19
2	Tankless	Rinnai / RU199iN	199,000	11 GPM / 0.93	Not active	10/19
3	Tankless	Rinnai / RU199iN	199,000	11 GPM / 0.93	On Timer	3/20
4	Tankless	Rinnai / RU199iN	199,000	11 GPM / 0.93	Demand based	3/20
5	Storage (50 Gal.)	Bradford White URG2D50S6N	40,000	81 GPH / 0.68	None	12/19

Source: GTI

Originally, the project team did not plan for recirculation during the second baseline, creating a challenge regarding the placement of the water flow meter, which was already plumbed in place during the first baseline and GHPWH monitoring periods. The team opted to maintain placement of the water flow meter immediately upstream of the tankless water heaters at Sites #1-#4 on the cold leg, which had the effect of permitting an accurate assessment of energy input/output to the water heater itself but did not permit disaggregating recirculation flow from actual DHW loads. The alternative would be to ignore the energy input/output of the tankless water heater during recirculation mode, which could be significant. Table 7 summarizes the measured characteristics of the second baseline at the five host sites.

Table 7: Characteristics and Summary of Measured Second Baseline Results

Site #	Measured Setpoint Temp.(F)	Hot Water Use (Gallons/Day)*	Annual Gas Use (therms)*	Measured Efficiency*
1	119	108.4	123.1	0.91
2	132	62.0	104.7	0.86
3	138	82.9	314.5	0.36
4	144	86.9	270.5	0.57
5	118	24.9	97.3	0.40
Average	**130**	**73.0**	**182.0**	**0.62**

*** Includes recirculation flow for Sites #1, #3, and #4**

Source: GTI

Detailed results comparing the second baseline performance to the original baseline and GHPWH are included in the following Heat Pump System Performance section and in Appendices B and C.

Extrapolate Baseline Measurements to General Case

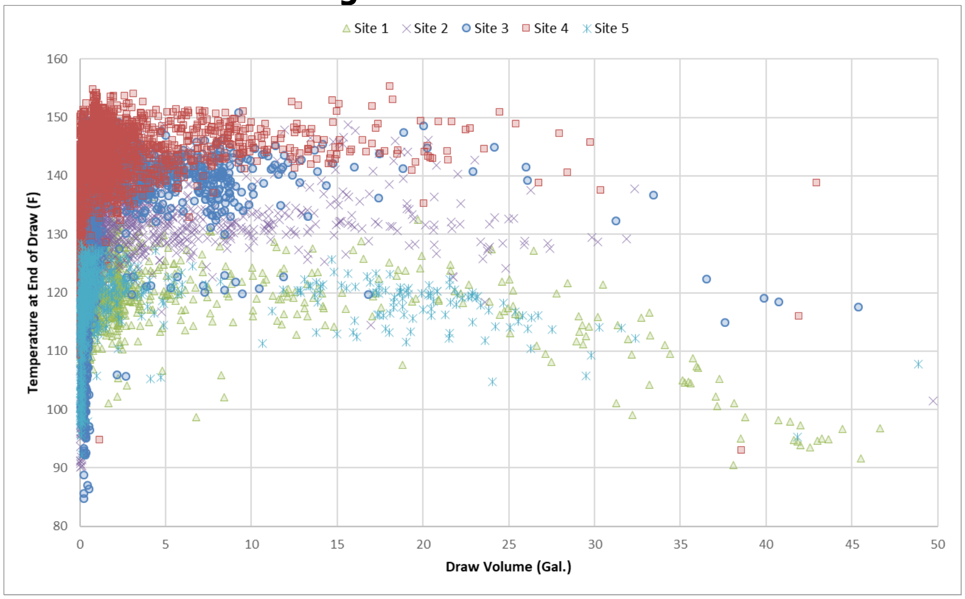
In addition to establishing site-specific baselines with independent M&V, GTI extrapolated from these datasets to analyze domestic hot water (DHW) loading, compare sizing of GHPWH units to expected loads, with projections of issues associated with capacity while also facilitating extrapolation across installation types throughout California. The GHPWH units have a reduced capacity compared to typical gas-fired water heating equipment, approximately 10,000 Btu/hr output (nominal) with additional, supplemental heating with an approximately 1200 W heating element. While this is a 2-2.5 times lower output capacity than the baseline gas water heating equipment at the host sites, the GHPWH's nominal 60-gallon tank volume is 50 percent greater than heaters at Sites #1-3 and #5, and 20 percent greater than the heater at Site #4. As such, the GHPWH units have the potential meet the same DHW demand as conventional gas-fired products through a larger storage tank, though the intermittency and clustering of DHW demand (when DHW is used) is critical. Using data collected on DHW consumption during the baseline monitoring stage, in this section the project team seeks to highlight if sites may run into GHPWH capacity issues.

With a means of assessing "worst-case" water heater sizing, referred to as the "Moving Window" analysis, GTI used the detailed DHW draw information to judge potential GHPWH sizing issues. A sizing analysis first described for residential applications in the 1990s by Hiller [Hiller, 1998], this analysis provides a conservative approach to analyzing detailed field hot water consumption data to estimate compatible water heater storage volumes and heating output rates. Using aggregated DHW draw patterns from the five sites during the original baseline monitoring period, with details in Appendices B and C, GTI estimated that, in general:

- The GHPWH units may be better able to satisfy DHW loading versus baseline equipment, particularly at Sites #3-#5.
- For Sites #1 and #2, over the remaining sites, the project team should pay close attention to GHPWH capacity and look for instances of "running out of hot water".

A more direct means of judging the capacity of the existing water heaters is to assess how often the home "runs out" of hot water. For each draw at the five sites, Figure 10 compares the final delivered temperature to the draw volume. While Sites 2-4 appear to be well served by their existing water heating equipment, in terms of capacity, sites with a more pronounced downward trend for draws > 5 gallons, Sites 1 and 5, the existing water heater appears to frequently be inadequate for their DHW needs.

Figure 10: Final Temperature at End of Draw versus Draw Volume Original Baseline Period



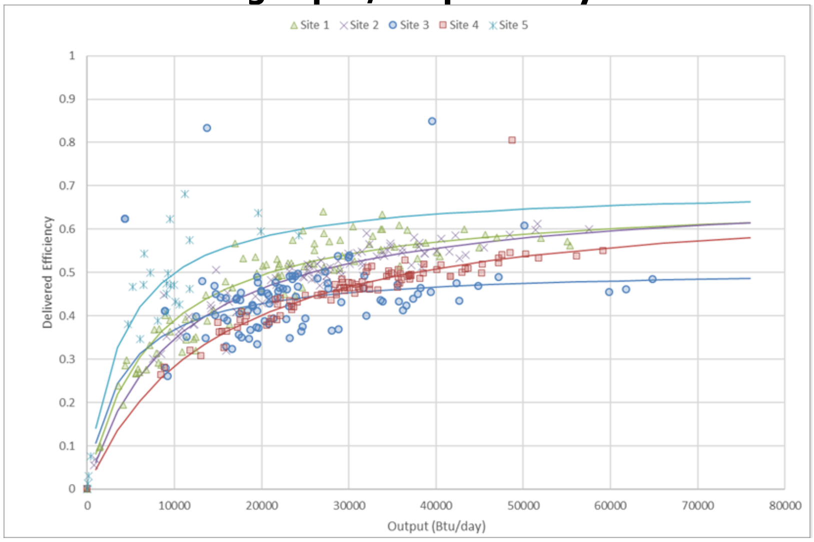
Source: GTI

In addition to judging capacity through the "Moving Window" analysis, another established methodology called the "Input/Output" analysis ("I/O") will be used to extrapolate energy savings to the general case and comparing GHPWH versus baseline performance across multiple laboratory and field studies. As outlined in the monitoring plan, this method posits that the daily energy input vs. output of a heating system can yield a delivered efficiency from their linear relationship of the transient energy input to the energy output [Bohac, 2010 and Butcher, 2011]. When plotted on an "I/O" chart the slope and y-intercept can be used to estimate the Delivered Efficiency (DE), as follows:

$$Input = m \cdot Output + b;\ \frac{Output}{Input} = DE = \left(m + \frac{b}{Output}\right)^{-1}$$

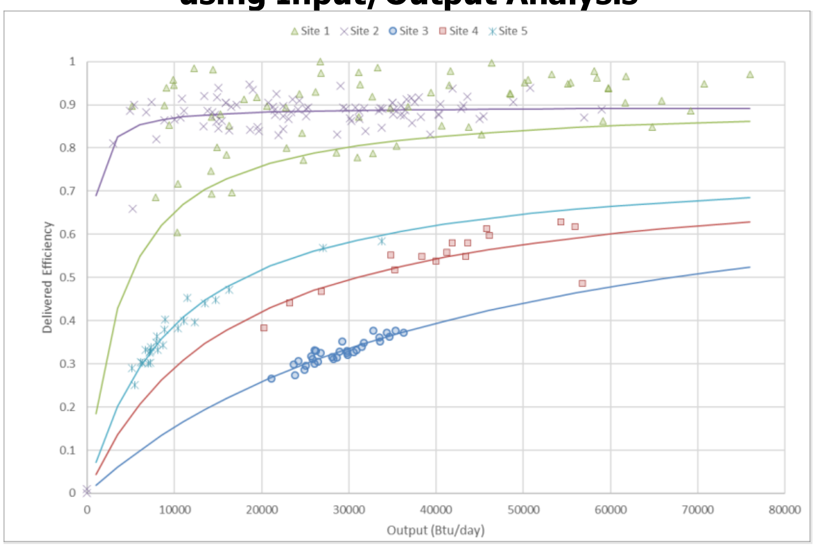
With detailed results per this analysis in the Appendices B and C, for original and 2nd baseline periods, the extrapolated delivered efficiency curves are shown in Figures 11 and 12, highlighting relative uniformity across original equipment during the former (Figure 11) while significant variation amongst the high-efficiency 2nd baseline equipment highlights the significant impact of recirculation control strategies used (Figure 12). These performance curves are used in later extrapolations in comparison to GHPWH performance.

Figure 11: Delivered Efficiency for Original Baseline Monitoring Period using Input/Output Analysis



Source: GTI

Figure 12: Delivered Efficiency for Second Baseline Monitoring Period using Input/Output Analysis

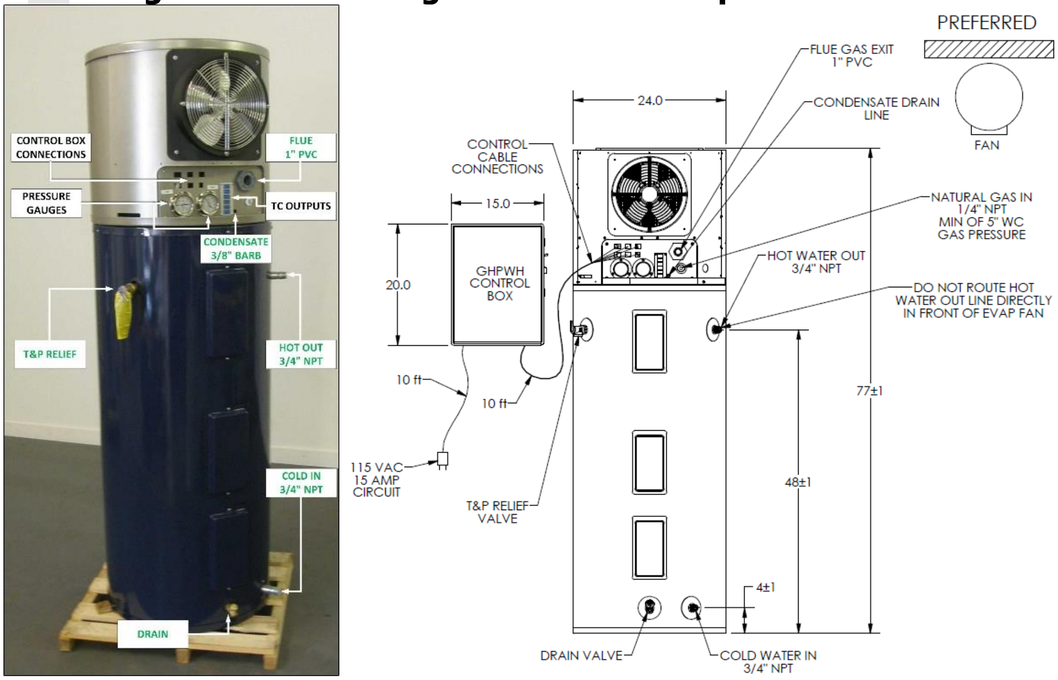


Source: GTI

Heat Pump Water Heater Installation and Commissioning

After the five GHPWH prototypes were built by SMTI and their manufacturing partners, GTI worked with SMTI to develop contractor training materials to assure a smooth installation and commissioning period. The location and type of connections, required setbacks, and operating procedures were prepared and issued to the installation contractor and host sites in advance of shipment (Figure 13).

Figure 13: Diagram and Drawing of Gas Heat Pump Water Heater Prototypes

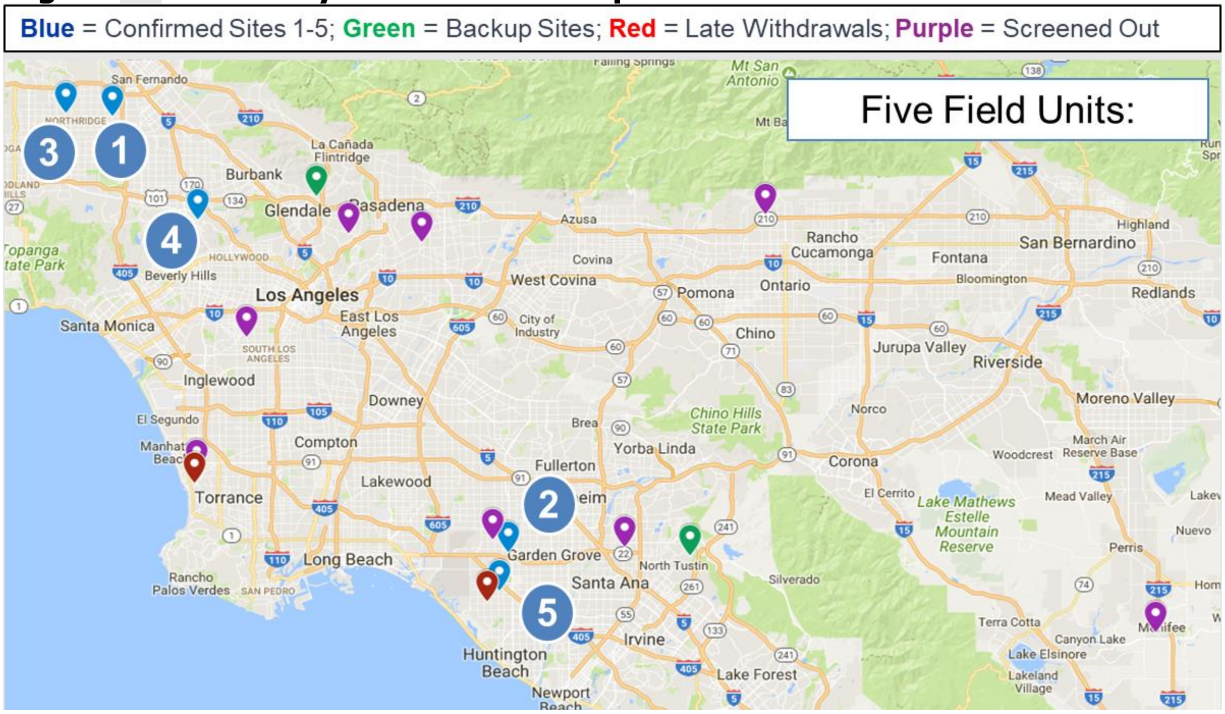


Source: GTI (Drawing Courtesy of Stone Mountain Technologies, Inc.)

