Gas-Fired Heat Pump Water Heating & Combi System Pilot Phase 1

Project Number ET22SWG0008

GAS EMERGING TECHOLOGIES PROGRAM (GET)

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Acknowledgements

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Abbreviations and Acronyms

Name	Abbreviation
American Society of Heating, Refrigeration and Air-Conditioning Engineers	ASHRAE
Average Hourly Emissions	AHE
Avoided Cost Calculator	ACC
California Independent System Operator	CAISO
California Public Utilities Commission	CPUC
Database for Energy Efficient Resources	DEER
Domestic Hot Water	DHW
Electric Heat Pump Water Heater	EHPWH
Electric Power Research Institute	EPRI
Electronically Commutated Motor	ECM
Gas Absorption Heat Pump Water Heater	GAHP
Gas Emerging Technologies	GET
Global Warming Potential	GWP
Greenhouse Gas	GHG
GTI Energy	GTI
Heat Exchanger	HX
High Heating Value	HHV
Hot Water	HW
Hydrofluorocarbon	HFC
Measure Package	MP
Measurement & Verification Plan	M&V Plan
Non-Routine Event	NRE
Service Hot Water	SHW

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Executive Summary

The Gas Emerging Technologies (GET) Program initiated this phase 1 project to enable the launch of future phases of a Gas Absorption Heat Pump Water Heater (GAHP) Pilot. The Pilot consists of lab and field work in multiple phases. This Phase 1 project provided deliverables to assist in site selection and system design for the field work phases. It also included developing a generic Measurement & Verification (M&V) Plan and calculation methodologies for both energy and source CO_2 comparisons. The Generic M&V Plan and CO_2 Analysis will be used as a guiding document to create site-specific M&V plans during the upcoming field work phases.

Project goal: The goal of this project was to address aspects of two (2) barriers to GAHP installations—barrier #2 is lack of awareness of gas-fired heat pumps in general and barrier #4 is heat pump sizing—and determine measurements and calculation methodologies to calculate and compare baseline and post-installation energy use and source CO_2. Barriers/Questions addressed in this study include:

- What type of buildings and/or heating water loads are good candidates for GAHPs?
- How can heating water base load be estimated for sizing purposes?
- What is the appropriate number of GAHP units based on hot water load profile?

Technology description: The GAHP pilot focuses on the gas-absorption heat pump water heaters and combination systems. The gas absorption cycle is driven by gas combustion that either uses ammonia as the refrigerant and water as the absorbent or water as the refrigerant and a solution of lithium bromide (LiBr) as the absorbent. GAHP units extract heat from the ambient air through an evaporator and deliver heat to hot water through a condenser.

Key Project Findings:

The project includes the following deliverables to enable launch of the GAHP field pilot:

- Site Screening Tool
- Design & Installation Checklist
- Generic M&V Plan
- Generic CO_2 Analysis

Based upon the work done in this project, the following gaps were found relative to the initiation of the field study phases:

- GAHP run-time is dependent upon both peak domestic hot water (DHW)/service hot water (SHW) load and re-circulation heat loss load. The Site Screening Tool can only account for peak DHW/SHW load. More information is needed to refine the Site Screening Tool to account for recirculation loss load.
- There may be a need to screen potential GAHP sites for the future GAHP energy efficiency measure using actual existing DHW/SHW equipment capacities. There is usually not enough information available at a typical site to determine if the GAHP systems are a good fit using only the existing DHW/SHW capacities since these systems are often oversized.
- The most commonly used DHW sizing methodology is unknown. The Site Screening tool uses the ASHRAE method [1] but would need to be refined to use other methods if ASHRAE is not the most commonly used method in the field. The method of sizing determines what inputs need to be collected to be used in the Site Screening Tool.
- The Design & Installation Checklist is a living document and needs to be refined and updated as the field work phases progress.

<u>Project Recommendations:</u>

- Gather hourly gas-usage data to pre-qualify/screen sites for field work to ensure maximum utilization of GAHP operating capacity.
- Initiate a study to compare in-situ DHW/SHW capacities with site peak loads to determine typical oversize factors.
- Initiate a study to determine most commonly used DHW sizing methods in the field.
- Refine Design & Installation Checklist with additional information and learning during field work phases.

Introduction

Gas Absorption Heat Pump Water Heaters

Thermally activated heat pumps that operate on natural gas have the potential to notably reduce energy use and greenhouse gas (GHG) emissions across various climates for both the residential and commercial markets in the US while avoiding the inefficiencies related to the electrical generation and transmission systems.

The Gas Absorption Heat Pump (GAHP) is one such technology. The gas absorption cycle is driven by gas combustion that uses ammonia as the refrigerant and water as the absorbent or uses water as the refrigerant and a solution of Lithium Bromide (LiBr) as the absorbent. Like electric air-source heat pump water heater technology, GAHP units extract heat from the ambient air through an evaporator and deliver heat hot water through a condenser. The primary difference between the gas absorption cycle and the vapor compression cycle used by electric heat pumps is that instead of an electrically driven compressor, GAHPs use a burner with a generator and absorber/regenerator to thermally-drive the flow of refrigerant. These systems present several potential advantages over their electrical counterparts, which can be summarized as follows:

1) GAHPs can deliver hot water at a lower cost, depending on the local gas and electric utility rates.
2) The use of GAHPs instead of air-to-water electric heat pumps could also result in lower source emissions.
3) GAHPs typically use ammonia as the refrigerant, which has a global warming potential (GWP) of zero. By contrast, electric heat pumps commonly use hydrofluorocarbon (HFC) refrigerants with GWPs greater than 1,000.
4) The prospect of all-in electrified solutions could pose a severe challenge to the utility grid structure, particularly when it comes to providing for heating loads. The grid components must be built for peak and not average loads. Thus, in places where the grid is currently designed for peak summar loads, assuming there would be a shift to peak winter heating loads, especially in colder climates, would require a massive expansion of the infrastructure that is currently in place.

Background

Previous GET Study Findings

A previous GET study (ET22SWG0002) identified several high priority water heating technologies and barriers to adoption for commercialized units and pre-commercialized units alike. Technologies recommended for further research included:

1) Gas-absorption heat pump water heater & combination system (Commercial & Residential)
2) Gas-adsorption heat pump water heater (Residential)
3) Gas-fired thermal compression heat pump water heater & combination system (Commercial & Residential)

Identified barriers to technology adoption included:

1) Lack of awareness of Decarbonization potential– the push for electrification has meant that customers are generally not aware that gas fired absorption heat pump can reduce the carbon footprint and are also not aware of the size of the quantitative impact.
2) Lack of awareness of gas-fired heat pumps in general – Customers and contractors generally are unaware of gas-fired heat pump technologies. They are unaware of what is required to install this equipment, what is needed to maintain this equipment, and what buildings or loads are good candidates for this equipment.
3) Uncertainty About Technology – Once customers and contractors are made aware of the technology, both are generally uncertain about its operation, its maintenance requirements & servicing needs, and how it ties into existing building systems. There is a need for contractor training to address these things.
4) Heat pump sizing – All of these technologies work best when they satisfy the base load. There is a need to understand what data is required to establish the base load and how to establish the base load so the appropriate number of units can be determined. There may be a need for contractors who do not generally work with an engineer on their projects to form relationships with an engineering firm to perform sizing calculations.
5) Need for performance data – A measure package exists for gas-absorption water heating in a multifamily building. However, there is no measure package for other building types and no planned measure package for combination space/DHW heating. Third-party performance data is critical to the development of a combi

measure package and will be critical to reinforcing the existing and proposed measure packages as uptake of these technologies increases.

6) Need for accurate Cost data – GTI noted via personal communications with the GET Team that equipment and installation cost data is the largest gap from their standpoint for gas-fired heat pump water heaters. This is further supported by the Study Team's experience trying to get equipment and installation costs for GAHP units to put together this pilot.
7) Need for Measure Package – Barrier 6 is tied to barriers 4 and 5. Measure packages (MPs) require accurate performance data and accurate cost data. Once these barriers are addressed, additional MPs can be created for gas-fired heat pump systems. The existence of a measure package will reduce the first-cost barrier since an incentive will be able to be offered.

GAHP Emerging Technology Pilot

The GAHP and the gas-fired thermal compression heat pump water heater & combination system were both recommended for field testing and lab testing[1]. Therefore, a multi-phase pilot was created to test these technologies in the lab and field. The pilot will test the gas-absorption heat pump (GAHP) technology[2], test mechanisms to overcome barriers, and provide useful information to improve adoption of the GAHP in California gas energy efficiency programs. The pilot project includes lab, modeling, and field studies in separate phases.

This project is phase 1 of the multi-phase pilot project for gas-fired heat pump water heaters & combination systems. This phase 1 project addresses initial planning and data gathering necessary for Phase 2F and 3F to launch. Phase 2F and 3F projects will install GAHP equipment at various sites around California. The future planned phases that are <u>not</u> part of this project's scope are:

- Phase 2M: Large Scale modeling work
- Phase 2F: Field testing work
- Phase 2L: Lab testing work
- Phase 3F: Additional field testing and/or field-testing hand-off
- Phase 3L: Additional lab testing
- Phase 3M: Additional modeling work

[1] The gas-adsorption heat pump water heater is not yet ready for field for lab testing by the GET program
[2] Gas-fired thermal compression technology may be tested if available within pilot timeline

The Phase 2F, 3F, 2M, 3M, 2L, and 3L projects are open to test both the GAHP as well as the gas-fired thermal compression heat pump water heater system. However, at this time, only one (1) GAHP unit is commercially available in the United States and no gas-fired thermal compression heat pump water heater systems are commercially available in the United States. Therefore, the phase 1 pilot outcomes are based around this commercially available unit. If another GAHP unit or a gas-fired thermal compression heat pump water heater unit become available for testing they may be tested in Phase 2F, 3F, 2M, 3M, 2L, or 3L and the deliverables from this Phase 1 project may be modified to accommodate them, if necessary.