While originally believed to be exempt from Ultra-low NOx requirements, the South Coast Air Quality Management District (SCAQMD), required that the project team pursue certification of the GHPWH units to the Rule 1121 standard. After extended communications with the SCAQMD, whose jurisdiction covers the demonstration area, the SCAQMD legal team determined that this project could neither a) demonstrate compliance with Rule 1121 through supplying GTI test data or source testing of actual prototypes nor b) receive a "research waiver" due to the temporary nature of the project or a formal variance of Rule 1121 compliance. As a result, SCAQMD determined that despite the nature of this project, the GHPWHs must be certified to comply with Rule 1121 which was a multi-day test performed by a pre-approved third-party laboratory. Due to the nature of equipment certification, where manufacturers commonly seek SCAQMD certification through testing at certified laboratories only, this was the only option. Thus, GTI and SMTI had the GHPWH prototype certified as Ultra-low NOx with the support of BR Laboratories (Huntington Beach, California) and provided technical support as necessary. Documentation associated with this certification is available upon request. Note that upon certification to Rule 1121, these GHPWHs will meet SCAQMD requirements in future efforts.

Upon receiving certification from SCAQMD, GTI and its project team, including SMTI, Scott Harrison Plumbing, and Rinnai, installed and commissioned six GHPWHs in the Los Angeles area, five at the residential sites and the sixth at the SCG Engineering Analysis Center (EAC). The locations of the residential sites are summarized in Figure 14, and selected commissioned GHPWH unit photos are in the subsequent figure. As noted in the monitoring plan, the GHPWHs were installed in parallel to the existing water heater to permit "switching over" to regain domestic hot water service during periods of GHPWH unit down-time (Figure 15). GHPWHs were installed with isolation valves to permit this "switching over", in practice performed by a project team member or the site host with training. As it relates to this monitoring task, GHPWH units never operated simultaneously with other water heaters.

Figure 14: Summary of Gas Heat Pump Water Heater Installation Locations



Source: GTI

Figure 15: Sites #2, #3, and #5 – Gas Heat Pump Water Heater Installations

Source: GTI

During installation and commissioning of the GHPWHs and expanded data collection equipment by the project team, across the five sites, spot measurements regarding GHPWH noise, combustion emissions, and gas quality were made. During the first few weeks of operation, several nuisance issues arose and were resolved, regarding:

- Discovering Site #3 had insufficient electrical service for supplemental heating, so it was disabled at this site only for this project, with monitoring assuring DHW capacity was not adversely affected.

- Proper sloping of vent runs for condensate disposal also at Site #3 was resolved after nuisance “blocked vent” errors caused early interruptions of GHPWH operation.
- During commissioning of the Site #4 GHPWH, it was discovered that the in-tank heat exchangers suffered vibrational damage during shipping, leading to a storage tank leak, with the tank later replaced during an on-site repair. A similar issue impacted the GHPWH shipped to the SCG laboratory, leading to a design change to limit future shipping damage

Additional photos and details concerning installation and commissioning are in Appendix C.

Heat Pump System Performance

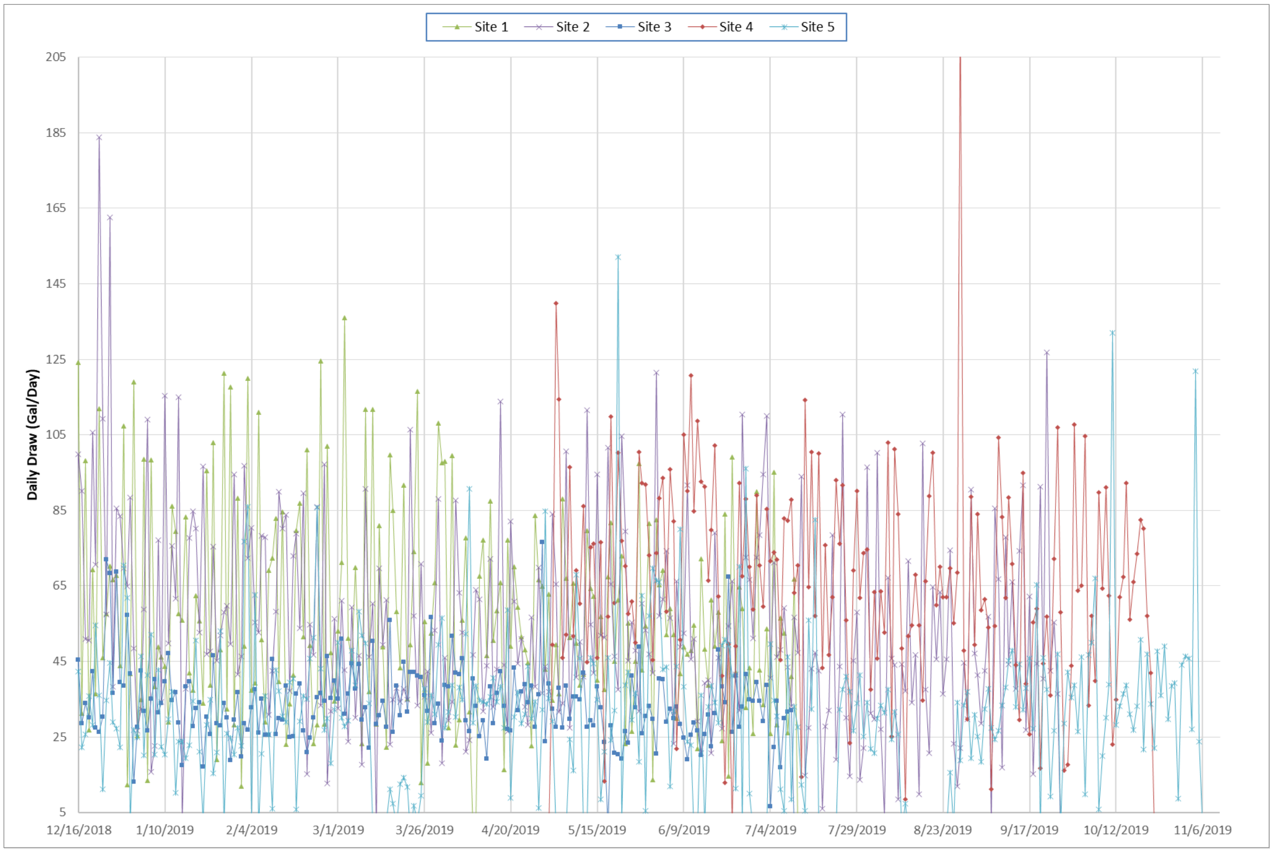
With all five GHPWH units commissioned, the monitoring phase began in mid-2018 and lasted through mid-to-late 2019. Unit activity is summarized in Table 8, highlighting the significant output and DHW activity at each site while the GHPWHs were operational. DHW consumption at all five sites did not differ greatly from that observed during the baseline monitoring period, with large variation between average and peak draws observed and the GHPWHs achieving the same delivered temperatures as well. This large variation in consumption is further summarized in Figure 16, highlighting large swings in consumption depending on weekday/weekend, inferred occupancy, and other behavioral factors. More details on the activity at each site are provided in Appendix C.

Table 8: Summarized Gas Heat Pump Water Heater Activity at Five Sites from Mid-2018 to Mid-to-late 2019

	Site #1	Site #2	Site #3	Site #4	Site #5
DHW Delivered (gal)	3,900.7	4,279.7	3,796.8	5,657.2	3,237.0
Average Draw (gal/day)	54.0	52.23	34.3	62.6	33.8
Peak Draw (gal/day)	136.0	183.9	76.7	217.5	174.0
Max Outlet (F)	127.1	126.9	131.9	136.0	128.1
Min inlet (F)	45.6	64.2	56.4	65.5	65.3
GHPWH Hours	985.3	1,123.7	772.0	859.1	910.1
GHPWH Cycles	421	533	337	457	481

Source: GTI

Figure 16: Domestic Hot Water Consumption During Gas Heat Pump Water Heater Phase



Source: GTI

Gas Heat Pump Water Heater Troubleshooting and Servicing

While all sites had the GHPWH installed for 12 months or more, unit up-time varied widely. This owed primarily to operational and maintenance issues with the GHPWH units themselves. These events and site-specific matters are summarized as follows:

- Solution Pump Servicing: An issue that affected all operating GHPWH units, materializing after 180-200 hrs. of operation and observed as over-temperature events leading to system shutdown, was traced to a design change made that was made in error and ultimately reversed. All GHPWH units in this study required removal, refurbishing, and replacement of solution pumps as a result. As a result of findings from this and parallel efforts, the manufacturer has incorporated a design revision into new solution pumps that addresses issues seen in this demonstration, with several pumps undergoing life testing at time of writing.
- Narrow Heat Exchangers Within Sealed System: Within the sealed system are "capillary tubes", small diameter tubes that allow for limited flow and pressure equalization within certain parts of the GHPWH units. These narrow passageways were found to be subject to intermittent instances of "vapor lock", resulting in low or no solution flow and leading to minor overheating of other vessels. Originally believed to be due to debris circulating within the sealed system, the manufacturer later determined this traced to the design of

the solution heat exchanger (SHX) which, due to findings from this project, has since been fixed.

This issue presented as abnormal performance for units installed at Sites #1, #4, and #5, which would experience intermittent, seemingly random system faults (over-temperature events). The issue varied in severity and resolution of this matter ranged from remote re-starts (Sites #1 and #5) to replacement of heat exchanger segments (Site #4, leading to significant down-time). Ultimately the variation in this issue is suspected to be due to magnitude of hot water consumption during GHPWH recovery events and minor variations in prototype manufacturing. As noted this has been designed around, with some passages made less restrictive or eliminated, and can be further eliminated through OEM-quality production.

- General Prototype Maintenance: On several occasions, the manufacturer performed general maintenance on the GHPWH units, including a more intensive visit to all sites in April 2019. These visits included some, or all of the following: cleaning evaporator coil and combustion air inlet filters (dust/lint), topping off hydronic loop water due to minor leaks, bleed non-condensable gases, adjust the NH3 charge if component servicing was performed previously (e.g. EEV or solution pump replacement), repair/replace electronic components due to loose wiring or failure, and check the solution pump belt/motor assembly.

Further details on GHPWH servicing and unit up-time are located in Appendix C.

Site-Specific Savings

The energy use for the first and second baseline gas water heaters and the GHPWHs are projected into estimated annual loads. Where the first baseline is discussed, it is referred to as 'baseline' while the second baseline is always noted as 'second baseline'. The gas and electric loads are combined as energy in units of kBTU. The results for each of the five demonstration homes and the average are shown in the tables below.

Table 9: Estimated Annual Natural Gas and Electrical Energy Use and Savings for GHPWHs versus Baseline Water Heating

Site #	GHPWH Gas Use (therms)	GHPWH Electric Use (kWh)	GHPWH Energy Use (kBTU)	GHPWH Versus Original Baseline Annual Savings (kBTU)	GHPWH Versus Original Baseline Percent GHPWH Savings	GHPWH Versus 2nd Baseline Annual Savings (kBTU)	GHPWH Versus 2nd Baseline Percent GHPWH Savings
1	44	299	5,449	10,970	67%	7,063	56%
2	77	433	9,208	10,339	53%	1,399	13%
3	65	325	7,620	13,772	64%	26,412	78%
4	103	664	12,613	11,340	47%	15,766	56%
5	50	299	6,003	1,808	23%	3,774	39%
Avg	**68**	**404**	**8,178**	**9,646**	**54%**	**10,883**	**57%**

Source: GTI

The estimated annual average total energy savings is 9,646 kBTU per home. This savings is equivalent to 9,365 cubic feet of natural gas per year. At $1.10 per therm, this amounts to a cost savings of $106 per year. The average energy savings is 54 percent (gas and electricity combined). The range of savings is from 23 percent to 67 percent with a median of 53 percent savings. The annual gas use was reduced by more than 61 percent.

It is notable that considering the average annual energy use savings in the above table, it appears the second baseline period is less efficient than the first baseline. Since the second baseline reflects the performance of high efficiency gas water heaters (four tankless units and one condensing storage unit), this is unexpected. However, Sites #1 through #4 had tankless systems with an integrated recirculation pump, controlled either on a timer or demand-based, which would activate the tankless water heater to pre-heat the loop assuring time delays to hot water at distant fixtures is minimized. All sites requested the recirculation fixtures but did not use it consistently. Site #1 and #4 used demand-based recirculation, Site #3 used timer-based recirculation, and Site #2 disabled the recirculation function all together. Some fraction of the water heating load for Sites #1, #3, and #4 is recirculation only and the energy input penalty for this is also included, with varying but significant impacts. Timer-based recirculation was a particularly significant efficiency loss at Site #3. No recirculation was present at Site #5, which did not have a tankless-type water heater installed for the 2nd baseline.

Further comparing characteristics that impact energy use and possibly performance, the water temperatures for the inlet (supply) and the setpoint (outlet) as shown in the table below. The heating setpoint is calculated as the average temperature of the highest temperature quartile of data when there is water flow above 0.5 gallons per minute. The average heating setpoint for the baseline is 137°F which is 10°F higher than the 127°F determined for the GHPWH. The inlet water temperature is calculated as the average temperature of the lowest temperature quartile of data when there is water flow above 0.5 gallons per minute. Inlet water temperatures are heavily influenced by garage temperatures for low volumes of water flow.

Table 10: Inlet and Hot Water Temperatures for Both Baseline Systems by Site

Site #	Measured Inlet Water Temp (F): Baseline	Measured Inlet Water Temp (F): 2nd Baseline	Measured Inlet Water Temp (F): GHPWH	Measured Setpoint Temp (F): Baseline	Measured Setpoint Temp (F): 2nd Baseline	Measured Setpoint Temp (F): GHPWH
1	61	70	76	127	119	124
2	68	71	66	142	132	124
3	63	69	60	144	138	128
4	63	71	68	149	144	133
5	72	75	69	122	118	123
Avg	**66**	**71**	**68**	**137**	**130**	**127**

Source: GTI

The amount of hot water used can influence the efficiency performance. The lower the hot water use the higher the standby losses become of the total energy use. Table 11 presents the average daily hot water use for the baseline and GHPWH periods by site. The average daily baseline hot water use is 50 gallons per day and dropped 12 percent to 43.5 gallons per day for the GHPWH operation. One of the five sites increased their water use. Note comparisons to the second baseline are challenging due to including recirculation flow at three sites.

Table 11: Average Daily Hot Water Use for Baseline and Gas Heat Pump Water Heater Periods by Site

Site #	Baseline Hot Water Use (Gallons/Day)	GHPWH Hot Water Use (Gallons/Day)	Percent Change
Site 1	58.6	42.9	-27%
Site 2	56.0	50.6	-10%
Site 3	52.3	34.3	-34%
Site 4	53.8	61.3	14%
Site 5	29.3	28.5	-3%
Avg	**50.0**	**43.5**	**-12%**

Source: GTI

As has been shown the GHPWH is more efficient and uses less energy than the baseline water heater. The calculation of greenhouse gas emissions is limited to carbon dioxide (CO_2). Carbon dioxide emissions of 0.1134 pounds CO_2 per cubic foot of natural gas are used in the calculation. The CO_2 emission from the use of electric energy is calculated as 0.4716 pounds CO_2 per kWh. The baseline water heater only has CO_2 emissions from the use of natural gas, while the GHPWH has fuel emissions from the use of natural gas and indirectly from the use of electricity from the grid. The average carbon dioxide emissions dropped from 1,960 pounds per year to 939 pounds per year, a 49 percent reduction as shown in Table 12 and Figure 17, noting the significant impact of recirculation during second baseline at Sites #3 and #4.