Field Study Barriers and Needs

Conversations with contractors and manufacturers indicated that some work needed to be done to address the following barriers so that contractors would be able to recruit appropriate sites for the field testing work:

- Barrier #2:
  - What buildings or loads are good candidates for this equipment?
- Barrier #4:
  - What data is required to establish the base load?
  - How to establish the base load so the appropriate number of GAHP units can be determined.

Additionally, a generic M&V plan and CO_2 analysis methodology were needed to determine the effort and cost required to gather data for the planned outcomes from field studies. Therefore, a Phase 1 project was created to address the knowledge gaps so the field study phases could launch.

Assessment Objectives

Below are the objectives of Phase 1:

1) Create a design & installation checklist to inform scope of work for each site installation in Phases 2F and 3F.
2) Create a site screening tool to quickly identify if potential sites are a good fit for gas-fired heat pump water heaters/combination systems.
3) Determine what data points to monitor and develop calculation methodology for water heating end-use gas and electric energy consumption (including parasitic electric loads).
4) Determine what data points to monitor to develop system performance curve data.

5) Determine what data points to monitor and develop calculation methodology for pre and post GHG emissions load shapes.

6) Determine incentive/approach for site recruitment.

The expected outcomes of this phase 1 project include:

1) Design & Installation Checklist
2) Site Screening Tool
3) Generic M&V plan
4) Generic hourly CO_2 analysis methodology

Site Screening Tool

There are currently two (2) manufacturers for GAHP units that have or plan to have commercially available units in the United States in 2023. Each unit is suitable for different building sizes and types. Conversations with contractors and manufacturers indicate that the general contractor community does not know how to identify suitable candidate buildings for GAHPs. Further, the GAHPs do not usually directly replace existing DHW/SHW equipment 1-1 as the GAHP is most effective when it is matched to the base-load of a building. The base load of the building cannot be reliably determined by using the existing capacity of the DHW/SHW system(s) since many existing systems are over-sized. There is a need to create a screening tool that the GET Team and installing contractors can use to quickly identify sites that would be good candidates for the Phase 2F and Phase 3F projects. This activity identified gaps in DHW and SHW sizing which are summarized in the Results & Discussion section of this report.

A spreadsheet-based screening tool was created using:

- Sizing methods from American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) Fundamentals Handbook – HVAC [1]
- Hourly DHW consumption profiles from the Database for Energy Efficient Resources (DEER) [2]

The User Guide for the tool is presented in this report. The spreadsheet tool itself is an internal resource that will be utilized in Phase 2F and 3F. The calculation methodology for the Site Screening Tool can be found in Appendix I .

Site Screening Tool User Guide

Introduction

- This tool is to quickly screen sites for a 123.5 kBtuh GAHP module
- This tool requires the following inputs
  - Building Type
  - Climate zone
  - Existing water heater capacities, efficiencies, and storage tank size (in gallons)
  - Existing boiler (DHW boiler and HHW boiler) capacities and efficiencies
  - Heating design temperature
  - Heating Hot Water set point temperature at design temperature
  - Maximum ambient temperature for heating
  - Water set point at the maximum ambient temperature
- The following additional inputs are necessary to size the domestic hot water system. If these inputs cannot be found, there is an override option
  - Multifamily
    - Number of apartments (or number of people)
    - Usage type (low, medium, high)
  - Nursing Home
    - Number of beds
  - Hotel/Motel
    - Number of Units
  - Foodservice
    - Sit down or fast food
    - Maximum number of hot meals/hour
  - Office
    - People in building
  - Dormitory
    - Number of Students
- This tool also checks for several other factors:
  - Maximum supply water temp
  - Efficiency of existing hot water heaters/boilers
  - Space requirements for new Robur system in mechanical room and outside
  - Distance from outside space to electrical and plumbing tie ins

Limitations

This sizing tool is meant to give a high-level screening of sites to see if they are good candidates for further investigation for the GET gas heat pump water heater field pilot. This tool is NOT intended to give design recommendations of any kind. This sizing tool makes broad assumptions of DHW load profiles and space heating loads using available information from ASHRAE [1] and the DEER database [2]. The tool is intended to be high-level, so it does not take into account high peaks or extended durations of DHW loads or SHW loads. The tool assumes that the recirculation losses during peak demand are negligible compared to end-use demand and does not account for them.

How to use the tool

1. Fill out Checklist on Front Page

The Checklist section of the Front Page gives criteria for site selection which is not related to DHW/SHW capacity that must be considered. Figure 1 gives a screenshot of the Front Page Checklist.

If any of the "Y/N" responses in the Front Page Checklist are highlighted in red, the site may not be a good fit and/or may require additional installation cost, controls, or design considerations. See the comments section of the Front Page Checklist for further details on each checklist item.

i Maximum Water Set Point 135 F or less – The GAHP supplies a water/glycol solution at a maximum temperature of 140°F to a heat exchanger. There will be temperature losses between the water/glycol solution and the DHW/SHW loop through the heat exchanger. If the maximum DHW/SHW water set point is greater than 135°F, the GAHP may not be able to satisfy the demand. In cases where the DHW/SHW set point is greater than 135°F, the GAHP may be able to augment the system **IF:**

1. The maximum set point exceeds 135°F less than 400 hours during the year.
2. The existing boiler is a condensing efficiency boiler (87% thermal efficiency or greater).

ii There is space on the ground outside to mount the new GAHP – the minimum amount of space required to mount the GAHP is 6 feet by 9 feet. It must be mounted outside or in a space that is covered and has adequate airflow to get rid of the products of combustion safely (a parking garage is an option). If more than (1) GAHP will be installed, space requirements go up, but do not double. See the specifications sheet for space requirements in that case.

iii Mounting space is 20 feet or less from electrical AND plumbing tie in – To control installation costs, the ideal site has mounting space outside that is within 20 feet of

BOTH electrical and plumbing tie ins. An installation is possible if this distance is greater than 20 feet but will be more expensive due to the additional connection costs.

iv There is space in existing mechanical room for a plate & frame HX and buffer tank – The GAHP uses a plate and frame heat exchanger or a tank heat exchanger to transfer heat into the DHW and SHW systems. It also requires a buffer tank in the GAHP loop. This equipment needs to be installed inside the mechanical room that houses the existing DHW/SHW equipment.

v The building served is 3 stories or less – This is the ideal candidate based upon the manufacturer's experience due to the heating load and location of the mechanical room in a taller building. Additionally, there are less likely to be water pressure concerns in a building that is 3 floors or less. However, installation in a 4+ story building may still be possible but may be more expensive.

vi There are no noise concerns where the new GAHP unit may be installed – the new GAHP unit will cause noise pollution where it did not previously exist. This item is to ensure that the noise pollution will not affect building occupants or will be acceptable to occupants.

vii Mechanical room on ground floor – The addition of a new HX and buffer tank in the mechanical room will add weight to the structure since most GAHP installations retain the existing DHW/SHW boilers and storage tanks. Therefore, it is recommended that mechanical rooms be located on the ground floor so additional structural permitting is not necessary. Installation in a mechanical room NOT located on the ground floor is possible but will be more expensive.

Figure 1: Front Page Checklist

Checklist	Y/N	Comments
Maximum Water Set Point 135F or less	No	Check existing boiler efficiency and GAHP runtime
There is space on ground outside to mount new GAHP (minimum of 6 ft x 9 ft)- more space needed for multiple units	No	Roof Mounting possible, but more expensive. Can also potentially mount in parking garage with open airflow
Mounting space is 20 feet or less from electrical AND plumbing tie in	Yes	
There is space in existing mechanical room for a plate & frame HX and water storage tank	Yes	
Building served is 3 stories or less	No	Installation possible but may be more expensive
There are no noise concerns where the new GAHP unit may be installed	Yes	
Mechanical room located on ground floor	Yes	

2. Enter info on Front Page in blue cells

Figure 2: Site Screening Tool – Front Page, Data Points a-f

Climate Zone	(a.)	CZ10	Always required
Intended Use	(b.)	DHW Only	Always required
Building Type	(c.)	Nursing Home	Always required
Unit Category	(d.)	Beds	
Number of Units	(e.)	500	
Average Daily Water Draw [gallons]	(f.)	9200	Automatically calculates
Number of Heat Pump Water Heaters	(g.)	1	Always Required, Currently built for Robur GAHP-A
Total Capacity [kbtuh]		123500	

The user must enter information for the systems the gas heat pump water heater will be augmenting. For example, if only DHW will be augmented, only DHW information is needed. If both DHW and heating will be augmented, information for both systems must be entered. If only heating will be augmented, only information for heating system needs to be entered.

a. *Title 24 Climate Zone* – Select building climate zone from drop down.
b. *Intended Use* – Select from drop down.
   - DHW Only – Heat pump water heater will only be augmenting the DHW system.
   - Combi – Heat pump water heater will be augmenting DHW and space heating systems.
   - Heating Only – Heat pump water heater will only be augmenting space heating system.
c. *Building Type* – Select appropriate building type from drop down.
d. *Unit Category* - Select appropriate unit category from drop down (Only needed for DHW Only and Combi).
e. *Number of Units* – Enter number of units based upon the building type and unit category (units/beds/people/average meals) (Only needed for DHW Only and Combi).
f. *Average Daily Water Draw* – This automatically calculates based upon inputs (d) and (e) using Average Daily from Table 6 from 2015 ASHRAE fundamentals Handbook – HVAC [1] which is pasted on the sheet "Hot Water Demands by Bldg Type" (shown below in **Error! Reference source not found.**).
g. *Number of Heat Pump Water Heaters* – Enter the number of gas heat pump water heaters that will be installed at this site. This number can be between (1) and (3).

Figure 3: ASHRAE Hot Water Demand and Use for Various Types of Buildings [1]

Table 6 Hot-Water Demands and Use for Various Types of Buildings*

Type of Building	Maximum Hourly	Maximum Daily	Average Daily
Men's dormitories	3.8 gal/student	22.0 gal/student	13.1 gal/student
Women's dormitories	5.0 gal/student	26.5 gal/student	12.3 gal/student
Motels: Number of units[a]			
20 or less	6.0 gal/unit	35.0 gal/unit	20.0 gal/unit
60	5.0 gal/unit	25.0 gal/unit	14.0 gal/unit
100 or more	4.0 gal/unit	15.0 gal/unit	10.0 gal/unit
Nursing homes	4.5 gal/bed	30.0 gal/bed	18.4 gal/bed
Office buildings	0.4 gal/person	2.0 gal/person	1.0 gal/person
Food service establishments			
Type A: Full-meal restaurants and cafeterias	1.5 gal/max meals/h	11.0 gal/max meals/day	2.4 gal/average meals/day[b]
Type B: Drive-ins, grills, luncheonettes, sandwich, and snack shops	0.7 gal/max meals/h	6.0 gal/max meals/day	0.7 gal/average meals/day[b]
Apartment houses: Number of apartments			
20 or less	12.0 gal/apartment	80.0 gal/apartment	42.0 gal/apartment
50	10.0 gal/apartment	73.0 gal/apartment	40.0 gal/apartment
75	8.5 gal/apartment	66.0 gal/apartment	38.0 gal/apartment
100	7.0 gal/apartment	60.0 gal/apartment	37.0 gal/apartment
200 or more	5.0 gal/apartment	50.0 gal/apartment	35.0 gal/apartment
Elementary schools	0.6 gal/student	1.5 gal/student	0.6 gal/student[b]
Junior and senior high schools	1.0 gal/student	3.6 gal/student	1.8 gal/student[b]

*Data predate modern low-flow fixtures and appliances. [a]Interpolate for intermediate values. [b]Per day of operation.

Figure 4: Front Page – Data Points h-o

DHW System Info											
Water Heaters/Boilers	#1	#2	#4	#4	#5	#6	#7	#8	#9	#10	
Water Heater/Boiler Capacity [btuh] (h.)											Required f
Water Heater/Boiler Efficiency											Required f

Storage Tanks	#1	#2	#4	#4	#5	#6	#7	#8	#9	#10
Tank Capacity [gallons] (i.)	200									

Total Heating Capacity [btuh]	0	
Avg. Efficiency	#DIV/0!	
Total Tank Capacity [Gallons]	200	
DHW Set Point Temp [F] (j.)	140	Required for DHW Only and Com

Heating System Info											
Boiler	#1	#2	#4	#4	#5	#6	#7	#8	#9	#10	
Boiler Capacity [btuh] (k.)											Required f
Boiler Efficiency											Required f

Total Heating Capacity [btuh]	0	
Avg. Efficiency	#DIV/0!	
Design Temp	(l.)	Required for Space Heating Only and Combi Look Up 99% Heating Dry Bulb Temp from ASHRAE
Water Set Point Temp @ Design Temp	(m.)	Required for Space Heating Only and Combi
Max Ambient Temp for Heating	(n.)	Required for Space Heating Only and Combi
Water Set Point Temp @ Max Ambient	(o.)	Required for Space Heating Only and Combi
Heating Load @ Design Temp	#DIV/0!	Includes assumption that actual heating load @ design temp is 75% of the rated boiler capacity

h. *Water Heater/Boiler Capacity & Water Heater/Boiler Efficiency* – Enter the capacity in Btuh and thermal efficiency for each water heater or boiler used for the DHW system that the gas heat pump water heater will be augmenting. If an existing water heater is rated with a uniform energy factor, convert this to a thermal efficiency.

   If boilers are used for both DHW and space heating, estimate how much of the total capacity is used for DHW and enter that value into the Water Heater/Boiler Capacity. The DHW load is estimated on the DHW Sizing tabs which can help estimate the DHW capacity.

i. *Storage Tank Capacity* – Enter the storage tank capacity in gallons for each storage tank connected to the system that the gas heat pump water heater will be augmenting. If the water heaters have internal storage tanks, put that storage capacity here. "Total Tank Capacity" should reflect all internal and external potable water storage in the DHW system that the gas heat pump water heater will be augmenting.

j. *DHW Set Point Temp* – Enter the water storage temperature for the DHW system.

k. *Boiler Capacity and Boiler Efficiency* – Enter the capacity in Btuh and thermal efficiency for each water heater or boiler used for the space heating system that the gas heat pump water heater will be augmenting.

l. *Design Temp* – Enter the design ambient outside air temp from the closest location available from ASHRAE.

m. *Water Set Point Temp for Heating* – Enter the set point temperature for the space heating water when the ambient temperature is at or below the design temperature. This should be the maximum water temperature supplied to the building.

n. *Max Ambient Temp for Heating* – This is the maximum outside air temperature where space heating would be necessary. If unknown, set this to 60F.

o. *Water Set Point Temp @Max Ambient* – Enter the set point temperature for the space heating water when the ambient temperature is at or above the Max Ambient Temp for Heating. This is used if there is a control to reset the space heating water temperature at different outside air temperatures. If there is no reset control, enter the same value as Water Set Point Temp for Heating.

3. DHW load

The tool uses information from the 2015 ASHRAE fundamentals Handbook – HVAC Applications Chapter 50 [1] to size the DHW system. Once the information on the front page is entered, <u>go to the DHW Sizing tab for the selected building type</u>. Enter the information required for the selected building type. If this information is not available, enter the estimated DHW load from the override.

a. *DHW Sizing – Multifamily Tab*

- Usage factor – See Table 1 from 2019 ASHRAE fundamentals Handbook – HVAC Applications Chapter 50 [1] which correlates demographic characteristics with the usage factor in Figure 5**Error! Reference source not found.**.

Figure 5: Demographic Characteristics Correlation to DHW Consumption [1]

Table 1. Demographic Characteristics Correlation to DHW Consumption	
Demographic characteristics	Usage factor
No occupants work Public assistance and low income (mix) Family and single-parent households (mix) High percentage of children Low income	High
Families Public assistance Singles Single-parent households	Medium
Couples Higher population density Middle income Seniors One person works, one stays home All occupants work	Low

The **DHW load** will automatically calculate with this information and other information from the Front Page (see Figure 6**Error! Reference source not found.**).

Figure 6: DHW Sizing – Multifamily Inputs

Climate Zone	CZ10
Usage factor	High
Number of Units	500
Number of Occupants	750
Water Set Point Temp [F]	140
Water Main Temp [F]	66
Existing Boiler Thermal Eff	85%
Existing Storage Tank [gal]	500
Boiler Size [btuh]	2,000,000
DHW Load [btu/hr]	**4,747,456**

b. *DHW Sizing - Nursing Home Tab*

The **DHW load** will automatically calculate with information from the Front Page (see Figure 7**Error! Reference source not found.**)

Figure 7: DHW Sizing – Nursing Home Inputs

Number of Beds	500
Storage Capacity	350
Usable Storage Capacity/Bed	0.7
Climate Zone	CZ10
Avg Water Temp	66
Set Point Temp	140
DHW Load [btu/hr]	**970,572.28**

c. *DHW Sizing - Motel/Hotel Tab*

The "Usable Storage Capacity [gal/unit]" automatically calculates using information from the Front Page (see Figure 8). User must estimate the Recovery Capacity using Figure 17 from 2015 ASHRAE fundamentals Handbook – HVAC [1] which gives Recovery Capacity as a function of Usable Storage Capacity for 100 + rooms, 60 rooms, and 20 or less rooms. Figure 17 from the ASHRAE Handbook is pasted on the DHW Sizing – Motel/Hotel Tab.

Figure 8: DHW Sizing – Motel Inputs

Number of Units	500
Storage Capacity	350
Usable Storage Capacity/Unit	0.7
Climate Zone	CZ10
Avg Water Temp	66
Set Point Temp	140
DHW Load [btu/hr]	**970,880.00**

	Usable Storage Capacity [gal/unit]	Recovery Capacity [gal/hr/unit]	
Actual	0.7	3.2	User estimate using Figure Below

d. *DHW Sizing – Foodservice Tab*

i Maximum meals/hour – the approximate maximum number of meals per hour served at the restaurant. The Front Page uses the average number of meals per day to calculate the daily DHW demand, but that value is not used in the chart of usable storage capacity vs. recovery capacity.