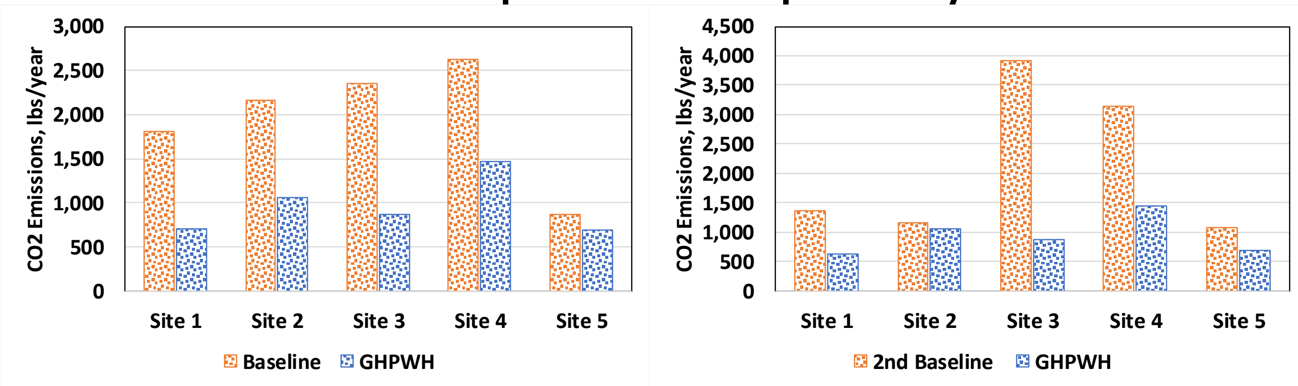
More detail concerning site-specific savings from the baseline and GHPWH monitoring periods can be found in Appendices B and C.

Table 12: Estimated Annual Carbon Dioxide Emissions for Baseline and Gas Heat Pump Water Heater Operation by Site

Site #	Baseline CO_2 Emissions, lbs./year	GHPWH CO_2 Emissions, lbs./year	Percent Change	Second Baseline CO_2 Emissions lbs./year	GHPWH CO_2 Emissions, lbs./year	Percent Change
Site 1	1,802	628	-65%	1,373	628	-54%
Site 2	2,160	1,057	-51%	1,163	1,057	-9%
Site 3	2,347	869	-63%	3,925	869	-78%
Site 4	2,630	1,449	-45%	3,140	1,449	-54%
Site 5	863	690	-20%	1,071	690	-36%
Avg	**1,960**	**939**	**-49%**	**2,134**	**939**	**-56%**

Source: GTI

Figure 17: Estimated Annual Carbon Dioxide Emissions for Baselines and Gas Heat Pump Water Heater Operation by Site



Source: GTI

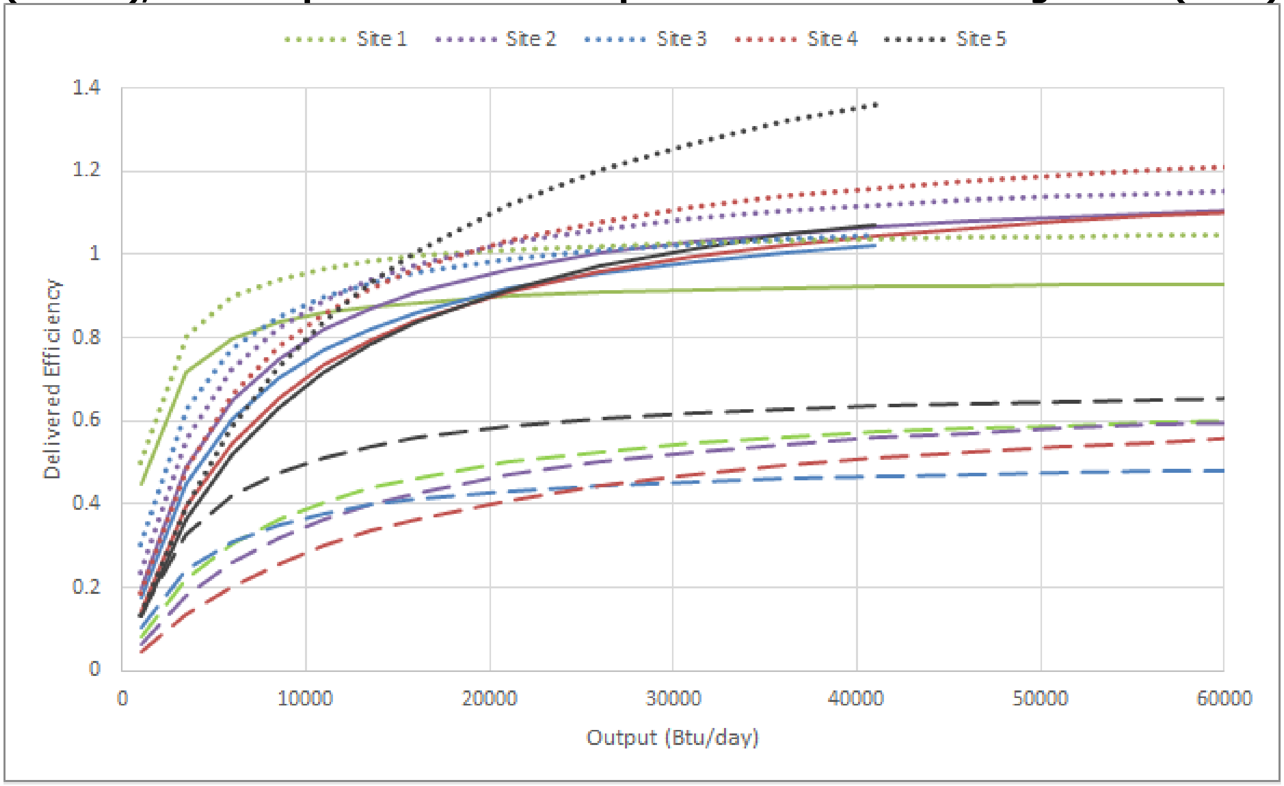
Generalized Gas Heat Pump Water Heater Performance

Independent measurement and evaluation (M&V) results were supplemented by an extrapolative analysis using the aforementioned Input/Output method. While the M&V results are a more accurate representation of the individual sites for this specific monitoring period, the Input/Output approach can be more readily extrapolated to other regions or operating conditions. With the significant run-time at all of the sites, the most extensive GHPWH operating periods measured to date, the first concern is the efficiency of the units relative to baseline. All sites have comparable efficiencies and standby losses, viewed as the relative magnitude of slope and intercepts. When extrapolated to all sites, the median time-averaged cycle efficiency as COP_{Gas} ranges from 1.25 to 1.60 depending on the GHPWH unit and local conditions. On electricity consumption, with moderate hot water consumption of 40-80 gallons/day, the GHPWHs consume 0.5-1.0 kWh/day, with an average of 9 Watt-hour per gallon (Wh/gallon) consumed above a constant 23 watts (W) (higher than future products due to custom prototype controls).

Examining the original baseline, Figure 18 highlights a) that the results are consistent with prior findings of ~50 percent or greater site-specific reduction in fuel consumption and b) there is a substantial variation in GHPWH performance amongst sites. Concerning the latter, the authors intend to clarify the exact contribution of the following at the close of this effort in post-decommissioning analysis: a) lower demand at higher efficiency sites and b) variability in GHPWH prototyping, installation quality, and instrumentation accuracy, where the authors speculate the GHPWH prototyping and installation variability playing a major role.

When examining the comparison to the second baseline as an alternative to a GHPWH retrofit, three trends emerge: 1) sites with tankless using limited or no recirculation (Site #1 and #2) showed comparable savings to the GHPWHs vs. the as-installed baseline but the GHPWH has a 15 percent improvement, 2) sites with tankless using significant recirculation (Site #3 and #4) show negative savings versus the as-installed baseline, with an additional significant power penalty (1-2 kWh/day) and for these sites the GHPWH has a significant advantage, and 3) slightly negative savings shown for the higher efficiency storage retrofit at Site #5 during second baseline versus as-installed baseline, due to greater estimated standby losses, again highlighting a GHPWH advantage.

Figure 18: Delivered Efficiency Water Heaters (I/O) for Baseline (Dashed), First ½ (Dotted), and Complete Gas Heat Pump Water Heater Monitoring Period (Solid)



Delivered efficiency (I/O) for Baseline (Dashed), First ½ (Dotted), and Complete Gas Heat Pump Water Heater Monitoring Period (Solid).

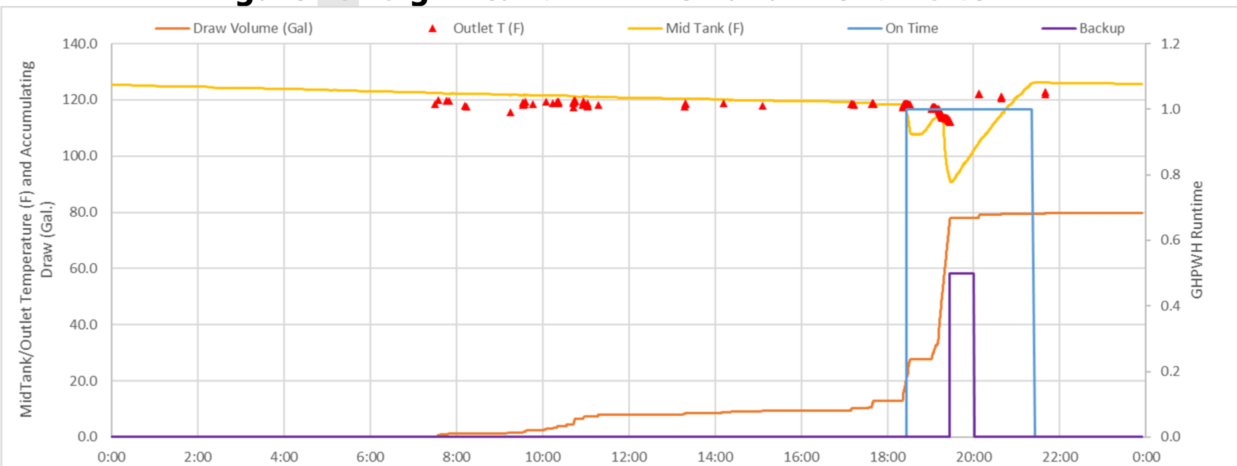
Source: GTI

On DHW capacity, it is understood that if the GHPWH has insufficient hot water capacity and the end user is uncomfortable, the success of this emerging product class is uncertain. Hot water capacity is judged quantitively and qualitatively, with the former determined by monitoring regarding DHW output and supplemental heat utilization, while the latter is handled in survey instruments.

- On supplemental heating energy consumption, as a fraction of power input as supplemental heating, Sites #1, #2, and #4 are large consumers, while Site #5 is quite moderate, recalling that the supplemental heating was disabled at Site #3. In terms of output, the delivered DHW ranges from 1 percent to 6 percent as supplemental heating, lower than the 15 percent-40 percent output from resistance heating typical for electric HPWHs [Ecotope, 2015 and Shapiro, 2016]. Use at these three sites increased with time, suggesting compensation for GHPWH "wear and tear".
- On delivered DHW capacity, the project team observed periods where the GHPWH "ran out" of hot water, primarily driven by turning over the storage volume in a short period of time. This was pronounced at Site #1, which was observed to have very clustered hot water draw events, the figure below shows a 24-hour period that would have been challenging for prior GHPWH generations. In this case, a very long standby period up past 6pm, followed by two large draws, ~15 gallons followed by ~50 gallons. The GHPWH is able to preemptively cycle on during the first draw and, with judicious use of supplemental heating, is able to keep outlet temperatures above 110°F despite mid-

tank temperatures reaching 90°F. Other examples of extreme DHW loading are shown in Appendix C.

Figure 19: Significant DHW Demand Event – Site #1



Source: GTI

- On host site surveys, four of five hosts found the GHPWH to be as effective or more effective in supplying hot water than their existing water heater, while one participant reported issues with maintaining hot water supply.

Further details on GHPWH installation, commissioning, monitoring, and host site surveys are located in Appendix C.

CHAPTER 4: Laboratory Performance and Extended Life Testing

Experimental Test Plan

This task concerns the performance and extended life testing of a prototype residential gas-fired heat pump water heater (GHPWH). The goals of this task, as outlined in this test plan, are to perform extensive laboratory testing of a Fourth Generation design of the GHPWH, as designed by Stone Mountain Technologies Inc. (SMTI), with technical support from the Gas Technology Institute (GTI) and several manufacturers of water heating products. One fourth generation GHPWH prototype, identical in design and construction to the five prototypes deployed in the field demonstration under Task 2, went through testing at the Southern California Gas Company's (SCG) Engineering Analysis Center (EAC). The plan includes performance testing and accelerated durability testing. Testing was led by SCG EAC staff, with support from GTI and SMTI, and was built on prior laboratory testing efforts on first through third generation prototypes at GTI (Figure 20). The detailed experimental test plan is provided in Appendix D.

Figure 20: Third Generation Gas Heat Pump Water Heating Testing at GTI in 2016

Source: GTI

Performance Testing

- Energy Efficiency performance testing via the Uniform Test Method for Measuring the Energy Consumption of Water Heaters protocol specified in the Code of Federal Regulations.[1]
- Emissions testing for criteria air pollutants, specifically CO2, CO, NOx and unburned hydrocarbons (UHC)[2] per South Coast Air Quality Management District (SCAQMD) methods. Southern California Gas Co. to determine methods for measuring emissions of interest not covered by SCAQMD.

Accelerated Durability Test

- Accelerated operating life tests operating as frequently as feasible using an automated test stand, extrapolated to equipment life based on average number of Southern California water heater cycles
- Spot checks to assess degradation of performance metrics and the effect of accelerated operation on emissions levels established during the performance testing, performed at 50 percent and 100 percent of the durability test schedule

Prior Prototype Gas Heat Pump Water Heater Laboratory Performance

Of some utility for this discussion of prior GHPWH performance, a discussion on the system itself may be useful. Key components are as follows for the fourth generation design:

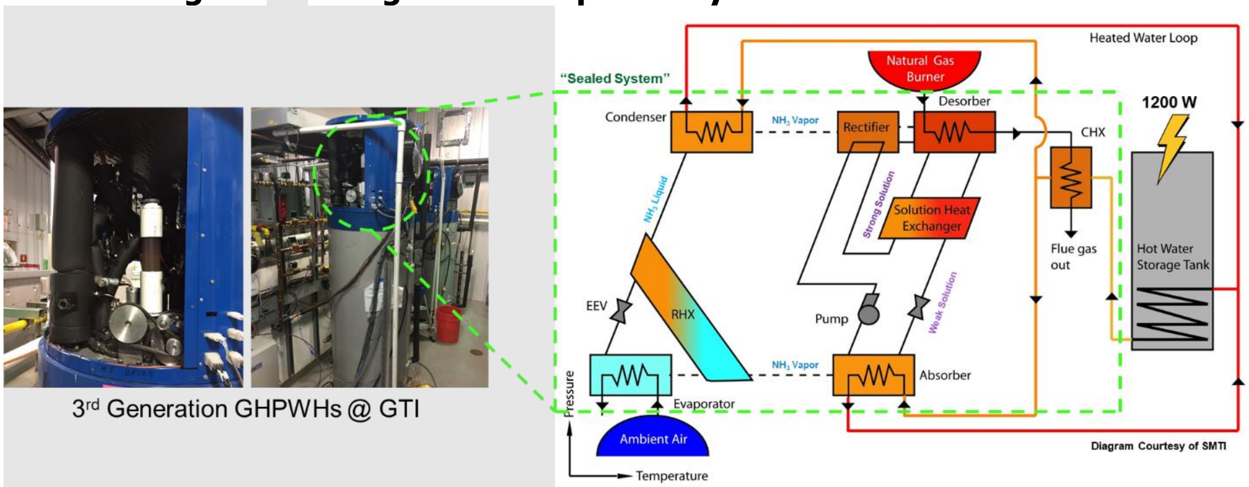
- "Sealed System", another name for the absorption cycle itself includes all components that come into contact with the refrigerant (NH3) and absorbent (H2O). As a typical vapor absorption cycle, the absorbent is not in a pure state, but rather cycled within the 'thermal compressor' as a weak or strong solution (low/high refrigerant concentration respectively). As shown in **Error! Reference source not found.**, the sealed system is comprised of nine primary components:
- At the absorber, low pressure vapor refrigerant is absorbed by weak solution, creating high-concentration strong solution and yielding heat of absorption which is recovered by a hydronic loop.
- The strong solution is pressurized by a solution pump, a single-speed pump lifting the pressure.
- Heat is recovered by the strong solution in the solution heat exchanger (SHX), recovered from weak solution.
- Pressurized strong solution is delivered to the desorber which, using a fire-tube design, heat of combustion boils off high-pressure vapor refrigerant. Exiting weak solution is

[1] DOE Uniform Test Method for Measuring the Energy Consumption of Water Heaters test protocol, 10 CFR Ch. II, Pt. 430, Subpt. B, App. E.