The "Usable Storage Capacity [gal/unit]" automatically calculates. User must estimate the Recovery Capacity using Figure 20 from 2015 ASHRAE fundamentals Handbook – HVAC which gives Recovery Capacity as a function of Usable Storage Capacity for full meal and drive thru restaurants [1] (see Figure 9**Error! Reference source not found.**)

Figure 9: DHW Sizing – Foodservice Inputs

Maximum Meals/hour	20	**This is Maximum meals/hr which is NOT the same as the average meals/hour used on the Front Page to determine total DHW gallons/day** May not have this readily available, use override if necessary
Storage Capacity	350	assume that 70% of storage is usable (ASHRAE Handbook HVAC Applications 2015 Pg 50.16)
Usable Storage Capacity/Maximum meals/hour	17.5	
Climate Zone	CZ10	
Avg Water Temp	66	
Set Point Temp	140	
DHW Load [btu/hr]	**7,281.60**	Override here if missing info

	Usable Storage Capacity [gal/unit]	Recovery Capacity [gal/hr/unit]	
Actual	17.5	0.6	User estimate using Figure Below

e. DHW Sizing – Office Tab

The "Usable Storage Capacity [gal/unit]" automatically calculates using information from the Front Page. User must estimate the Recovery Capacity using Figure 19 from 2015 ASHRAE fundamentals Handbook – HVAC which gives Recovery Capacity as a function of Usable Storage Capacity [1] (see Figure 10**Error! Reference source not found.**).

Figure 10: Office Inputs

People in Building	500	May not have this readily available, use override if necessary
Storage Capacity	350	assume that 70% of storage is usable (ASHRAE Handbook HVAC Applications 2015 Pg 50.16)
Storage Capacity/Person/Hour	0.7	
Climate Zone	CZ10	
Avg Water Temp	66	
Set Point Temp	140	
DHW Load [btu/hr]	**36,408.00**	Override here if missing info

	Usable Storage Capacity [gal/unit]	Recovery Capacity [gal/hr/unit]	
Actual	0.7	0.12	User estimate using Figure Below

f. DHW Sizing – Dormitory Tab

The "Usable Storage Capacity [gal/unit]" automatically calculates using information from the Front Page. User must estimate the Recovery Capacity using Figure 16 from 2015 ASHRAE fundamentals Handbook – HVAC [1] which gives Recovery Capacity as a function of Usable Storage Capacity for men's dormitories and women's dormitories (see Figure 11**Error! Reference source not found.**).

Figure 11: DHW Sizing – Dormitory Inputs

Students	500	May not have this readily available, use override if necessary
Storage Capacity	350	assume that 70% of storage is usable (ASHRAE Handbook HVAC Applications 2015 Pg 50.16)
Storage Capacity/Student/Hour	0.7	
Climate Zone	CZ10	
Avg Water Temp	66	
Set Point Temp	140	
DHW Load [btu/hr]	**682,650.00**	Override here if missing info

	Usable Storage Capacity [gal/Student	Recovery Capacity [gal/hr/unit]	
Actual	0.7	2.25	User estimate using Figure Below

g. DHW Sizing – Other Tab

The user must enter the DHW load for any building type not listed in the tool. This can be done using the provided ASHRAE Figures on the sheet, by using the existing water heater capacity and efficiency, or some other way. This tab includes Figures 22 and 23 from 2015 ASHRAE fundamentals Handbook – HVAC [1] which gives Recovery Capacity as a function of Usable Storage Capacity for High Schools (Figure 23 of ASHRAE Handbook) and Elementary Schools (Figure 22 of ASHRAE Handbook). This tab also includes the Override box which calculates water heating load using existing water heating capacity and efficiency (see Figure 12**Error! Reference source not found.**).

Figure 12: DHW Sizing – Other Inputs

Climate Zone	CZ07	
Avg Water Temp	64	
Set Point Temp	140	
DHW Load [btu/hr]	-	Load = m*Cp*dT Override here if needed

h. Override

If information is unavailable on a tab, there is an override box that estimates the DHW demand based upon the existing water heating system capacity and efficiency. Replace the cell that gives DHW load with what is given in the override box (see Figure 13**Error! Reference source not found.**).

Figure 13: Override

Maximum Meals/hour		**This is Maximum meals/hr which is NOT the same as the average meals/hour used on the Front Page to determine total DHW gallons/day** May not have this readily available, use override if necessary
Storage Capacity	350	assume that 70% of storage is usable (ASHRAE Handbook HVAC Applications 2015 Pg 50.16)
Usable Storage Capacity/Maximum meals/hour	#DIV/0!	
Climate Zone	CZ10	
Avg Water Temp	66	
Set Point Temp	140	
DHW Load [btu/hr]	-	Override here if missing info
Override		
Existing Water Heater Capacity	500,000.00	
Existing Water Heater Avg. Efficiency	0.85	
Estimated Maximum DHW Load	318,750.00	Includes 25% oversizing

4. Space Heating Load

The space heating load will automatically calculate when the Front-Page information is entered.

5. Screening Results

a. *DHW Only*

The DHW Only section on the front page automatically pulls in the DHW load from the appropriate tab. It gives the percentage capacity that the gas heat pump water heater serves. The gas heat pump water heater typically should serve between 40%-60% of the total DHW load. User may change the number of gas heat pump water heaters to change the percentage capacity that the gas heat pump water heater serves to meet this range (see Figure 14 for an example of the DHW Only selection information in the tool)

<u>A good candidate site is one where the 40%-60% capacity can be met with (1) – (3) gas heat pump water heaters.</u>

Figure 14: DHW Only Selection

DHW Only	**DHW Load [btuh]**
Multifamily	-
Nursing Home	-
Hotel/Motel	-
Food Service	-
Office	-
Other	-
HPWH % Cap of System Size	**#DIV/0!**

b. Heating Only

The Heating Only section on the front page automatically pulls in the heating load at design temperature, water set point at design temperature, and existing boiler thermal efficiency. An hourly analysis is done to approximate the hourly heating load of the building and the hourly capacity of the gas heat pump water heater.

A good candidate site is one where the water set point at design temperature is 135 F or less and the gas heat pump water heater meets between 40-60% of the heating load at the design temperature (see **Error! Reference source not found.** for a n example of the Heating Only selection information in the tool).

i. If the water set point at design temperature is greater than 135°F, then a good candidate site must meet one of the following criteria:

   1. An existing boiler efficiency of 87% or greater (i.e., condensing boiler(s)).
   2. Gas heat pump water heater must satisfy the load 90% or more of the hours in the year.

Figure 15: Space Heating Only Selection

Heating Only	
Heating Load @ Design Temp [btuh]	-
Water Set Point @ Design Temp [F]	-
HPWH % Cap of System Size	**-**
HPWH satisfies load % Hours	**-**
Existing Boiler Efficiency	**-**

c. Combi System

1. The Combi section on the front page automatically pulls in the DHW load for the selected building type as well as the heating load at design temperature, water set point at design temperature, existing space heating boiler efficiency, and the maximum water temperature set point (between the DHW and space heating systems). This section sums the DHW load and the space heating load at the design temperature to come up with a total system load. An hourly analysis is done to approximate the hourly DHW and heating load of the building and the hourly capacity of the gas heat pump water heater (see

Figure 16**Error! Reference source not found.** for an example of the Combi selection information in the tool).

A good candidate site is one where the maximum water set point is 135°F or less and the gas heat pump water heater meets between 40-60% of the total system load.

j. If the maximum water set point temperature is greater than 135°F, then a good candidate site must meet one of the following criteria:

1. An existing boiler efficiency of 87% or greater (i.e., condensing boiler(s)).
2. Gas heat pump water heater must satisfy the load 90% or more of the hours in the year.

Figure 16: Combi Selection

Combi	
DHW	**DHW Load [btuh]**
Multifamily	-
Nursing Home	181,870
Hotel/Motel	-
Food Service	-
Office	-
Other	-
Heating	
Heating Load @ Design Temp [btuh]	618,750
Water Set Point @ Design Temp [F]	140
Combination	
Total System Load [btuh]	**800,620**
Maximum Water Set Point [F]	**140**
HPWH % Cap of System Size	**31%**
HPWH satisfies load % Hours	**78%**

Site Screening Gaps

Over the course of site screening tool development, gaps were found in site screening that cannot be overcome by the simplified tool created in this project.

Recirculation Losses

The goal of the sizing is to maximize the run-time of the GAHP. The site screening tool sizes the GAHP based upon the hot water system's peak demand. This is based on feedback from the GAHP manufacturer of the commercially available unit. DHW recirculation losses is an additional load on the water heating system that affects the energy use of the water heater. Recirculation loads depend upon multiple factors including:

- Length of distribution piping

- Diameter of distribution piping
- Type of distribution piping
- Supply water temperature
- Recirculation controls
- Site DHW usage patterns

Recirculation loads vary greatly from site to site depending on these factors. A report by the California Energy Commission (CEC) that studied multifamily central domestic hot water distribution systems in (28) multifamily buildings found that average annual recirculation losses ranged from 7% to 49% [4]. The recirculation load will affect the run time of the GAHP but it was not accounted for in the site screening tool since it requires more complex modeling to give meaningful results. It was assumed that during the peak demand time, the distribution heat losses are small (less than 2%).

Interviews with the representatives of the Toronto site as well as an engineer who worked on a NEEA study for a GAHP [5], indicate that recirculation loads are an important consideration to ensure that the GAHP unit does not cycle frequently. Recirculation loads will be addressed during Phase 2F and 3F when actual sites are selected, and more site-specific data is available.

Existing System Capacity

There is still a desire among contractors to select pilot projects based upon the existing DHW/HW boiler capacity(ies) since that is a metric they will most commonly have for hot water systems that they service. The desired outcome of the overall GAHP pilot is to reinforce the existing measure package SWWH033 and/or expand the GAHP to other measure packages. If this occurs, it is likely that contractors will want to use the existing system capacity to determine if they want to pitch the GAHP as an energy efficiency measure to a customer. Therefore, it would be beneficial to have some guidance on what actual system capacity ranges would be a good fit for a GAHP retrofit. There is evidence that hot water system capacities are oversized, but there is no publicly available information that gives a range or an average of how system capacity compares with actual loads. Phase 2F and 3F of the pilot will provide this information but will only have data for a handful of sites. A follow-up emerging technology project comparing actual hot water system capacities with actual hot water system loads from additional sites is recommended.

Sizing Methods

ASHRAE was used as the sizing method in the site screening tool. However, there may be other sizing methods in use in the industry such as DHW boiler manufacturer sizing methods. A follow-up project is recommended to determine the most prevalent sizing methods used in the United States with an emphasis on the California market.

Design & Installation Checklist

The Project Team visited a site where a GAHP unit was installed in a domestic hot water (DHW) application. The Project Team worked with a California-based contractor who has extensive experience retrofitting existing DHW systems to create a Design & Installation Checklist for the GAHP system using information obtained from the site visit and the contractor's existing knowledge.

Site Visit

A Project Team representative visited a site located in Toronto, Canada to observe a facility where a GAHP water heater had been installed and integrated with an existing hot water/domestic hot water system. The project was completed in May of 2021 and largely sponsored by the gas utility of Toronto – Enbridge Gas. Below are the details of the site visit. See Figure 17 for a diagram of the system with the integrated GAHP.

Site Characteristics

- Multifamily property
- Vintage 1970
- Brick construction
- ≈ 60,000 sqft. conditioned area
- 75 apartments (1-2 bedrooms)

Existing System Parameters

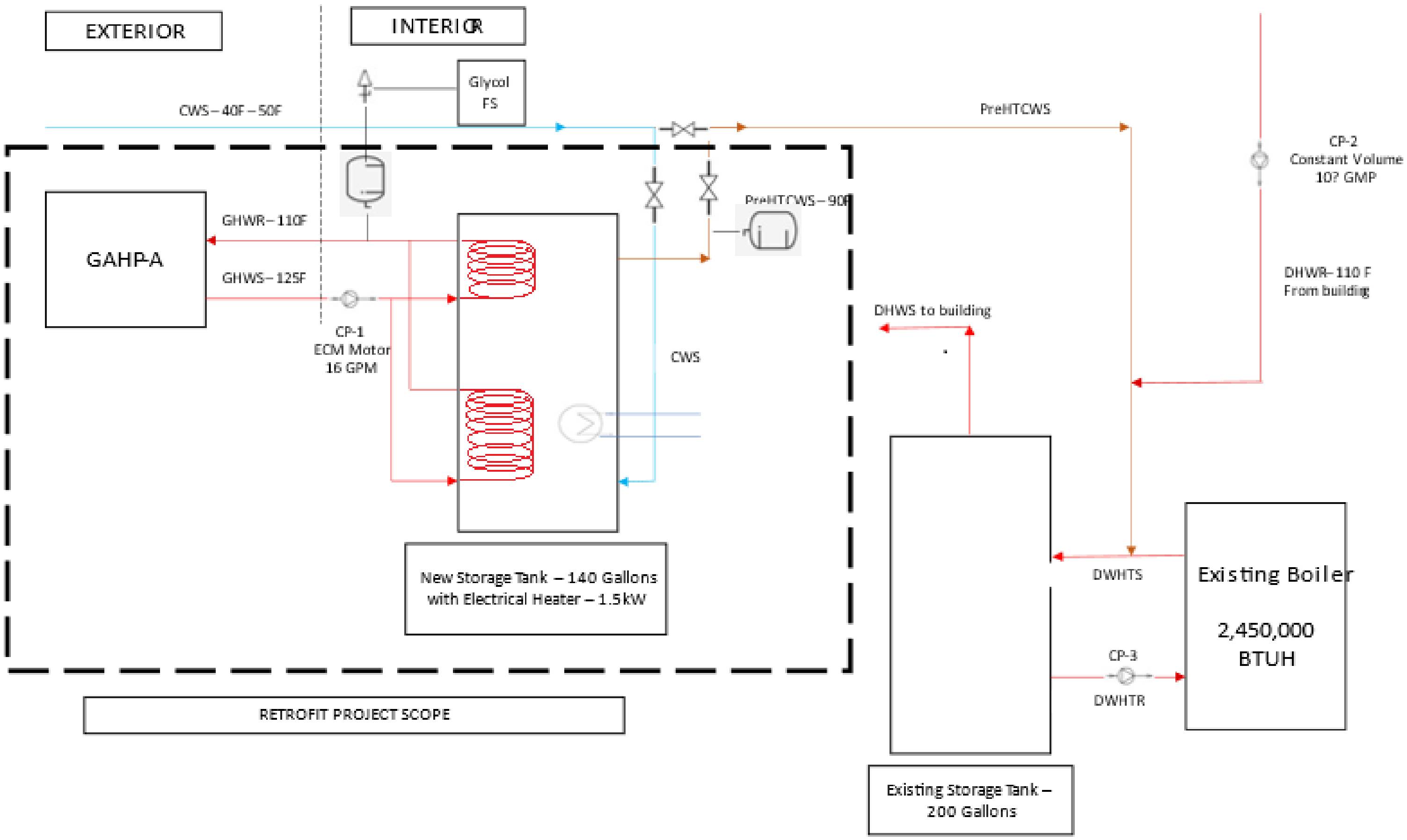
- DHW System – Raypak WH3-0514, 2-stage 511,500 Btuh non-condensing Hot Water Heater, with a recirculation pump and water storage tank (200 gallons approximately).
- Service Water Heating (SHW) – Laars Gas-Fired Non-Condensing Hot Water Boiler 2,450,000 Btuh – 180 F water leaving temperature.

GAHP Retrofit Project Parameters

- DHW System –
  - Addition of a GAHP to the main intake cold water line as a pre-heat stage.

  - Installation of a variable speed Electronically Commuted Motor (ECM) recirculation pump, with a range of 10 to 16 GPM, field programmed for the speed command to match the system load.
  - Connection of GAHP to the existing system is through a double, parallel double input, single output heat exchanger (HX) storage tank of 120 gallons. The storage tank includes an electric heater, operating on a timer, for Legionella and other contaminant-related prevention.
  - The existing system remains as is, and the new unit operates connected to the existing system through one point of connection and appropriate isolation valves.
  - GAHP control is through its own DDC controller, factory programmed, and field commissioned. This control includes operating mode, alarm monitoring, setpoint adjustment and operating schedule parameter selection.
  - Refer to Figure 17 for further detail.
- SHW System – No alteration to the existing system.

Figure 17: DHW System Diagram with Integrated GAHP



Project Results

- Successful integration of the GAHP unit into the DHW system. After commissioning was completed and return and supply water/glycol mixture temperatures were adjusted, no major issues have been reported.
- Between 25% to 35% reported natural gas utility bill energy savings during periods of non-space heating load (May, June, and July) in 2022 compared to the pre-installation period in 2021.

Project Challenges/Learnings

- Size of the storage tank should be considered when selecting the GAHP unit size and pump size to minimize the GAHP system cycling. From additional research and contact to manufacturer representatives, the following recommendations regarding buffer and indirect storage tanks have been gathered to maximize the operating cycle length.
  - For hydronic heating systems, the number of zones should be noted. For 2-3 zone systems, a buffer tank is probably not required to prevent excessive cycling. For highly zoned systems (greater than 3), a buffer tank is recommended to prevent heat pump cycling. The thermostat on the buffer tank should have a delta T of at least 20°F.
  - For combi or domestic hot water applications, if an indirect storage tank (IST) is to be installed, select a tank with a volume of at least 60 gallons (75-80 preferred) with the aquastat located at the approximate mid-height of the tank in order to prevent short heat pump recovery cycles. Aquastats set low in the tank will create short cycling and may impact efficiency. The internal heat exchanger must be large enough to allow adequate tank heating at low hydronic supply temperatures (use ISTs designed for connection to condensing boilers or thermal solar systems). Note ISTs supplied or recommended by manufacturer have been vetted for proper operations with GHP.
- To have a steady GAHP operation, a constant recirculation volume pump operation is required.
- GAHP exterior install location needs to consider noise concerns caused by the system's operation.

GAHP Water Heater Design & Installation Checklist

The checklist for the installation of a GAHP system has been created with input from the Project Team and contractor with information collected during the site visit.

Purpose

The purpose of the Design & Installation Checklist is to assist hot water system designers and/or installing contractors in selecting the appropriate number of GAHP modules, designing the hot water systems (DHW and SHW) with an integrated GAHP and installing the GAHP and heat exchanger(s).

Contractors have their own checklists for sales, project management, installation, and commissioning. Likewise, GAHP manufacturers have their own commissioning checklists and hot water designers have their own checklists when designing hot water systems. However, the contractor and hot water designer checklists may not include items that are specific to GAHPs, and the GAHP manufacturer checklist may not include items that are specific to the contractor. This checklist is meant to fill in gaps that exist so GAHP design and installation is successful.

This document is meant to provide guidance and may not include all of the project specific considerations or requirements for a GAHP design and installation. Many items on the checklist were added as work on this study progressed such as the need for a buffer tank in the GAHP loop, and it is expected that additional items will need to be added as the field pilot phases progress. This is a living document and will be updated as the GET Team gains experience during the field pilot phases.

Audience

This Design & Installation Checklist is intended to be completed by the hot water system designer and/or the installing contractor. If the installing contractor will be designing the system with the GAHP, only the installing contractor needs to complete the checklist.

Organization

The Design & Installation Checklist is organized by design, installation, and commissioning considerations.

The Design section should be completed before the new DHW/SHW system with integrated GAHP design is finalized.

The Installation section should be completed before GAHP installation is scheduled.