[2] Emissions testing will be carried out per South Coast Air Quality Management District Test Method 1121/1146.2 and 100.1 Procedure for Continuous Gaseous Emission Stack Sampling. Testing will check for compliance with SCAQMD Rule 1121 (low NOx). Unburned hydrocarbons will be measured and evaluated per discretion of SCG.

cooled at the SHX and pressure is reduced by a fixed restriction en route back to the absorber.

Figure 21: Diagram of Simplified Cycle with Annotations



Source: GTI

- Vapor refrigerant exiting the desorber is further purified by the rectifier, with trace absorbent removed, in part through cooling by strong solution.
- Leaving the 'thermal compressor', high-pressure vapor refrigerant is directed to the condenser, which like the absorber is cooled by a hydronic loop.
- Moving from the high to low-side pressure, heat is recovered from the liquid refrigerant via the refrigerant heat exchanger (RHX), before pressure is reduced by the electronic expansion valve (EEV).
- Liquid refrigerant changes phase within the air-cooled evaporator, with heat recovered to the low-pressure vapor refrigerant through the RHX.
- While housed in the same location as the "sealed system", the warm flue gases (250°F-350°F) exit the desorber and pass through a separate condensing heat exchanger (CHX) acting in effect as an economizer. The return of the main hydronic loop from the storage tank is preheated by the CHX prior to splitting towards the condenser and absorber. Note that prior generations of GHPWH units had a separate, immersed condensing heat exchanger within the storage tank, directly yielding heat to the tank instead of the intermediary hydronic loop.
- Connecting the heat output of the absorption heat pump and the CHX to the storage tank is a closed, pumped hydronic loop, which exchanges heat with the storage tank with an immersed hydronic heat exchanger (HHX). Rough estimates of heat absorbed by this hydronic loop from prior GTI studies are: 55 percent of heat output from the absorber (in effect, heat recovery), 35 percent from the condenser (the 'heat pump' effect), and 10 percent from the CHX [Glanville, 2016].
- For extreme hot water demands, a supplemental heating element within the tank provides boost heating simultaneous with heat pump operation, for these GHPWH units

this element is sized to fit with common 15 A/120 VAC service and not intended to operate as backup (for example independent of heat pump portion).

- Additional features of the GHPWH are common to many existing water heating products, including the tank itself, plumbing connections, and other hardware.

Summary of Prior Laboratory Testing

First and Second Generation Development & Testing

First generation prototypes, shown in Figure 22, were developed and tested under a Department of Energy contract DE-EE0003985, which included GTI testing per the original "Energy Factor" (EF) procedure (pre-NAECA III changes). This prior test procedure was defined by a 64 gallons per day draw pattern with six equal, hourly draws, followed by an extended standby period. During this initial "beta" prototype testing program, the project team demonstrated analytically that a 1.30 EF was technically feasible and GTI demonstrated that this initial prototype could demonstrate a 1.10 EF with a) a reduction in electricity demand by 1/3 from that measured – resulting in 0.7-0.8 kWh/day and b) an improvement in storage tank insulation to reach a heat loss factor (UA) of 3.0 Btu/hr-°F with NO_x emissions of approximately 10-15 ppm @ 3 percent O_2 adjusted [Garrabrant, 2013].

Figure 22: Early Gas Heat Pump Water Heater Prototypes in GTI Lab and Field Testing

Source: GTI

In this study, GTI outlined the design criteria this prototype would need to meet to achieve a 1.30 EF, as adapted from the project final report[3].

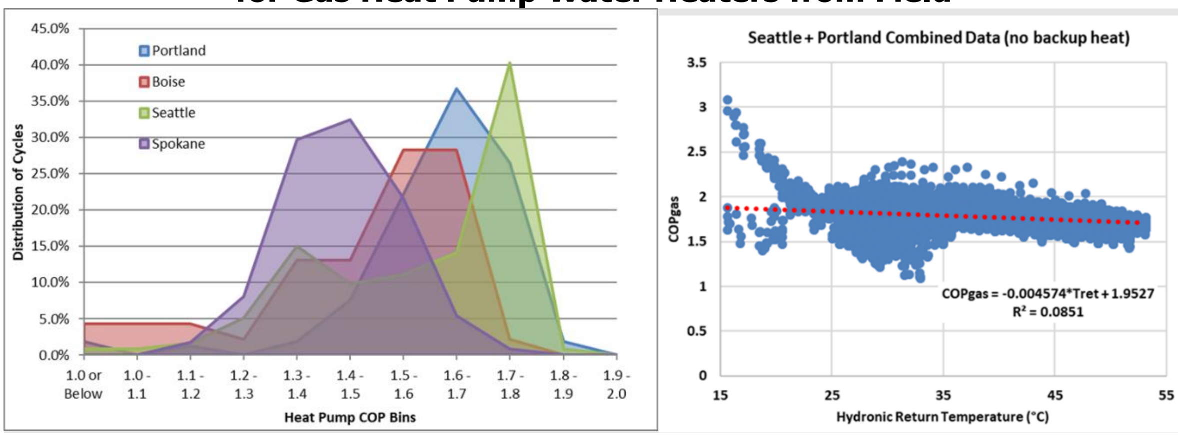
Third Generation Demonstration and Testing

Following early controlled demonstrations of GHPWH prototypes (second generation) and an expanded field demonstration in the Pacific Northwest (third generation) [Glanville, 2016], GTI performed extended laboratory testing of these same third generation prototypes. Field data suggested that the four prototype GHPWH units installed in Washington, Oregon, and Idaho had heat pump cycle and system COP_{Gas} values (**Error! Reference source not found.**), in addition to delivered temperature and combustion efficiency, consistent with the 1.30 EF goals in Table 13. Regarding combustion efficiency, the exiting flue gas temperatures measured were regularly well below the 90°F target, often only 10°F-15°F above the incoming water

[3] https://www.osti.gov/servlets/purl/1060285

mains temperature. However standby loss factors and power use were high. For the four units, the standby heat loss coefficients were estimated at 9.3-11.0 Btu/hr-°F and power consumption was on average 44 gallons delivered/kWh consumed as opposed to the ~90 gallons delivered/kWh consumed target, neglecting supplemental heating element usage.

Figure 23: Third Generation Performance Bins and Curves for Gas Heat Pump Water Heaters from Field



Source: Glanville, 2016

Table 13: Early Prototype Testing – Performance Goals for 1.30 Energy Factor vs. Actual Performance

Performance Criteria Necessary to Achieve 1.30 EF	Measured Performance
Average heat pump cycle $COP_{Gas} \geq 1.65$	Up to 1.61 observed
Average system COP ≥ 1.50	Up to 1.45 observed over typical range of hydronic return temperatures
Average combustion efficiency ≥ 95% ($T_{flue\ gas} \leq$ 90 °F)	Average $T_{flue\ gas}$ was as low as 95°F (alpha) and 110°F (beta)
Average delivered hot water temperature at or above starting average tank temperature	A 4°F difference was observed with beta testing
Standby loss coefficient of 2.5 Btu/hr-°F or less	Estimated effective UA was greater than 5.0 Btu/hr-°F
Power use must < 120 W (active) and < 10 W (standby)	Unknown due to use of industrial PLCs (programmable logic controllers)

Source: GTI

Following the development and field demonstration of these six third generation GHPWH units, GTI partnered with SMTI to perform a focused laboratory testing program of these units in support of developing the fourth generation design [Glanville, 2016]. This included focused efforts concerning the assessment and re-design of key components (EEV, solution pump, RHX/SHX), investigation of combustion system issues that arose during demos, exploring design and control scheme alternatives to address DHW capacity challenges using a calibrated model, and an experimental assessment of component and system reliability. During this program, the findings relevant to EF and the newly applicable “Uniform Energy Factor” (UEF) were:

- Focused and extended standby loss testing, with improvements to avoid conduction losses such as heat traps) and adverse thermosiphons in the internal hydronic loop, result in a UA factor of 4.5 Btu/hr-°F, a significant improvement over field-derived values of twice or greater. Further improvements in tank insulation during production, difficult during prototyping, could readily achieve the target of less than 2.5.
- Concerning the sealed system, significant improvements were made to component hardware and cycle controls. Most notably was that the EEV used to date, an off-the-shelf control valve, was replaced with a custom design to greatly improve system reliability and net heat pump COP by up to 15 percent overall. This revised EEV design was fed forward into all fourth generation GHPWH units, including those in this current study.
- A major implication of the new test procedure, outlined in some detail below, is the triggering of two or more shorter on-cycles as compared to the single on-cycle with the previous test procedure ("EF" test), which has the net effect of a warmer storage tank during the heat pump operation. As noted in prior studies, the efficiency and capacity of the absorption cycle is a much stronger function of storage tank temperature (e.g. hydronic loop) than ambient temperature (such as evaporator), with the efficacy of and heat recovery from the 'thermal compressor' strongly impacted by temperatures [Garrabrant, 2014]. On-cycles with colder storage tank temperatures, leading to reduced hydronic return temperatures, will have larger fraction of GHPWH output at higher efficiency (Figure 24). Thus, while the steady-state COP_{Gas} was improved with 3rd generation designs, the impact of operating more often with warmer tank temperatures per the new test procedure had the effect of negating these gains.

Figure 24: Third Generation Gas Heat Pump Water Heaters During GTI Program

- Simulated use testing (SUT) per the current, revised method of test[4] resulting in the new UEF metric was performed on a modified third generation GHPWH unit using the "Mid" and "High" usage patterns, 55 gal/day and 84 gal/day respectively. While actual First Hour Ratings were measured between 61-64 gallons/hour, short of the 75

[4] DOE Uniform Test Method for Measuring the Energy Consumption of Water Heaters test protocol, 10 CFR Ch. II, Pt. 430, Subpt. B, App. E.

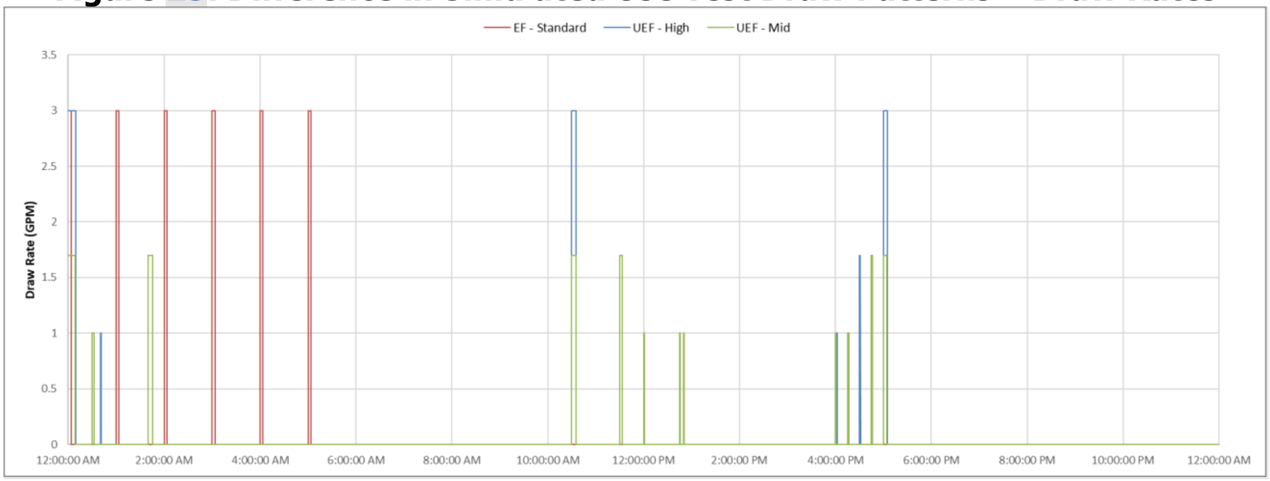
gallons/hour criterion for the "High" use pattern, nonetheless both usage patterns were used. Key findings from these tests were:

- Standby Heat Loss UA factors, as defined by the "UEF" test procedure, were calculated as 7.2 and 10.2 Btu/hr-°F for the "High" and "Mid" tests respectively, closer to field-derived values but well above the extended standby loss factor of 4.5 for the same GHPWH.
- Delivered Temperatures were improved over prior generation testing, average delivered temperatures over the test sequence were 124.3°F and 125.1°F, quite close to the 125°F setpoint for this test.
- Power Consumption was slightly improved from field testing, with 73 and 58 gallons delivered per kWh consumed for the "High" and "Mid" tests respectively, closer to the target of 90 gallons delivered/kWh consumed.
- Recovery Efficiency (ηr) is a term calculated in the test procedure which is intended to represent the water heater efficiency during the first recovery, as close as the procedure gets to a steady state-type efficiency (for example, COPGas or thermal efficiency). This term is used throughout the UEF calculation, when numerous adjustments are made regarding input and output conditions. As defined, this is approximately equal to the "System COP" discussed earlier, but reflects the specific test sequence from which is it derived. The aforementioned "alpha" and "beta" prototype testing of first and second generation GHPWHs yielded 120 percent < ηr < 135 percent, which was below the 150 percent target to meet the 1.30 EF target but sufficient to meet a 1.20 EF target.

While the definition of recovery efficiency is largely unchanged from the prior to the current method of test, a combination of delivered efficiency of hot water combined with an adjustment for change in stored energy during the first recovery period, the new draw patterns introduce challenges with for heat pump water heaters with large storage volumes. The primary challenge is that, for water heaters with slower recovery rates, extended recovery periods initiated later have the effect of increasing the impact of standby losses on the recovery efficiency. Generally a recovery is triggered by the first draw cluster, such that the water heater is primarily heating during the defined recovery period. For the original "EF" test, the six sequential draws would trigger a recovery after 2-3 draws typically and the recovery complete following the final draw, and while this drew out the recovery period to beyond the "5:00" mark, the water heater was recovering for a majority of the recovery period (as defined by the calculation) [Glanville, 2015]. Viewing the comparison of hot water draw patterns in the figures below, one critique of the new MOT is that the initial draw cluster may be insufficient to trigger a recovery in some HPWHs.