The Commissioning section should be completed after the GAHP has been installed and commissioning activities listed have been completed.

Design Considerations

General Building Information

- Building Type
- Building Sqft
- Number of Hotel or Apartment units, if applicable

DHW and SHW System Information

- Existing System Type(s)
- Facility and DHW/SHW system Layout
- Size of existing DHW storage tank
- Expected hot water loads
- DHW Recirculation losses

GAHP Design

- GAHP sized properly to reduce cycling of GAHP
  - GAHP should be sized to 40-60% of the peak DHW/SHW load
  - GAHP does not modulate
- Additional DHW storage necessary to reduce cycling of GAHP (if applicable)
- Supply Temperature Requirement (Maximum GAHP supply water temperature limit is 135°F)
- GAHP Return Water Temperature Limitation (Maximum return water temperature to GAHP is 122°F)
- DHW Recirculation
  - Pump sized properly to reduce cycling of GAHP
  - Pump controls such that return water temperature is at or below 122°F, or:
  - GAHP not integrated into recirculation loop with constant speed (return water temperature usually exceeds 122°F in a constant speed recirculation loop)

GAHP Controls

- Supply Temperatures
  - Control strategy when supply temp ≤135°F
  - Control strategy when supply temp requirement > 135°F

- Control Type
  - GAHP on-board controls
  - GAHP manufacturer DDC controls
  - Interface with existing SHW/DHW or Building BMS controls
- Space and accessibility requirements for new equipment and demolition
  - Outside Space Requirement for new GAHP (minimum for (1) GAHP module is 6 feet by 9 feet)
  - GAHP mounting area airflow
    - Enough airflow to safely remove products of combustion/evaporator.
  - Mechanical Room Space Requirement for new Heat Exchanger
  - Mechanical room space requirement for new GAHP buffer tank
  - Mechanical room space requirement for additional hot water storage tank, if necessary

New Material/Equipment

- New GAHP(s)
- New HX(s) to interface with existing DHW/SHW loop(s)
- New GAHP buffer tank (50-80 gallon)
- GAHP loop pump
- New piping from HX to GAHP
- New electrical conduit and panels for GAHP and GAHP circulation pump power, controls, and communications
- New housekeeping pad for GAHP mounting
- Include GAHP bypass valves for maintenance and/or emergencies

Installation Considerations

Potential Demolition

- Demolition space requirements
- Components of existing system to be demolished or repurposed, if applicable
- Components of existing system to be abandoned in place to be clearly identified, if applicable
- Components of existing system to be replaced, if applicable
- Contractor with disposal license required

Jurisdictional Ordinances

- Jurisdictional ordinance for screening new equipment outside
- Jurisdictional ordinance for noise dampening for new equipment outside

SHW/DHW System Operation Interruption During Installation

- Number of interruptions
- Duration of each interruption

Installation Labor Activities

- Facility Scheduling/Coordination
  - Emergency/Safety Procedures
  - Point of Contact
- Seismic securing requirements per building codes
  - Plan ahead for bolting GAHP to structure

Permit Requirements

- Equipment submittal and engineering drawings for permit
  - Plumbing drawings
  - Electrical drawings
  - Structural drawings
- Additional structural permit requirements if GAHP is to be installed on roof
- Additional structural permit requirements if mechanical room is NOT on ground floor (new HX and buffer tank need to be installed in mechanical room and will add overall weight)
- Seismic strapping or bolting of new buffer tank

Commissioning Requirements

Start-Up/Checkout

- Check all piping connections
- Check all piping insulation
- Check gas pressure regulator
- Check water pressure/flow rate of Primary/Secondary loops
- Verify electrical connections
- Check temperature and pressure of HX Primary/Secondary loops

- Check HX connections
- Check that all gauges are functioning correctly
- Start-Up Requirements for Refrigerant Circuit
- Complete manufacturer Start-Up checklist

Operational Checks

- Operation of GAHP alone
- Operation of GAHP combined with existing system

GAHP Control Checks

- Setup remote data access connection
- Program GAHP per manual directions

Training Requirements

- Facility staff training
- Record group training per contractor-facility contract requirements

Project Documentation and O&M

- Service Contact Information
- As-Built Drawings
- O&M Manual
- Sequence of Operation Manual
- Sign-Off Document

Results & Discussion

This GET project has resulted in the following outputs that will impact Phase 2F and 3F.

- Site Screening Tool: This tool was created for the participating contractor(s) in Phases 2F and 3F to use readily available information to select candidate sites for the GAHP installations.
  - This has addressed the following barriers:
    - Barrier #2:
      - What buildings or loads are good candidates for this equipment
    - Barrier #4:
      - What data is required to establish the base load

    - How to establish the base load so the appropriate number of GAHP units can be determined.
  - Limitations: This tool has limitations and is intended to narrow down the number of potential sites so contractors can focus their marketing efforts on those sites most likely to be a "good fit" for a GAHP system. Utility gas usage data will be collected for all sites and an initial site visit will be conducted to qualify all sites before enrolling them into Phase 2F or 3F. Site Screening Tool outputs will be compared with site visit and gas usage data for actual sites to further refine the Site Screening Tool in Phases 2F and 3F.
  - Gaps: The following gaps were found during the creation of the Site Screening Tool which could not be addressed within the scope of this project
    - Recirculation Loads: Recirculation loads are dependent upon actual site conditions and (at this time) cannot be quickly determined by information that is readily available to a contractor or site contact. The Site Screening Tool sizes based upon peak DHW/SHW loads, but recirculation loads will affect the total run time of the GAHP unit which is an important consideration.
    - Existing System Capacity: Conversations with one participating contractor have revealed that contractors may still desire to narrow down sites using the existing DHW/SHW system boiler capacities (Btuh). Contractors should be comfortable with the methods to select suitable sites for GAHP installations for the GAHP pilot and for the GAHP energy efficiency measure later on. It is recommended that another study be initiated to gather data comparing existing system capacities to actual peak DHW/SHW loads so this input can be used in the Site Screening Tool.
    - Sizing Methods: The Site Screening Tool uses ASHRAE methods to determine the peak design capacity and then determines if the commercially available GAHP unit is within 40-60% of that peak load. There are other methods available to determine this peak load, and it is not clear from publicly available documents which method is the most common. It is recommended that a study be initiated to survey subject matter experts in the area of DHW/SHW design to ascertain the most commonly used method or methods and update the Site Screening Tool as appropriate.
- Design & Installation Checklist: This checklist was created with input from the Study Team and a participating contractor who has extensive experience installing DHW systems in California. The resulting checklist will be available for use by the participating contractor and DHW system designer in Phases 2F and 3F. This Design & Installation Checklist has attempted to close any gaps between those existing checklists and need for GAHP installations. However, there may be additional gaps and there may be overlaps. This checklist will be refined in Phases 2F and 3F as more

information about design & installation considerations becomes available through actual installations and designs. Contractors, DHW designers, and the manufacturers also have checklists related to DHW systems or GAHPs.

- Generic M&V Plan and CO2 Analysis: The Generic M&V Plan which includes the methodology for CO2 analysis has been created for use in Phase 2F and 3F. The M&V Plan was reviewed by other subject matter experts in the area of gas-fired water heating and energy efficiency measures, and their feedback was incorporated. This M&V Plan will be used to create a site-specific M&V plan for each site selected in Phase 2F and 3F.

These concrete deliverables have paved the way for the launch of Phases 2F and 3F. Refined versions of the Site Screening Tool and Design & Installation Checklist may be available from the Project Reports from Phase 2F and 3F. The Site Screening Tool has been provided to participating contractor(s) but it is not a public-facing document at the time of this writing. The Design & Installation Checklist and Generic M&V Plan are publicly available via this Project Report.

Conclusions and Recommendations

The outcomes from this Phase 1 project will be used to successfully execute Phase 2F and 3F. All deliverables have been or will be made available to the GET Team and contractors participating in Phase 2F and 3F.

The following recommendations are made:

- Gather hourly DHW gas-usage data before site enrollment: The site screening tool does not calculate hourly DHW-only water heating loads nor does it account for recirculation heat losses. These hourly loads will affect the overall run-time of the GAHP. It is recommended that hourly site annual gas-usage data be obtained to analyze hourly loads and predict run-time of the GAHP before site enrollment in Phase 2F and 3FHourly gas-usage data will reflect other loads on the gas meter such as: pool heating, space heating, commercial kitchen, gas dryers, etc. and these loads should be considered and/or estimated (if possible) when analyzing the hourly gas-usage data.
- Refine Site Screening Tool with Phase 2F and 3F data: The Site Screening Tool should be refined using the results from the hourly gas-usage data, if needed. Only a handful of sites are going to be in Phase 2F and 3F so they may not provide enough data to further refine the Site Screening Tool on their own.

- Initiate a field study to compare actual DHW capacities to actual peak loads: There is evidence that DHW systems are oversized even after considering a reasonable factor of safety. However, there is no data available to characterize how much an existing system may be oversized in relation to its actual peak hot water loads. This information would be valuable to the contractor community that will be installing GAHPs as well as DHW system designers and can benefit traditional condensing DHW boilers, GAHPs and EHPWHs since all of these technologies benefit from right-sizing equipment capacity. If it turns out that the average system is 50% oversized, for example, this could be communicated to contractor and DHW design organizations to help both groups right-size DHW equipment and reduce equipment first-costs. The findings from this study should also be used to refine the Site Screening Tool.
- Initiate a study to ascertain the most common method(s) used to size DHW systems: Over the course of this study, other DHW sizing methods were found, but no data was found that indicates which method is the most commonly used or how accurate each method is. The chosen method impacts what data is gathered to screen sites, and how the peak load in the Site Screening Tool is calculated, so knowing the most commonly used methods will help to further refine the Site Screening Tool.
- Refine Design & Installation Checklist during field phases: It is recommended that contractor, DHW designer, and manufacturer checklists be gathered during the Phases 2F and 3F to identify any additional gaps or overlap between those checklists and the Design & Installation checklist. Additionally, learnings from Phases 2F and 3F should be incorporated into the Design & Installation Checklist.