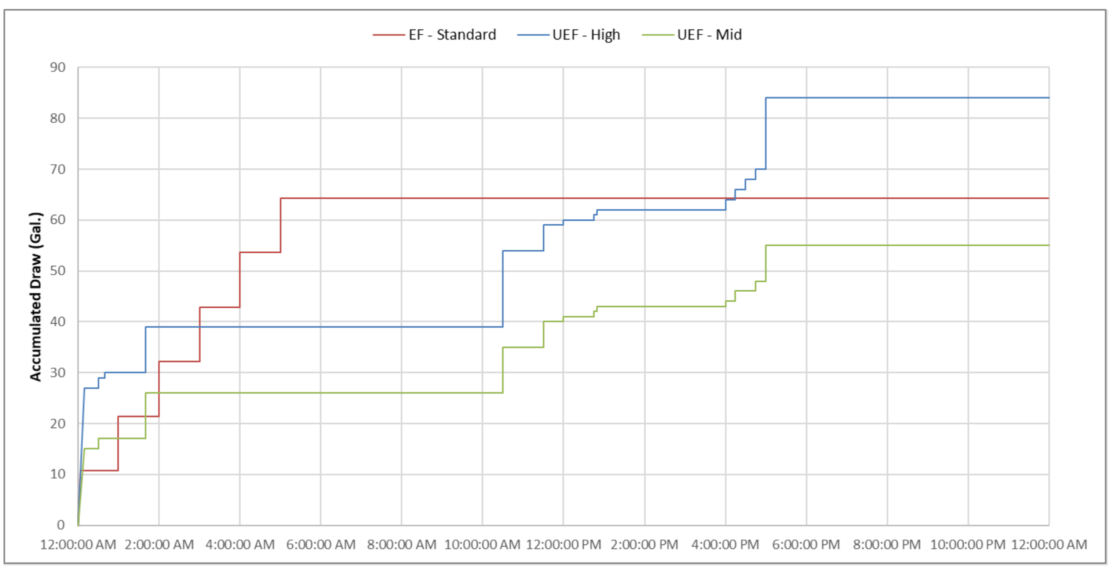
During the "High" usage test for the third generation GHPWH, the first recovery was triggered during the second draw (within the first cluster) running from 12:31 am to 3:08 am (test time), resulting in a 123 percent recovery efficiency. During the "Mid" usage test, the recovery was triggered during the standby period between draw clusters, running from 4:43 am to 6:31 am (test time), which had the impact of including 6.5 hours of standby losses instead of 3 hours. The draw patterns from these tests are shown in Figure 25, and the accumulated water volume in Figure 26. Based on the calculated heat loss rate for the respective tests, recovery period standby losses as a proportion of recovery period energy input are 6 percent for the "High" ηr but 28 percent for the "Mid" ηr. As a result, the calculated "Mid" ηr was significantly reduced, to 108 percent.

Figure 25: Difference in Simulated Use Test Draw Patterns – Draw Rates



Source: GTI

Figure 26: Difference in Simulated Use Test Draw Patterns Accumulated Domestic Hot Water Volume



Source: GTI

- Uniform Energy Factor (UEF) of 1.10 ("High") and 1.0 ("Mid") was the overall result when power consumption was adjusted to meet the design target of 110 W active / 5 W standby. Despite the improvements in heat pump COPGas and similar standby heat loss values to 1st and 2nd generation GHPWHs, the shift in test procedure had the net effect of keeping efficiency metrics static. Per performance targets in Table 13, which translate to the new MOT effectively, the focus of 4th generation performance should remain 1) continuing improvement in recovery efficiency with heat pump COPGas, further approaching steady-state performance, 2) reducing standby heat loss, 3) approaching low power consumption targets.

Prototype Gas Heat Pump Water Heater Laboratory Performance – Fourth Generation

Pre-shipment Testing of Fourth Generation Gas Heat Pump Water Heater Units

As noted previously, key differences between prior generations of GHPWH units and those built and installed as part of this project are:

- The absorption heat pump component is integrated with a smaller tank, built on a nominal 65-gallon storage versus an 80-gallon storage tank platform with prior generations. This has the primary impact of firmly placing this GHPWH into the "Mid" usage category, with a 55 gallon/day draw pattern per the prior discussion. For this size platform, due to the aforementioned challenges with test procedure, the performance goal was shifted to a 1.20 UEF, where larger GHPWHs (such as 80-gallon versions) may more readily achieve the previously described 1.30 UEF goal.
- With product advantages in mind, the CHX was shifted from a separate immersed heat exchanger within the storage tank (in addition to the HHX), to integrated with the hydronic loop on the return-side. Advantages include permitting the flue outlet at the top of the tank versus the bottom, adding installation flexibility and hydraulic head for condensate disposal, and reducing GHPWH cost and complexity overall. For performance, this has the negative impact of raising the hydronic return temperature to the condenser/absorber by ~1°F, decreasing the capacity and efficiency of the heat pump module overall, and slightly reducing the combustion efficiency as well.

Figure 27 shows a GHPWH unit prepped for shipment. During pre-shipment testing of the GHPWH units, the manufacturer issued a test report in regards to projected UEF and general performance. For the modified 1.20 UEF target, per the 55 gallons/day test procedure, the performance targets outlined in Table 13 are only modified concerning the system COP_{Gas} target, which must be ≥ 1.45, time-averaged over the test. Targets concerning combustion efficiency, power consumption, standby losses, and delivered temperatures remain the same and just as achievable. During pre-shipment testing, the manufacturer noted the following:

- System COP: The pre-shipment testing showed that during the "UEF" test procedure, time-averaged system COPGas was ~10 percent below the modified target and about 6 percent below the third generation GHPWH performance for the same test procedure. Brought on in part by design changes noted above, the manufacturer noted that the issues lie not with the absorption heat pump hardware, but its integration with the storage tank, specifically the HHX. Small modifications to the HHX geometry would take greater advantage of colder, lower tank temperatures and thus, improve system COPGas with reduced hydronic return temperatures. To some extent, the HHX in these GHPWH units were optimized for the older "EF" test procedure and it has been redesigned informed by findings from this task.
- Standby Heat Loss: Extended standby testing of packaged GHPWHs showed UA values remaining between 5.0 – 10.0 Btu/hr-°F, possibly due to anomalies with the application of tank insulation. As such, no improvement over third generation GHPWHs, but known techniques in production can reach the performance targets.

Figure 27: Gas Heat Pump Water Heater Prepped for Shipment

Source: GTI

- Power Consumption: While improvements were not anticipated until pre-production builds, so not a significant improvement with these fourth generation GHPWHs, with moving from programmable logic-type controllers to standard printed circuit boards and improving pump, blower, and fan motor performance, the manufacturer has reached the performance target in subsequent testing.
- Estimated Uniform Energy Factor: With the net impact of these issues, the manufacturer estimated an as-measured UEF of 0.95 to 1.0. Additionally, the manufacturer outlined in detail how a production GHPWH unit could readily meet the 1.20 UEF goal through standard improvements in 1) storage tank insulation, 2) low-power components, and 3) minor changes to the immersed HHX.

On the topic of emissions, the GHPWH units were necessarily certified as *Ultra-low* NO_x, per the South Coast Air Quality Management District's (SCAQMD) Rule 1121, as noted in the Task 2 section. As performed by an independent certifying laboratory, a fourth generation GHPWH unit was certified with an emission rate of less than 10 ng NO_x/J.

Laboratory Assessment of Fourth Generation Gas Heat Pump Water Heater Unit

This section contains independent laboratory test results from SCG.

In parallel to the GHPWH unit installations at five Los Angeles-area residential test sites, under Task 2, an additional GHPWH unit was shipped to the SCG *Engineering Analysis Center* (EAC) to perform an assessment per the previously described experimental test plan (Figure 28). Overall, the test program had above-average operational issues, in excess of what was observed during the field demonstration task. While the test plan was not completed in its entirely, the EAC team admirably completed several tests while facing the following operational challenges laid out in Table 14.

Figure 28: Gas Heat Pump Water Heater Unit at Southern California Gas Engineering Analysis Center

Undergoing standard testing (left) and emissions sampling (right).

Source: GTI

Table 14: Operational Issues with Gas Heat Pump Water Heater Equipment During Engineering Analysis Center Test Program

Time	Equipment Issue	Resolution
May, 2018	Cracked HHX within tank causes leak, due to vibration damages during shipment*	A replacement storage tank was installed by the manufacturer, retaining the heat pump portion
July, 2018	Emergency water pumps in laboratory cause pressure spike within GHPWH tank, causing damage and leak	A 2^{nd} replacement tank was shipped, however replacement tank was damaged in shipment, a 3^{rd} replacement tank was shipped and installed by EAC staff in Oct. 2018
November, 2018	Operational issue with GHPWH solution pump required pump replacement*	Replacement pump was installed by manufacturer on-site, however issues identified during commissioning required further refurbishing, final replacement installed in Jan. 2019 by EAC staff

***Issue also experienced by one or more field units (Task 2 section)**

Source: GTI

Test Methodology

Except as previously outlined in the test plan, the following considerations for these tests performed at the EAC apply, as communicated by the EAC:

- The First-Hour Rating (FHR) and Uniform Energy Factor (UEF) were determined using test procedures detailed in the Department of Energy's Uniform Test Method for Measuring the Energy Consumption of Water Heaters, 10 CFR Ch. II, Pt. 430, Subpt. B, App. E (2015). Coefficient of Performance (COP) was also calculated[5].
- Emissions testing was performed using SCAQMD Method 100.1 Procedure for Continuous Gaseous Emission Stack Sampling and SCAQMD Rule 1121 Compliance Testing for Natural Gas-Fired Water Heaters and Small Boilers. Rule 1121 specifies maximum allowable NOx limits. Method 100.1 requires a Continuous Emissions Monitoring System (CEMS), which was not available during the test period, so a Testo 350 portable gas analyzer was used instead.
- Durability was evaluated using accelerated life cycle testing. A ten-year GHPWH lifetime was assumed, meaning that 5,800 cycles are needed to achieve 100 percent GHPWH life. The procedure for durability testing was planned as:
  - Set the GHPWH temperature setpoint to 125°F.
  - When the GHPWH has fully recovered, begin drawing water at a constant 3.0 gal/min.
  - Stop drawing water when the GHPWH initiates a recovery cycle.
  - Repeat steps 2–3.

Control points and monitored values are as shown in the Tables 15 and 16.

Table 15: Engineering Analysis Center Controlled Points During Testing

Parameter	Value
Water Supply Pressure	45 ± 2 psig
Natural Gas Supply Pressure	7 ± 2 inches of water column
Water Heater Temperature Set Point	125°F: UEF Testing 125°F: First-Hour Rating and Accelerated Life Testing
Water Heater Outlet Flow Rate	1.0, 1.7 gpm: UEF Testing 3.0 gpm: First-Hour Rating and Accelerated Life Testing
Ambient Temperature	68 ± 2°F

Source: GTI

[5] Using the same method as applied during the Task 2 field assessment.

Table 16: Engineering Analysis Center Parameters Monitored

Parameter	Monitoring Instrument
Tank Temperature (6 locations)	Resistance Temperature Detector (RTD)
Inlet Water Temperature	Resistance Temperature Detector (RTD)
Outlet Water Temperature	Resistance Temperature Detector (RTD)
Ambient Temperature	Type T Thermocouple
Natural Gas Temperature	Type T Thermocouple
Inlet Water Pressure	Pressure Transducer
Natural Gas Supply Pressure	Pressure Transducer
Barometric Pressure	Pressure Transducer
Relative Humidity	Humidity and Temperature Transmitter
Natural Gas Usage	Gas Meter w/Pulser
Power Consumption	Watt-Hour Transducer
Water Flow Rate/Consumption	Water Flow Meter w/Transmitter
Products of Combustion	Portable Gas Analyzer

Source: GTI

Summary of Test Results

With a *First Hour Rating* test performed, the GHPWH unit had a measured capacity of 55.1 gallons per hour, from the nominal 62.2-gallon storage volume. Using the 55 gallons per day draw pattern, per the simulated use test was performed with several repetitions, before and after the solution pump replacement. The recovery efficiencies reported were below those reported by the manufacturer during pre-shipment testing, 18 percent below pre-shipment testing and 26 percent below that necessary for the 1.20 UEF target. Concerning standby losses, the calculated UA factors were similar to those from pre-shipment testing, between 5.0 and 10.0 Btu/hr-°F, and similarly concerning power measurement, the daily power draw was comparable to prior third generation testing, 51 versus 58 gallons delivered per kWh consumed. In total, resulting estimated UEFs were 4 percent-6 percent lower than the expected manufacturer performance, based on pre-shipment testing of the prototypes, attributable to issues with the average system COP_{Gas} recorded as between 1.20 to 1.30 for hydronic supply temperatures ranging from 108°F-122°F. The system COP_{Gas} for the field demonstration units, as shown in the Task 2 report, range from 1.20 to 1.80 for the same ambient condition, showing a significant variation in heat pump performance between prototypes built. It is likely that, like the GHPWH unit at Site #4, variations in prototype assembly could be attributed to the lower than expected heat pump performance. This will be explored further in a subsequent evaluation of this specific heat pump. Due to the aforementioned equipment issues, the durability testing was not complete, with only 213 cycles recorded. The project team noted the operational issues with this specific GHPWH unit and determined that a task extension to accommodate further extended life testing was not warranted.

In other testing, regarding emissions sampling the EAC performed eight tests to the SCAQMD Rule 1121 standard, with seven of eight in compliance with the Ultra-low NO_x limit. The EAC expanded the flue to accommodate a laminar flow section, to even out observed fluctuations (Figure 29). Additionally, the team used a modified probe, with multiple sample points along its length to capture a more representative sample. Tests with the off-the-shelf versus custom probes are noted as such, shown in the figure below. Table 17 highlights the overall emissions testing results, with only test #7 slightly above the require emission rate.

Figure 29: Testo Portable Gas Analyzer and Custom Integrated 4" Sampling Probe

Source: GTI

Table 17: NO_x Emission Test Results for Gas Heat Pump Water Heater

Probe Type	Test #	Flue Temperature (F)	O2 (%)	CO2 (%)	NOx (ppm raw)	NOx (ppm @ 3% O2)	NOX (ng/J)
Testo Probe	1	136.1	4.5	8.9	18.4	20.0	9.6
Testo Probe	2	136.3	5.0	8.5	14.7	16.6	7.5
Testo Probe	3	136.1	4.8	8.5	15.6	17.3	8.8
Testo Probe	4	135.4	5.1	Analyzer Problem	13.3	15.0	N/A
New Probe	5	136.0	4.6	8.5	17.8	19.5	9.3
New Probe	6	136.3	4.8	8.5	15.6	17.4	7.8
New Probe	7	135.9	4.4	8.8	18.8	20.4	10.1
New Probe	8	136.2	4.7	8.5	17.0	18.7	9.5

Source: GTI

Fourth Generation Test Conclusion

As noted, the fourth generation GHPWH units unfortunately did not see improvements in the three key areas from the fourth generation GHPWH units described in detail, that is: recovery efficiency, standby heat losses, and power consumption, which was confirmed in pre-shipment manufacturer testing and third party testing at the SCG EAC. While other GHPWH design features remained in line for the 1.20 UEF performance target (60 gallon) and 1.30 UEF performance target (80 gallon), specifically delivered temperature, combustion efficiency, emissions, and heat pump COP_{Gas} (as observed with field GHPWH units). On emissions Ultra-low NO_x emissions were verified in independent testing and certification and on durability testing, operational issues prevented the EAC from carrying out this longer-term test program. With future GHPWH production units, the three key areas identified to meet these UEF targets were identified as improvements in 1) storage tank insulation, 2) low-power components, and 3) minor changes to the immersed HHX, all readily achievable per manufacturer guidance.

CHAPTER 5: Assessment of Market Barriers

The goal of this task was to survey and quantify market barriers to broad GHPWH adoption in the Los Angeles Basin and beyond, once commercialized. Barriers considered include real and perceived obstacles to consumer adoption and contractor recommendation (home performance contractors, HVAC, and plumbing contractors included). To assess these barriers, a market research plan was developed using a two-step approach: an initial qualitative step, comprising in-depth interviews and focus groups and a second quantitative step, comprising a larger-scale online survey. Applied Research-West, ARW, led the design and implementation of this two-step approach.

Qualitative Assessment Approach and Results

ARW conducted face-to-face, in-depth interviews (IDIs) with 27 plumbing, HVAC, and/or home energy improvement contractors lasting 90 minutes each. Each interviewee was identified and invited to participate due to their role as a decision-maker or key influencer regarding equipment offered by the contracting business (such as owners or at minimum department managers). In addition to IDIs with contractors, ARW performed focus groups with both contractors and homeowners. ARW conducted four professionally-moderated, face-to-face focus groups in California, with some regional variety, lasting approximately 2 hours each and engaging 8 to 12 participants per group. Beyond these California focus groups, ARW conducted a further 4 focus groups with a national focus (Northeast, Mid-west, and Northwest) using an internet-video meeting methodology. These online video groups served both as a validity check to the face-to-face groups as well as provided an opportunity to expose any regional (and outside of California) patterns in the data. Key objectives of this task were to:

- Gather information from industry experts
- Determine key issues facing business owners within the water heater space
- Determine competitive advantages of the new technology among both industry experts and consumers
- Ascertain what opportunities might be available and strategies to employ to expand sales of the new technology
- Conduct research to provide results and insights from qualitative research with industry experts and consumers which will then guide the research design of the quantitative phase of the study

The combined results of the in-depth interviews and focus groups are summarized in Table 18 and Table 19.

Table 18: Gas Heat Pump Water Heater Primary and Secondary Market Strengths

Primary Strengths	Secondary Strengths
• Low cost of ownership over lifetime • Affordable maintenance cost • Brand recognition and comfort • 10-year warranty • Comparable replacement cost if there is an existing power vent water heater on-site	• Mid-range price perceived as somewhere between current tank technology and tankless • Environmental friendliness/green, especially in communities with customers with high levels of education • If available, rebates would accelerate sales

Source: GTI

Table 19: Gas Heat Pump Water Heater Market Opportunities and Deterrents

Opportunities	Deterrents
• Installation price of tankless is much higher than most customers expect, thus curtailing sales and providing an opening for a mid-priced, higher efficiency product • Leading with long-term cost savings of a GHPWH overcomes some of the barrier of the upfront cost increases.	• Physical size is perceived as "big" unlike tankless which is perceived as "space saving" and "aesthetically pleasing" • Tankless units have dominated some markets with the perception of "endless hot water", appealing to customers. • Recharge time perceived less favorably than tankless

Source: GTI

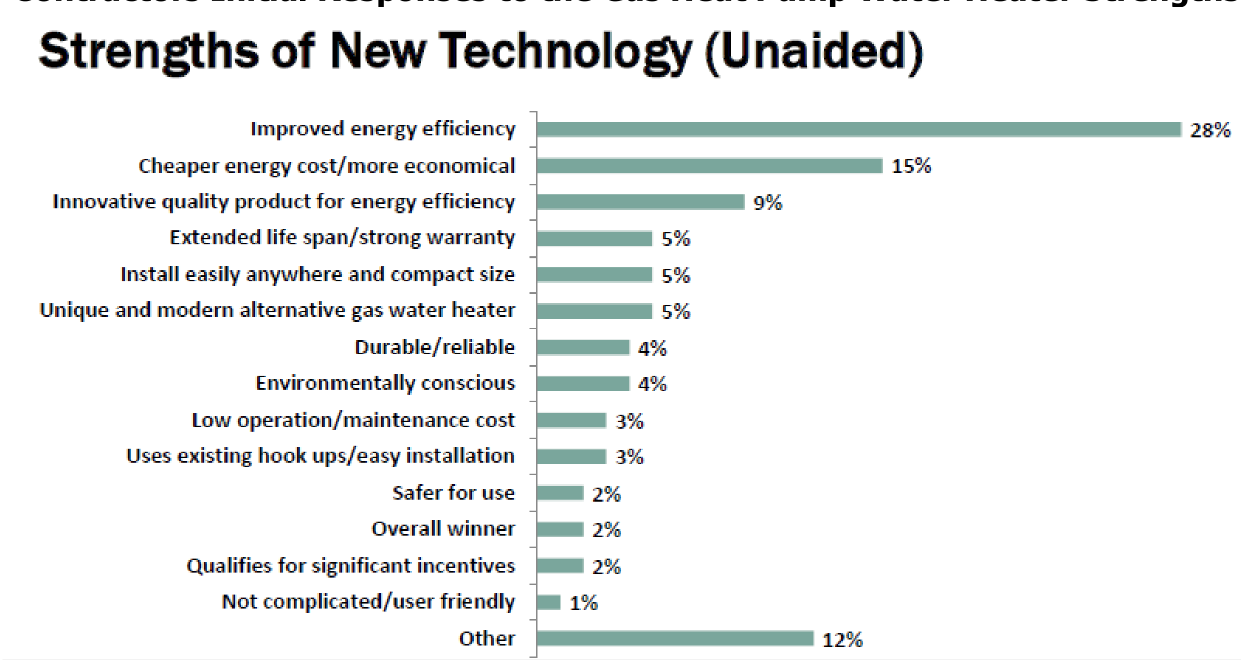
Quantitative Assessment Approach and Results

The results and insights gained from the qualitative research phase served as the foundation for the survey design of the quantitative phase, which included the development, launch, and analysis of results from two national surveys – one for home contractors and one for homeowners. More than 370 contractors were surveyed nationally with special consideration paid to businesses found in California, the Pacific Northwest, Northeast, and upper Midwest. The survey was structured as a series of questions to measure, in conjoint style, various forced-choice product features. The survey also focused on demographics and purchasing/stocking decision behaviors. A similar approach as used for the design of the national homeowner survey, for which there were 1,131 respondents. To qualify for the homeowner survey, respondents must have:

- Bought a domestic hot water heater within the last two years.
- Live in a home where domestic hot water is heated with natural gas or propane.
- Own their single-family home and be directly involved in the choice of installation contractor and/or the water heating equipment itself.
- Not installed their last water heater themselves.

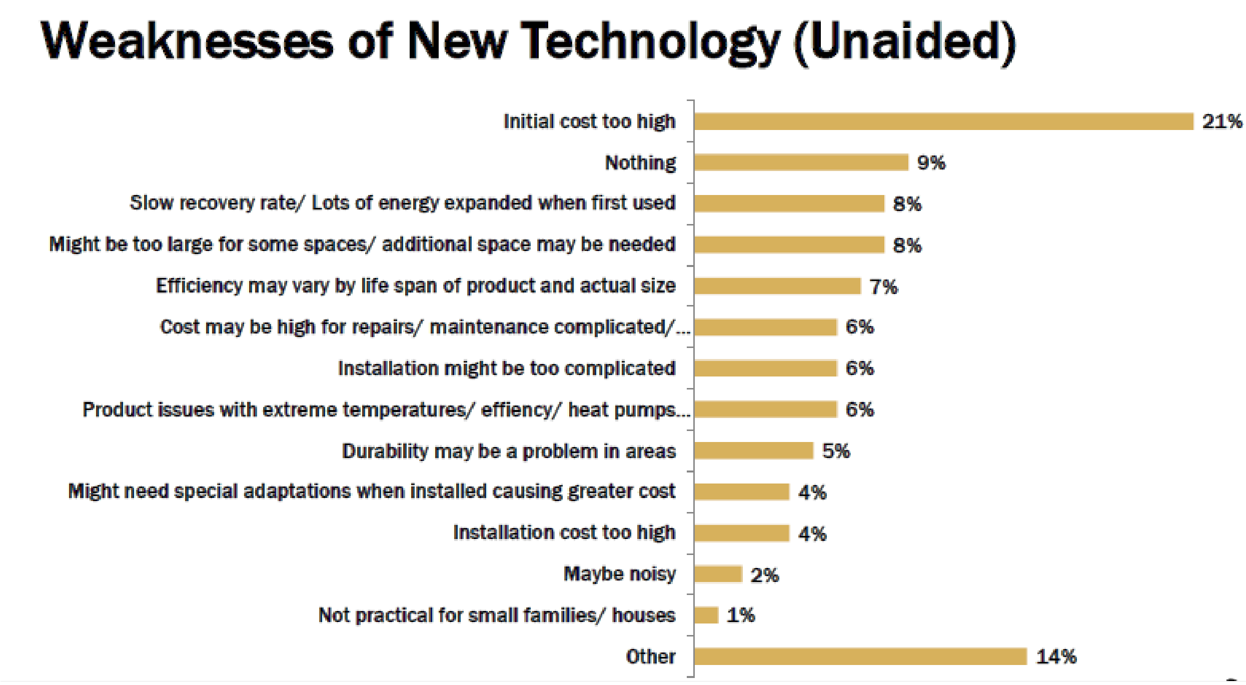
Based on the data gathered through these surveys, the majority of contractors thought they were very likely to sell this new product (57 percent), while an additional 37 percent would be somewhat likely to sell to some customers. Overall, surveyed contractors estimated they could sell an average of 55 GHPWHs per year, with a "worse case" being identified as 33 units/year. The implication is that plumbing and HVAC contractors think that in a mature market GHPWHs could account for one-fifth to one-third of their annual water heater sales. Most contractors thought there were no physical limitations (weight, size, capacity) for selling the product and that the initial cost would be the primary obstacle for consumer acceptance, not the recovery time or other impacts on end user comfort. Summaries of contractor responses to the GHPWH ("New Technology") are shown Figures 30 and 31.

Figure 30: National Survey of Plumbing/Heating/Ventilation/Air-Conditioning Contractors Initial Responses to the Gas Heat Pump Water Heater Strengths



Source: GTI

Figure 31: National Survey of Plumbing/ Heating/Ventilation/Air-Conditioning Contractors Initial Responses to the Gas Heat Pump Water Heater Weaknesses



Source: GTI

Based on the data collected from the national survey for homeowners, the GHPWH was perceived to be a better concept than the standard tank and tankless systems in regard to efficiency and cost savings. The GHPWH acceptance followed a typical pricing pattern scenario. It was more often the chosen product against standard tank technology until the cost of the GHPWH was approximately $1,000 more than the standard tank. While the tankless technology was usually perceived to be too expensive, it retained a limited and loyal audience. Operating cost also appeared to be a key driver for those choosing the GHPWH. The trigger to purchase a GHPWH on operating cost savings, versus the standard tank, is saving $100 per year or more. When asked to rank order the most important attributes of the GHPWH, consumers cited the low lifetime cost as the most important (45 percent), followed by low annual cost (43 percent), and in third position were the environmental benefits (67 percent).

Consumers fell into five categories regarding their likelihood to select a GHPWH:

- Very likely (31 percent)
- Can be persuaded (12 percent)
- On the fence (14 percent)
- Not likely to buy/unlikely (11 percent)
- Very unlikely (31 percent)

Those that were identified as "very likely" to buy a GHPWH were more inclined to:

- Be between the ages of 46-64 (50 percent)
- Be married (81 percent)
- Be employed (82 percent)

- Have 3+ people in the household
- Have a 13-23 year-old living in the household (26 percent)
- Have at least a 4-year college degree (62 percent)
- Have a household income of $75,000+/year
- Live in the suburbs (62 percent)
- Intend to stay in the current home 10+ years (52 percent)

Consumers that fell into the "can be persuaded" category had similar attributes as those in the "very likely" to buy category, with the exception that they tended to have smaller households and lower household incomes. In contrast, those that fell into the "unlikely" and "very unlikely" to buy categories tended to:

- Be either under 45 or over 65.
- Have a 7- to 12-year old in the household.
- Less education.
- More likely to be retired.
- Living in the city/urban setting.
- Plan to stay in their home less than 10 years.

This group also expressed more skepticism about the GHPWH itself, with more than 42 percent questioning the technology with the majority of those questions concerning cost and payback (27 percent). This suggests there is an opportunity to potentially reach this group through focused educational outreach. Introducing the technology, offering examples of experiences and savings from other real-life consumers, and having the support of a well-informed plumbing contractor may go a long way with this group. Regarding this group's sensitivity to costs/payback, a mechanism such as an energy efficiency rebate to help offset some of the upfront cost may help alleviate this barrier.

Individual feedback was also solicited from the five homeowners and the plumbing installer participating in the project based on their own experiences. The results of that feedback can be read in detail in the Complete Gas Heat Pump Water Heater Field Monitoring Results section of Appendix C.

CHAPTER 6: Technology/Knowledge/Market Transfer Activities

Educational Outreach Events

Effective knowledge transfer is critical to the ability for research to build on previous work. As such, as part of this project it was intended that the project team would pursue opportunities to educate prospective GHPWH consumers, installation contractors, and other affected stakeholders. In February 2020, GTI presented a detailed overview of this project at the 2020 ASHRAE Winter Conference as well as a companion conference paper. This was an excellent outreach event with strong attendance and participation, featured in an industry journal[6]. It was also originally intended that the project team would work closely with partner SCG to host an in-person public GHPWH workshop at their Engineering Analysis Center. Unfortunately, due to the emergence of the COVID-19 global pandemic, hosting an in-person event was not possible in the first half of 2020. The project team transitioned this to an online event and hosted it on December 10, 2020. A moderated session focusing exclusively on residential gas heat pumps was held at the 2020 ACEEE Hot Water Forum. GTI presented the findings of this project in detail alongside other residential gas heat pump research and facilitated group discussions on this topic amongst key stakeholders. The Hot Water Forum was postponed and held virtually on July 29, 2020 in light of shelter-in-place restrictions. Additionally, the manufacturing partner discussed the market research task findings in a comprehensive webinar for utilities. The project team is also developing GHPWH educational and training materials targeted for installation contractors and a GHPWH Technology Snapshot that is targeted at prospective consumers. The Final Project Fact Sheet will be available for online distribution through the California Energy Commission's Energize Innovation and other websites.

Simulation Model Development and Title 24 Analysis

As reviewed in the Task 2 and Task 3 sections, the project team has developed numerous performance datasets in laboratory and field-based assessments of prototype gas-fired heat pump water heater (GHPWH) units over their development history. With a potential for a ~50 percent reduction in natural gas consumption and accompanying greenhouse gas (GHG) emissions seen in prior demonstrations[7], stakeholders have expressed interest in extrapolating from these findings to applications with other use characteristics, climate zones, and installation types. This has prompted GTI to extrapolate findings through development of detailed and simplified model representations GHPWH, including:

[6] https://www.cibsejournal.com/technical/bridging-the-gap-gas-fired-absorption-heat-pumps/

[7] Glanville, P., Vadnal, H., and Garrabrant, M., (2016) Field testing of a prototype residential gas-fired heat pump water heater, Proceedings of the 2016 ASHRAE Winter Conference, Orlando, FL.