Appendix I Site Screening Tool Calculation Methodology

This section provides the sizing calculation methodology used in the tool.

DHW Load

The 2015 ASHRAE Handbook – HVAC Applications Chapter 50 Section 9 gives information for hot water load and equipment sizing [1]. This section provides recovery rates (gallons/hour) per usable storage capacity (gallons) that can be used to size systems with fixed recovery rates or fixed storage capacities. The recovery rate of the system will change once the GAHP is installed, but it is assumed that the storage capacity in the system will remain the same. Therefore, these figures of recovery rate vs. storage capacity were used to determine the DHW load. The actual capacity of the system should include safety factors and consider heat losses and potential peak demand events. This tool does not calculate DHW capacity because that will be calculated by a licensed professional engineer for each site. This tool estimates the DHW and SHW loads since the goal is for the GAHP to satisfy 40%-60% of the load.

This tool calculates DHW capacity using information that should be readily available and easy to gather without a site visit. Fixture flow rates and counts are purposely not used since it may require a site visit to gather those data points. The site information used in the tool is intended to be information that site personnel already has access to or can easily gather with little effort.

Multifamily

DHW load calculations are done using the simplified method in the 2015 ASHRAE Handbook – HVAC Applications Chapter 50 Section 9 [1]. The simplified method calculates combinations of DHW input and hot water storage that can serve the load at cumulative peak intervals of 5 minutes, 15 minutes, 30 minutes, 60 minutes, 120 minutes, and 180 minutes. The peak design cumulative storage volume is calculated by Equation$V total_{,i}$ = $GPPi_{,UF}$ * *People* (.

$$V_{total,i} = GPP_{i,UF} * People \qquad (1)$$

Where:

$V_{total,i}$ is the total water volume required at each cumulative peak interval (5-180 minutes)

$GPP_{i,UF}$ is the average gallons per person at the specified usage factor

People is the average number of people in each multifamily building

The Usage factor is determined using the occupant demographics and Table 1 of the 2019 ASHRAE Handbook – HVAC Applications (which is the same information as in the 2015 Handbook but put in a table format) [1]. This table is included below as Figure 18.

Figure 18: Demographic Characteristics and DHW Usage Factors [1]

Table 1. Demographic Characteristics Correlation to DHW Consumption

Demographic characteristics	Usage factor
No occupants work Public assistance and low income (mix) Family and single-parent households (mix) High percentage of children Low income	High
Families Public assistance Singles Single-parent households	Medium
Couples Higher population density Middle income Seniors One person works, one stays home All occupants work	Low

The gallons per person at each usage factor and cumulative time interval is determined using Table 7 from the 2015 ASHRAE Handbook – HVAC Applications Chapter 50 Section 9 [1] which is shown below in Figure 19.

Figure 19: Hot Water Demand and Use Guidelines for Apartment Buildings [1]

Table 7 Hot-Water Demand and Use Guidelines for Apartment Buildings (Gallons per Person at 120°F Delivered to Fixtures)

	Peak Minutes							
Guideline	5	15	30	60	120	180	Maximum Daily	Average Daily
Low	0.4	1.0	1.7	2.8	4.5	6.1	20	14
Medium	0.7	1.7	2.9	4.8	8.0	11.0	49	30
High	1.2	3.0	5.1	8.5	14.5	19.0	90	54

The average number of people in the building is determined by multiplying the number of apartment units by 2.6 people/apartment. This value comes from the 2019 California Residential Appliance Saturation Study – Executive Summary Table ES-2 [3]. This value is the average number of residents per multifamily dwelling.

The average flow rate over the cumulative minutes is given by Equation $\dot{m}_i = Vi$ (1).

$$\dot{m}_i = \frac{V}{i} \quad (1)$$

Where:

$\dot{m}_i$ is the average flow rate over the cumulative interval

i is the cumulative interval (5 minutes, 15 minutes, 30 minutes, 60 minutes, 120 minutes, 180 minutes)

The DHW heating rate is calculated by Equation $\dot{q}_i = \frac{\dot{m}_i\left[\frac{gal}{min}\right]*60\left[\frac{min}{hour}\right]*8.4\left[\frac{lbm}{gallon}\right]*1\left[\frac{btu}{lbm-F}\right]*(T_{Storage}-T_{Main})}{\eta_{input}}$ (2).

$$\dot{q}_i = \frac{\dot{m}_i\left[\frac{gal}{min}\right]*60\left[\frac{min}{hour}\right]*8.4\left[\frac{lbm}{gallon}\right]*1\left[\frac{btu}{lbm-F}\right]*(T_{Storage}-T_{Main})}{\eta_{input}} \quad (2)$$

Where:

$\dot{q}_i$ is the DHW heating rate for the cumulative interval

$T_{Storage}$ is the water storage temperature (also called the water set point temperature)

T_{Main} is the water main temperature

η_{Input} is the weighted average efficiency of the existing DHW system

The water main temperature is taken from the average water main temperature for each climate zone from the DEER Water Heating Calculator [2].

The total storage tank volume is calculated using Equation$V_{storage,i} = \frac{V_{Total,i}}{0.7}$ (3)

$$V_{storage,i} = \frac{V_{Total,i}}{0.7} \quad (3)$$

Where:

$V_{stoage,i}$ is the total required storage tank capacity at each cumulative time interval assuming that only 70% of the storage tank water can be extracted

An example of this simplified method is given in the ASHRAE Handbook for a 58-unit apartment building [1]. The combinations of DHW input and storage tank volume from that example are shown below in Figure 20)

Figure 20: Combinations of DHW Input and Storage Volume for Multifamily from 2015 ASHRAE Handbook – HVAC Applications Example [1]

Table 8 Example 1, Simplified Method: Heating Rate and Storage Volume Options

Time, min	Gallons per Person	Total Gallons for 198 People	Average Gallons per Minute	Heating Rate, Btu/h	Storage Volume, gal
5	0.7	139	28	1,397,088	198
15	1.7	337	22	1,130,976	481
30	2.9	574	19	964,656	820
60	4.8	950	16	798,336	1358
120	8	1584	13	665,280	2263
180	11	2178	12	609,840	3111
1440	49	9702	7	339,570	13,860

The sizing tool calculates these DHW inputs and storage volumes at each cumulative time interval. See Figure 21 below.

Figure 21: DHW Inputs and Storage Volumes at Cumulative Time Intervals from Sizing Tool – Multifamily

Climate Zone	CZ10			
Usage factor	High			
Number of Units	500			
Number of Occupants	750	2.6 comes form RASS Table ES-2 pg 6 of Executive summary		
Water Set Point Temp [F]	140			
Water Main Temp [F]	66			
Existing Boiler Thermal Eff	85%			
Existing Storage Tank [gal]	500			
Boiler Size [btuh]	500,000			
DHW Load [btu/hr]	**4,747,456**			
Time [min]	Gal/Person	Gal/Min	Plant input [btuh]	Actual Hot water storage [gal]
5	1.2	120.0	5,223,529.4	1,286
15	3	100.0	4,352,941.2	3,214
30	5.1	85.0	3,700,000.0	5,464
60	8.5	70.8	3,083,333.3	9,107
120	14.5	60.4	2,629,902.0	15,536
180	19	52.8	2,297,385.6	20,357
DHW Sizing				
	Plant input [btuh]	Actual Hot Water Storage		
Actual	**4,747,456**	**500.00**		

The chart of time intervals, plant input, and hot water storage creates a curve where the combination of plant input and storage meet the load of the building. The actual hot water storage in the existing system falls somewhere on or beyond that curve. A linear interpolation is used to estimate the actual DHW input needed with the existing hot water storage in the system.

Other Building Types

For all other building types, the figures of recovery capacity vs. usable storage capacity were used to determine the DHW load. For some building types, the selection tool automatically calculates the recovery capacity using the actual usable storage capacity of the existing system. For the other building types, the tool automatically calculates the usage storage capacity per unit (bed, student, meal, etc.) but the user must enter the recovery capacity/unit.

Nursing Home and Office

The charts of recovery capacity vs. usage storage capacity were converted into a data table using online software that allows a user to pull data points off of the image of an uploaded chart. See

Figure 22 below for a Nursing home example.

Figure 22: Recovery Capacity vs. Usable Storage Capacity for Nursing Home from 2015 ASHRAE [1]

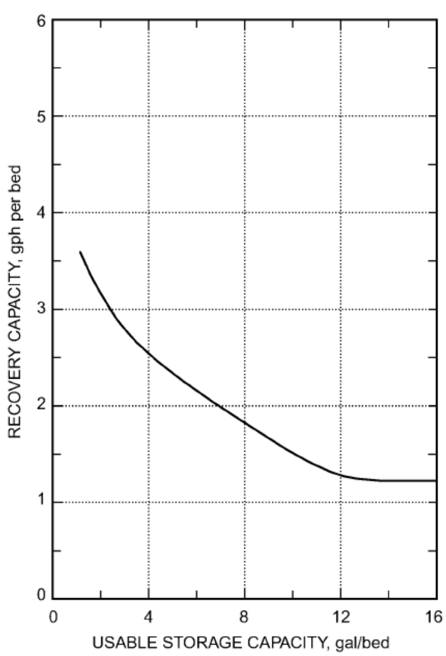


Fig. 18 Nursing Homes

Usable Storage Capacity [gal/bed	Recovery Capacity [gal/hr/bed]
1.16	3.58
2	3.15
4	2.5
6	2.1
8	1.8
10	1.5
12	1.3
14	1.21
16	1.22

The number of beds is entered into the selection tool on this tab and the usable storage capacity/bed is calculated by Equation *Usable_Storage_Capacity [Gallons/Bed] = Actual_Storage_Capacity * 70%* (4).

$$Usable\_Storage\_Capacity\ [Gallons/Bed] = Actual\_Storage\_Capacity * 70\% \quad \textbf{(4)}$$

Where:

Usable_Storage_Capacity is the usable storage capacity assuming that only 70% of the actual storage capacity is able to be withdrawn from the storage tanks.