- During the development of the fourth generation GHPWH design, GTI developed and calibrated a proprietary GHPWH model to investigate design changes based on a given daily draw pattern [Glanville, 2016].
- More recently GTI developed an approach to model the third generation GHPWH to investigate its impact on residential HVAC through false loading heating and supplementing cooling equipment, through modifications to the *EnergyPlus* building energy simulation tool, performing a parametric study in the Pacific Northwest [Glanville, 2020].
- GTI has added the prototype GHPWH product category to its *Energy Planning and Analysis Tool*, as an option for comparing to other residential energy technologies, based on performance curves derived from previously noted studies (http://epat.gastechnology.org)

With the tools useful in product development or analytical studies, an updated and user-friendly model is needed for this emerging GHPWH product category. With a focus on the unique requirements of California Building Efficiency Standards (Title 24)[8], Frontier Energy provided unique expertise to meet this goal in partnership with Beyond Efficiency, each organization with demonstrated experience developing water heating technology models. While the work in this section is speculative, performed in advance of a commercially available product, it is expected to be useful once GHPWH products enter the California market.

California Gas Heat Pump Water Heater Performance Model

The goal of developing a simulation model was defined to 1) an easy to use tool that could provide a high level comparison of energy use, operating costs, and carbon emissions (for project managers and planners to use), and 2) a more detailed model that would provide detailed and flexible tools to engineers, designers, and researchers provide assessments of the energy impacts of the technology. Both tools relied on a python script for modeling the GHPWH's performance on a user-defined time step (5 minutes or shorter is recommended). A key distinction between the two models is that the simple model provides an annual summary of performance, while the detailed model provides output in EXCEL compatible .csv format on the user-specified time step interval. More details on the python model development and algorithms can be found in the companion User's Guide that was developed.

To complement the estimates of GHPWH performance, the simple model combines the annual summary results with results from the 2019 Title 24 compliance software (California Building Energy Compliance Calculator for Residential Buildings, or CBECC-Res). The water heating algorithms in CBECC-Res allow for modeling a range of water heating system types in all 16 California climate zones, as well as for a range of water heating load magnitudes. The water heating load magnitudes depend on the number of bedrooms in the dwelling and are based on combining monitored real home daily draw profiles to create an annual draw profile. Details on the modeling capabilities and basic algorithms can be found in the California Energy Commission's *2019 Residential Alternative Calculation Method (ACM) Reference Manual*.

The level of detail of the current CBECC-Res water heating methodology varies as the algorithms has evolved over many decades beginning with the earliest Title 24 water heating methodology which was developed in the early 1990's. More recent water heating algorithms,

[8] Title 24 of the California Building Standard Code, Parts 6 and 11.

specifically the electric heat pump water heater (HPWH) model (which was added to the 2016 CBECC-Res compliance software), relies on a very detailed product-specific algorithm that represents the details of how HPWH control settings impact use of the heat pump or resistance elements depending upon the timing, duration, and flow rate of hot water draw events. Other CBECC-Res algorithms, such as the gas tankless water heater model, are simplistic and rely on empirical adjustment factors to determine energy use in response to hot water loads. As technologies hit the market or new data becomes available better characterizing performance, algorithms are updated as deemed appropriate by the Energy Commission and its compliance software consulting team. Limited resources play a role in determining CBECC development goals.

With the advent of the detailed 2016 HPWH model, more accurate and detailed hot water load profiles were needed to drive the model. Without accurate and realistic modeling of hot water load profiles, the nuances associated with different HPWH control strategies could not be properly modeled. The DHW hot water load modeling was reverse engineered for this project to allow integration of the exact same subhourly hot water loads and cold water inlet water temperatures into the GHPWH model as is used by CBECC-Res.

The conventional system types modeled in the simple tool include conventional center flue gas storage water heaters (historically, the predominant California residential DHW system type), condensing gas storage water heaters, gas tankless water heaters, electric resistance storage water heaters, electric HPWHs, and the emerging Sanden electric CO_2 HPWH. Table 20 summarizes the nominal efficiency of each water heater type simulated in CBECC-Res.

Table 20: Summary of Water Heater Types Simulated in 2019 California Building Energy Compliance Calculator for Residential Buildings

System Type	Description
Electric Storage Water Heater	50 gal, 0.92 UEF
Electric HPWH #1	AO Smith FPTU66120, 66 gal, 3.35 UEF
Electric HPWH #2	Rheem PROPH50T2RH350D, 50 gal, 3.55 UEF
Electric HPWH #3	Sanden CO2 HPWH, 43 gal, 3.09 UEF
Electric HPWH #4	Generic Federal Minimum 2.0 UEF
Gas Storage Water Heater	50 gal, 0.62 UEF
Gas Tankless Water Heater #1	Non-condensing, 0.81 UEF
Gas Tankless Water Heater #2	Condensing, 0.92 UEF
Condensing Gas Storage Water Heater	50 gal, 0.83 UEF

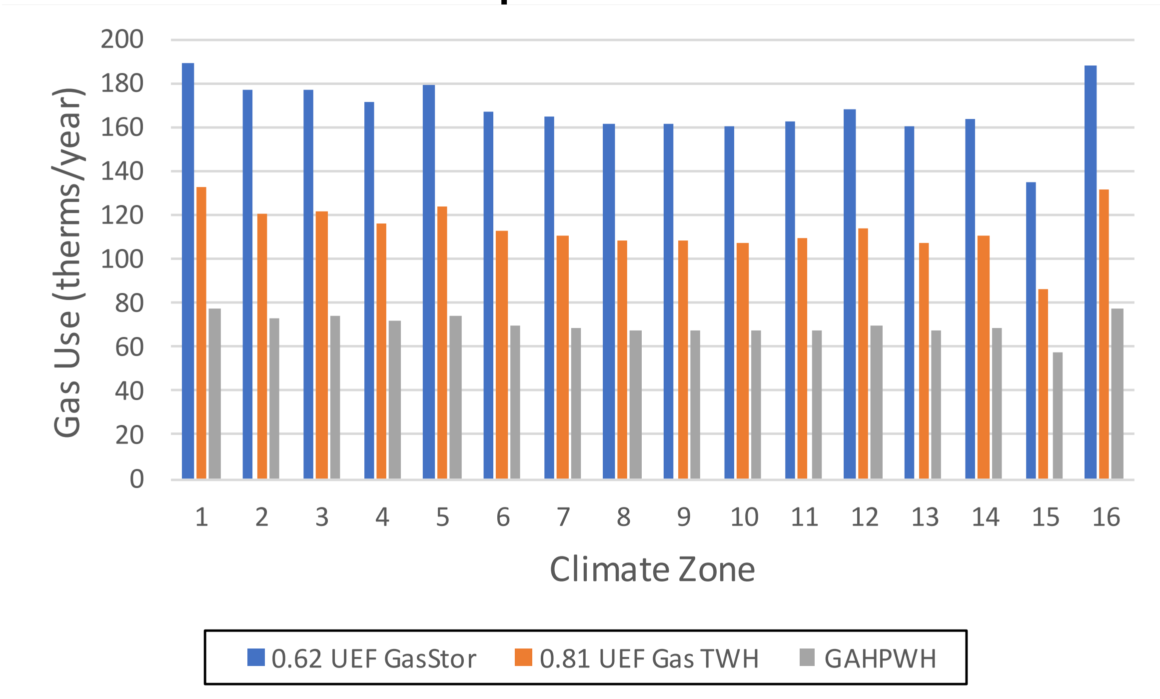
Source: GTI

Several graphs are included here to provide a selected snapshot of the results. Results are shown for all 16 climate zones for the mid-level hot water load case (3-bedroom assumption).

Figure 32 plots annual projected gas consumption for a 0.62 UEF gas storage water heater, a 0.81 UEF gas tankless water heater, and the GHPWH. Gas storage water heater usage is around 200 therms per year in most climate zones, except the hot desert climate zone 15 where water heating loads are reduced due to higher cold water inlet temperatures. Gas tankless shows significant reductions in usage, with annual consumption generally in the 110-130 therm range. The GHPWH is projected to further reduce consumption with annual usage generally in the 70-80 therm range. Note that the latter two gas water heaters also have electric consumption, which is not reflected in this plot.

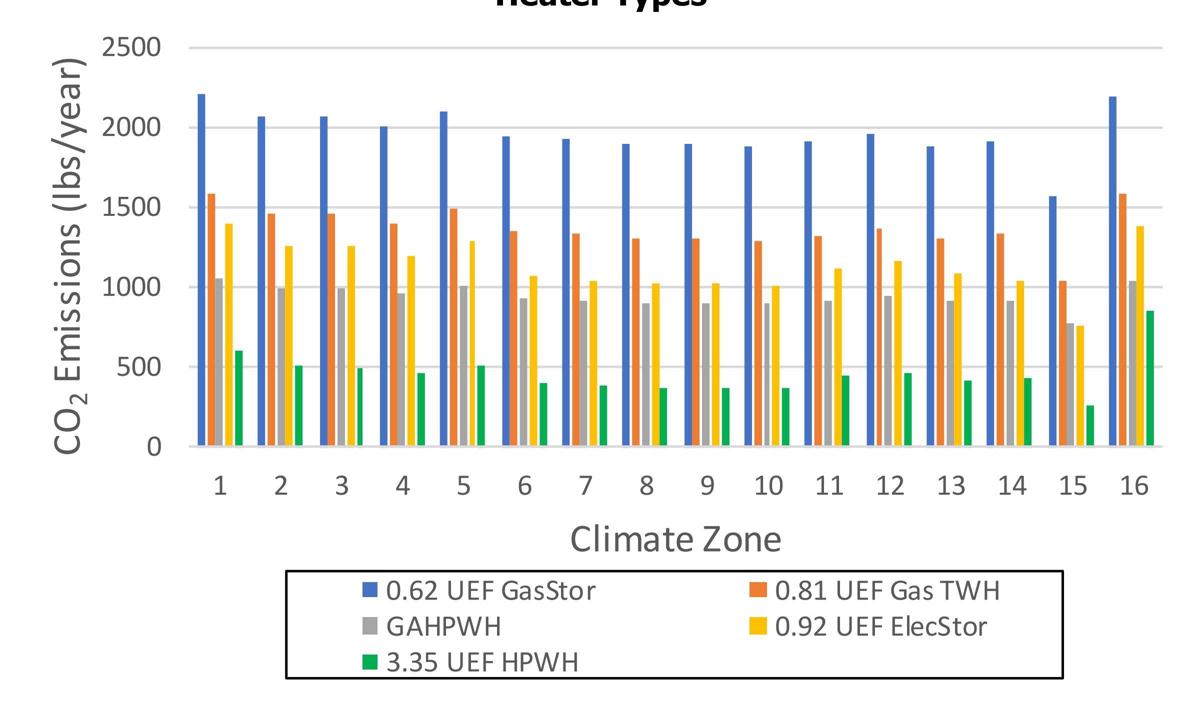
Figure 33 plots annual CO_2 emission estimates (for the 3-bedroom load case) for gas water heaters shown, as well as two electric water heater types (a conventional electric storage water heater, and a conventional HPWH). Using the 2022 Title 24 CO_2 values results in a strong emissions benefit for all the electric water heater types. The 0.62 UEF gas storage water heater is projected to average about 2,000 lbs per year of emissions, with variations due to gas usage. The gas tankless and GHPWH show significant reductions with the GHPWH averaging around 950 lbs per year (a 52 percent reduction). The electric storage water heater is slightly higher than the GHPWH at an average of 1,130 lbs. The conventional HPWH, which is more than twice as efficient as the electric storage water heater is projected to average about 460 lbs (slightly over half of the GHPWH). It is important to note that these comparisons are specific to the California generation environment where significant renewables content is present.

Figure 32: Annual Gas Use for Standard Gas Storage, Gas Tankless, and Gas Heat Pump Water Heater



Source: GTI

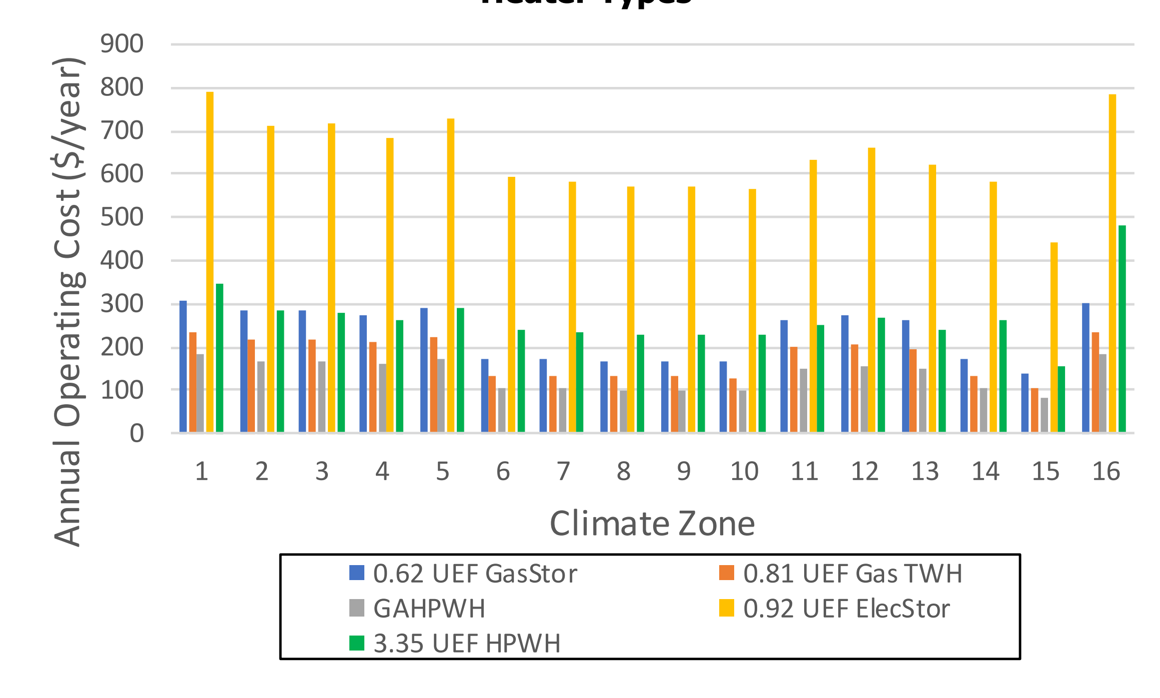
Figure 33: Annual Estimated CO2 Emissions for Sample Gas and Electric Water Heater Types



Source: GTI

Figure 34 depicts annual estimated operating costs (for the 3-bedroom load case) for the water heater types shown using the rates assumptions previously identified.[9] This graph reflects the relative high costs of electricity relative to gas in California. The GHPWH projection shows the lowest average operating cost in all climate zones at around $140 per year. The gas tankless water heater costs are about 30 percent higher, averaging around $180. The 0.62 UEF gas storage water heater is projected to have average costs around $230 a year, or about 15 percent less than the statewide average cost for the HPWH. There is a fairly significant shift in the cost comparisons of these two water heater types between Northern and Southern California, due to the differences in utility rates. The other significant outlier is the cold CZ16 where the low ambient temperatures result in higher HPWH energy use and costs. The electric storage water heater costs are by far the highest, at more than $600 per year in most zones.

Figure 34: Annual Estimated Operating Costs for Sample Gas and Electric Water Heater Types



Source: GTI

A sample cost effectiveness calculation is included here based on the operating cost assumptions shown in Figure 35 and estimated installed cost data provided by the GTI project manager. Two cost effectiveness comparisons are made relative to conventional residential equipment options (0.62 gas storage water heater and 0.92 UEF electric storage water heater). Several assumptions are made in this simple payback analysis:

- No differences in maintenance cost among system types is assumed.
- The existing retrofit site is assumed to have available electric and gas service at the water heater location (specifically no additional cost for modifying existing service is included).

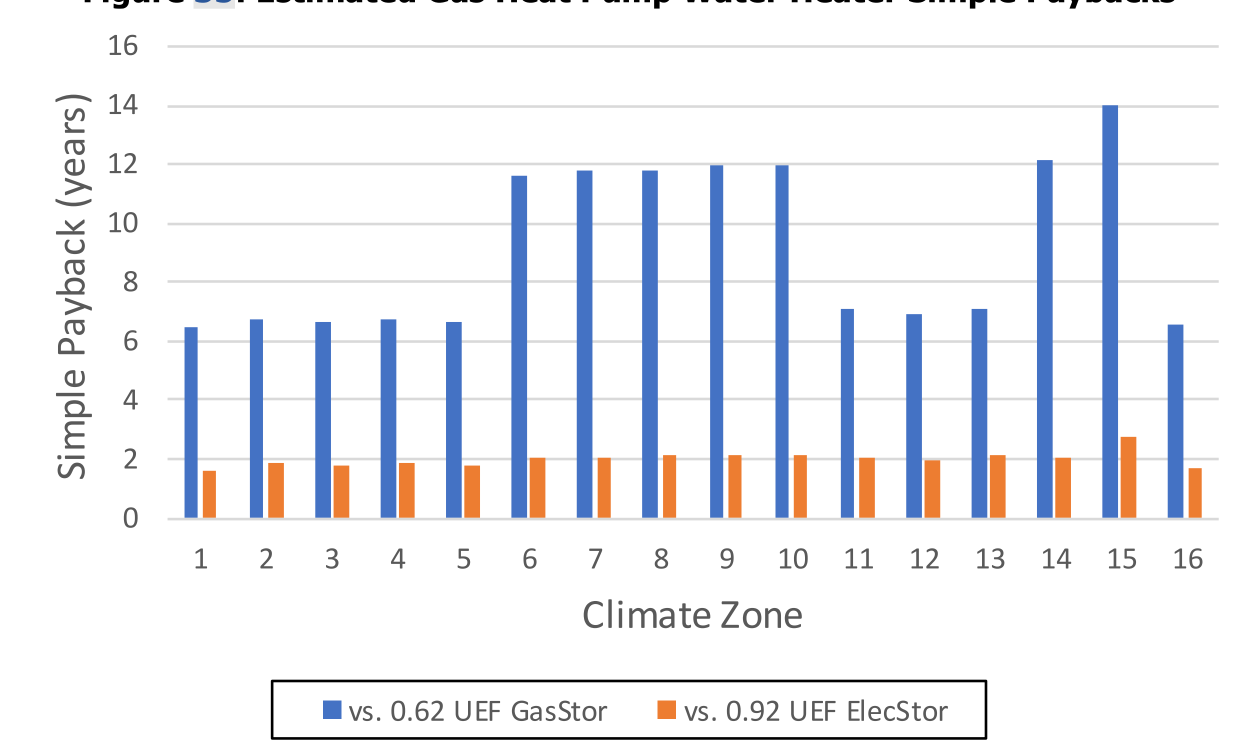
[9] Costs represent fuel costs only. No maintenance costs were factored into this analysis.

- Water heater lifetimes are equal for all system types.
- No incentives are reflected in this analysis.

GTI estimated installed costs for a commercially available GHPWH at $1600 with a conventional gas storage water heater estimated at $800. Frontier estimated installed costs for an electric storage water heater at $600. These are based on projections at high volumes and not on contractor estimates from prior tasks.

With these cost assumptions, a simple payback could be calculated based on the incremental cost and the estimated savings by climate zone. **Error! Reference source not found.** plots the projected simple payback period in years compared to the mainstream gas and electric storage water heater options. Relative to the gas storage water heater option, simple paybacks range from about six years to up to 14 years. Higher paybacks are projected for the Southern California climate zones where assumed natural gas prices are considerably lower than for Norther California climate zones. Relative to the electric storage water heater option, simple paybacks are roughly in the 2-year range.

Figure 35: Estimated Gas Heat Pump Water Heater Simple Paybacks



Source: GTI

Options for Future Inclusion in Title 24 Compliance Software

Title 24 code development operates on a three-year cycle. The 2019 Title 24 code was recently adopted on January 1, 2020 and the 2022 code is currently in the midst of development by the Statewide Codes and Standards Team[10] in conjunction with the Energy Commission. The Statewide Team supports the Energy Commission with technical

[10] Sponsored by most California investor owned utilities and some municipal utilities

development of individual measures which ranges from prescriptive and mandatory measures, to compliance options, and compliance software enhancements. As the code development process unfolds, efficiency or load shifting measures are identified and ranked for potential inclusion in the next standards development cycle. This list is reviewed by the Statewide Team and the Energy Commission, and a determination is made to identify which measures are carried forward for more detailed evaluation, performance characterization, and cost effectiveness determination. This last step is only for measures that are being proposed as mandatory or prescriptive requirements. Measures that are compliance options, such as would be likely for the initial introduction of the GHPWH to the market, would not require this cost effectiveness step.

To further explore the potential of future recognition of the GHPWH technology within Title 24, the project team held a call a member of the CBECC-Res software development team who is focused on hot water modeling. Given the fact that the HPWH simulation model currently in CBECC-Res uses Ecotope's HPWHsim algorithm, it is in the best interest of the team to include Ecotope in future mode implementation efforts as their experience with both HPWHsim and CBECC integration make them the ideal consultant for performing this work.

Further details on model documentation and validation are included in Appendix E.

Papers and Presentations

GTI has developed and delivered multiple presentations regarding this project, in addition to a conference paper.

- Presentations:
    - 2019 ACEEE Hot Water Forum, Nashville, TN, March 11-13.
    - 2019 GTI Emerging Technology Program Collaborative spring meeting, Los Angeles, CA, April 24-25. Members from over two dozen utilities in attendance.
    - 2019 GTI Emerging Technology Program Collaborative fall meeting, Chicago, IL, November 6-7.
    - 2020 ASHRAE Winter Conference, Orlando, FL, February 1-5.
    - 2020 North American Gas Heat Pump Collaborative, online meeting hosted by Resource Innovations, April 14.
    - 2020 GTI Emerging Technology Program Collaborative spring meeting, online meeting hosted by GTI, April 21-22.
    - 2020 ACEEE Hot Water Forum, Atlanta, GA, July 20-21 (originally slated for late March 2020, but postponed due to COVID-19 restrictions).
- Papers
    - Abstract submitted to the Energy & Environmental Building Alliance (EEBA) for consideration as a presentation paper at the High-Performance Home Summit in October 2018.
    - ASHRAE 2019 Winter Conference Paper.

In addition to these efforts, there have been several other limited opportunities to provide updates on the project through brief slide presentations and casual conversations. GTI and the project team have striven to share technical and market knowledge with as wide a group as possible.

CHAPTER 7: Conclusions and Recommendations

The project was successful in meeting all the contractual goals and objectives identified at the start of this effort. The goals and objectives were closely intertwined and included:

1. Demonstrate five "fourth generation" GHPWHs in single-family homes, using datasets to estimate annual energy, operating cost, and emissions savings.
2. Quantify GHPWH energy efficiency, emissions, and reliability through performance and extended life laboratory testing.
3. As a new product category, prepare stakeholders and code officials with information sharing, model development, and analysis.
4. Assess and evaluate market barriers to entry for the GHPWH in California.
5. Obtain valuable feedback from end users, installation contractors, and other stakeholders prior to GHPWH commercial introduction.

The GHPWHs showed significant promise, albeit with variable savings owing to equipment variation and occupant/behavioral dynamics, with average energy savings of 54 percent across the five sites and CO_2 emissions reductions of 49 percent. Key accomplishments in this effort include: the monitoring of first and second baseline conditions at five single family homes in the Los Angeles Basin; receiving Ultra-low NOx certification for the prototype; the construction, installation, and commissioning of five GHPWH units at test sites; shipment and installation of a GHPWH unit in a SCG Laboratory for testing of key performance areas and emissions; and the operation more than a year at the host sites generating more than 20,870 gallons of hot water over nearly 5,000 operating hours, with a median time-averaged cycle efficiency of COP_{gas} ranging from 1.25 to 1.60 across all sites. Surveys found that 80 percent of the participants said they never ran out of hot water and 20 percent said they sometimes have run out of hot water.

Model simulations indicated the relative savings the unit can offer against other gas water heating and electric HPWH options, indicating this new technology class could have unique leverage to impact the chronically low-efficiency water heating market in California. An assessment of the market opportunities and barriers further validated this with both contractors and homeowners citing higher energy efficiency and low lifetime operating costs as compelling features. The greatest challenges to the new GHPWH technology were the higher equipment costs as compared to minimum efficiency gas storage water heaters and some of the technical issues surrounding the current stage of product development, such as the solution pump and heat exchanger designs.

Looking ahead, the project team outlined several future research needs in advance of broad GHPWH production, adoption, and rollout, including:

- Improve Reliability of GHPWH Units:
  - As found in this study, design changes were necessary to avoid damage of the units during shipment, which were made swiftly by the manufacturing partners

over the course of the project. With "drop testing" and other vibration testing assured during production, this should be addressed.
  - Large variation in performance between sites was partially explained by site variations and differences in usage, but also found to be due in part to variance in prototyping quality. Design changes implemented from findings in this study have improved reliability, however better onboard diagnostics will improve discovering future needs.
- Rigorous Installation Requirements:
  - Despite the limited sample size in this study revealed potential site challenges regarding venting (proper sloping, issues with long runs), electrical service, and challenges with space requirements for the demonstration equipment during recruitment. Additional consideration towards installation requirements and best practices are needed in this regard, in addition to cementing the technician commissioning procedure, tuning combustion and judging successful absorption cycle operation (appropriate charge), though these are artifacts of the prototype designs and will be phased out during production.
- DHW Capacity Concerns:
  - Further product development attention is needed to appropriately address supplemental heating, predictive/learning controls, and customer interaction – to prevent loss of hot water. In addition to learning from recent advances in electric HPWH controls, it would be beneficial for GHPWHs to detect minor changes in gas input to identify impact on DHW capacity.

CHAPTER 8: Benefits to Ratepayers

The commercialization and adoption of a high efficiency gas absorption heat pump water heater in California would provide several notable benefits to ratepayers. The following is an explicit outline of assumptions, supporting data, and methods used to calculate the estimated annual energy, cost, and emissions savings of an individual GHPWH in a California ratepayer's home.

GHPWH Prototype Performance

- Operating Efficiency (projected, 60 gallon format): 1.20 UEF.
- Baseline Efficiency: 0.49, minimum efficiency gas storage water heater, representing 95 percent of residential gas water heaters in California (Seto 2013).
- Energy Savings of GHPWH vs. Baseline: 54 percent, average of direct measurements at the field sites.
- GHG Savings of GHPWH vs. Baseline: 54 percent, directly proportional to reduction in natural gas consumption.

GHPWH Benefits Calculation

- (84 gallons of hot water per day per DOE 2014) * (498 Btu/gallon[11]) * (365 days/year) = 15.3 MMBtu hot water used per year
- [(15.3 MMBtu output) / (0.49 baseline) – (15.3 MMBtu output) / (1.30 UEF GHPWH)] / (1 MMBtu input/10 therms input) = 195 therms saved per year
- (195 therms saved) * (11.7 lbs CO_2e/therm saved) = 2,276 lbs CO_2e/therm saved per year
- Using $1.00/therm and with a 3 percent price escalation rate, the savings are $2,235 over a 10-year period.

Considering this individual savings estimate and scaling it up to the cumulative impact of widespread market adoption across California IOU service territories is exploring in the following calculations.

California IOU-wide Energy and Emissions from Residential Water Heating

- Total natural gas consumed: 1,744 million therms in 2015 (California Energy Commission 2016).
- Total GHG: 9.26 MMTCO2e (California Energy Commission 2016).
- GHG emissions from Aliso Canyon natural gas leak: 2.4 MMTCO2e (CARB 2016).

[11] Assumes specific heat = 1 Btu/lb*°F; density = 8.3 lb/gal; 60°F temperature rise

California IOU-wide Energy Savings Calculation

Based on the current distribution of gas water heating product types and their respective efficiencies (non-condensing gas storage (0.62 UEF), tankless (0.82 UEF), and condensing storage (0.78 UEF)), as representing 95 percent, 4 percent, and 1 percent of the California residential gas water heating market respectively, the weighted average efficiency of California gas water heating is 0.6296 UEF. For the 1,744 million therms consumed in 2015, and using assumed UEFs, the non-condensing gas storage water heaters represent 95 percent of units installed in the state and consume 96.4 percent of total therms for residential water heating (due to lower efficiency), or 1,683 million therms consumed in 2015.

The calculations in Table 21 assume 54 percent therms savings from GHPWH, 11.7 lbs CO2e/therm saved, $1.00/therm, and a reduction in NOx from 10 ng/J output (baseline) to 6.8 ng/J output (GHPWH), the emissions rate from the highest case laboratory run as part of SCAQMD certification in 2018.

Table 21: Estimated California Investor-Owned Utility-wide Energy, Cost and Emissions Savings from Gas Heat Pump Water Heater Market Adoption

GHPWH Market Penetration	Annual Therm Savings (Therms/yr)	Annual Operating Cost Savings ($/yr)	Annual GHG Reduction ($MMTCO_2e$/yr)	Annual NO_x Reduction (lbs/yr)
10%	90,882,000	$90,882,000	0.482	81,869
50%	454,410,000	$454,410,000	2.412	409,343
100%	908,820,000	$908,820,000	4.824	818,686

Source: GTI

California IOU-wide Emissions Savings Calculation

- 1,744 million therms * 54 percent savings (assuming 100 percent GHPWH deployment) * 11.7 lbs CO2e/therm saved) * (MMTCO2e/2,204 lbs CO2e) = 5.0 MMTCO2e saved annually by GHPWHs
- 2.4 MMTCO2e from Aliso Canyon leak / 5.0 MMTCO2e saved per year by GHPWHs = just under 6 months of GHPWH GHG savings quals the Aliso Canyon natural gas leak GHG impact.

LIST OF ACRONYMS

Term	Definition
AFUE	Annual fuel utilization efficiency
CARB	California Air Resources Board
CBECC-Res	California Building Energy Compliance Calculator for Residential Buildings
CHX	Condensing heat exchanger
CO2	Carbon dioxide
CO2e	Carbon dioxide equivalent
EAC	Engineering Analysis Center
EEV	Electronic expansion valve
FD&D	Fault detection and diagnosis
GAHPWH	Gas absorption heat pump water heater
GHG	Greenhouse gases
GHPWH	Gas heat pump water heater
HPWH	Heat pump water heater
HVAC	Heating, ventilation, and air-conditioning
kWh	Kilowatt-hour
MMT	Million metric ton
M&V	Measurement and verification
NEEA	Northwest Energy Efficiency Alliance
NOx	Nitrogen oxides
SCAQMD	South Coast Air Quality Management District
SCG	Southern California Gas
SMTI	Stone Mountain Technologies, Inc.
UEF	Uniform Energy Factor
UPS	Uninterrupted power supply

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APPENDICES

The following appendices are available under separate cover (Publication Number CEC-500-2020-XX-APA-F) by contacting Jackson Thach at Jackson.Thach@energy.ca.gov.

Appendix A: Field Test Execution and Monitoring Plan

Appendix B: Complete Baseline Field Monitoring Results

Appendix C: Complete Gas Heat Pump Water Heater Field Monitoring Results

Appendix D: Experimental Test Plan

Appendix E: Simulation Model Development and Validation

Appendix F: Simulation Model User's Guide