Actual_Storage_Capacity is the total hot water storage capacity of the existing DHW system which is entered on the front page of the tool.

Figure 23 shows usable storage capacity per bed based on the inputs "Number of Beds" and "Storage Capacity." This actual usable storage capacity at the existing site falls somewhere on the chart of usable storage capacity vs. recovery capacity in

Figure 22. A linear interpolation is done to calculate the actual recovery capacity needed for the site based on the actual usage storage capacity based on the data in

Figure 22. See Figure 24 below for the example calculation of actual Usage Storage Capacity [gal/bed] based on actual Recovery Capacity [gal/hr/bed].

Figure 23: Nursing Home DHW Load Inputs – Usable Storage Capacity/Bed

Number of Beds	500
Storage Capacity	350
Usable Storage Capacity/Bed	0.7
Climate Zone	CZ10
Avg Water Temp	66
Set Point Temp	140
DHW Load [btu/hr]	**970,572.28**

Figure 24: Nursing Home Actual Required DHW Recovery Capacity

	Usable Storage Capacity [gal/bed	Recovery Capacity [gal/hr/bed]
Actual	**0.70**	**3.20**

The actual DHW load is calculated by Equation $\dot{q} = RC_{actual}\left[\frac{gallons}{hr-bed}\right] * \#beds * 8.2\left[\frac{lbm}{gallon}\right] * 1\left[\frac{btu}{lbm-F}\right] * (T_{storage} - T_{main})$ (5)

$$\dot{q} = RC_{actual}\left[\frac{gallons}{hr-bed}\right] * \#beds * 8.2\left[\frac{lbm}{gallon}\right] * 1\left[\frac{btu}{lbm-F}\right] * (T_{storage} - T_{main}) \quad \textbf{(5)}$$

Where:

$\dot{q}$ is the DHW load.

RC_{actual} is the actual required recovery capacity for the existing system using the existing usable storage capacity.

#beds is the number of beds in the facility.

$T_{Storage}$ is the water storage temperature (also called the water set point temperature).

T_{Main} is the water main temperature.

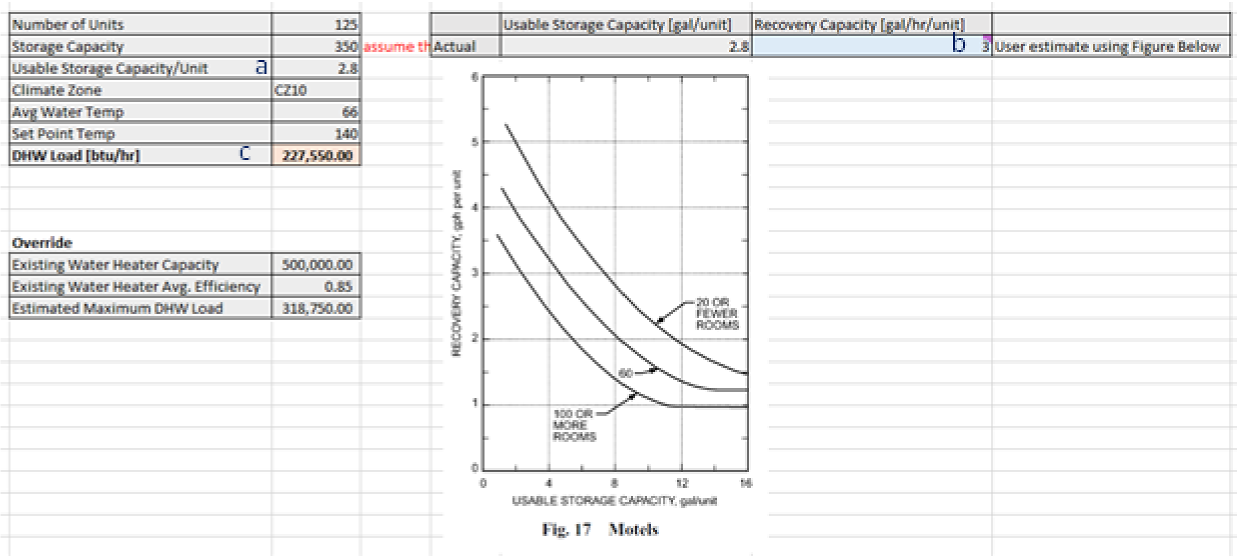
The water main temperature is taken from the average water main temperature for each climate zone from the DEER Water Heating Calculator [2].

This calculation is the same for the Office except the normalizing unit is people rather than beds.

Motel, Foodservice, Dormitory, Elementary School, High School

The same methodology is used for these building types as for Nursing Home and Office, except the user must estimate the recovery capacity using the provided figures. The figures of recovery capacity vs usable storage capacity have multiple lines. For example, motel has three lines (100+ units, 60 units and 20 units or less). In order to use the automatic linear interpolation, much more programming would have to be done because there are two criteria to match (number of units and usable storage capacity). Since the tool did not need to be fully automated, this additional effort was foregone. An example of how this works is shown below for a motel in Figure 25.

Figure 25: Calculation of DHW Capacity for a Motel [1]



Number of Units	125	
Storage Capacity	350	assume th
Usable Storage Capacity/Unit a	2.8	
Climate Zone	CZ10	
Avg Water Temp	66	
Set Point Temp	140	
DHW Load [btu/hr] c	227,550.00	

Override	
Existing Water Heater Capacity	500,000.00
Existing Water Heater Avg. Efficiency	0.85
Estimated Maximum DHW Load	318,750.00

	Usable Storage Capacity [gal/unit]	Recovery Capacity [gal/hr/unit]	
Actual	2.8	b 3	User estimate using Figure Below

a. Usable Storage Capacity/Unit is automatically calculated (2.8 gal/unit).

b. The corresponding recovery capacity from Figure 17 of the 2015 ASHRAE Handbook [1] is about 3.0 gallons/hour/unit.

c. 3.0 gallons/hour/unit is plugged into the recovery capacity and the DHW load is calculated using **Error! Reference source not found.**.

Space Heating Load

Once heating load is calculated, the tool calculates the percentage of capacity that the gas heat pump water heater serves as well as the percentage of hours/year that the gas heat pump water heater can serve the entire load. It is more likely that space heating may require temperatures greater than 135F, which means that the gas heat pump must operate with a condensing boiler or it must shut-off while a non-condensing boiler operates. The field test seeks to find sites where the run time of the gas heat pump water heater is maximized.

Design Heating Load

The total heating load at the design temperature is calculated by Equation $\dot{q}_{heating,Design} = \dot{q}_{heating,capacity} * \eta_{boiler} * 75\%$ (6)

$$\dot{q}_{heating,Design} = \dot{q}_{heating,capacity} * \eta_{boiler} * 75\% \quad (6)$$

Where:

$\dot{q}_{heating,design}$ is the heating load at the design outdoor air temperature.

$\dot{q}_{heating,capacity}$ is the total space heating boiler capacity.

$\dot{\eta}_{boiler}$ is the average efficiency of the space heating boilers.

The factor of 75% is an assumption that the space heating boilers are 25% oversized to account for losses and a factor of safety.

Hourly Heating Load

The heating load at the design condition is used to calculate the hourly heating using Equation $\dot{q}_{heating,hourly} = \dot{q}_{heating,design} \frac{65F - T_{amb}}{65F - T_{design}}$ (7).

$$\dot{q}_{heating,hourly} = \dot{q}_{heating,design} \frac{65F - T_{amb}}{65F - T_{design}} \quad (7)$$

Where:

$\dot{q}_{heating,hourly}$ is the hourly heating load.

T_{amb} is the hourly ambient outside air temperature.

T_{desgin} is the design temperature entered on the Front Page.

65°F is the reference temperature. It is assumed that no heating is required above this outdoor ambient air temperature.

T_{amb} values come from DEER models for each climate zone.

Combination Load

The combination load is the DHW load added to the space heating load. The calculations for the space heating load are summarized in the section above. All that remains is the DHW load.

DHW Daily Load Profile

The 2015 ASHRAE Handbook – HVAC Fundamentals [1] gives charts for the average hourly DHW usage each hour of the day for several building types (reference). These charts were loaded into an online software tool that allows a user to extract data points from an image of a chart. The hourly average water usage (gallons) for each building type in the tool were extracted. The total average daily usage was summed and the hourly percentage usage was calculated. For Multifamily, the “Typical Families” data series was used and for all other building types the "Average of All Days During Tests" series was used. See Figure 26 and Figure 27 for Multifamily and Nursing Homes for examples.

Figure 26: Multifamily DHW Daily Load Profile [1].

Total Gallons/da	63.44	
Hour	Avg Hrly Use [gal]	% Daily Usage
1	0.76	1%
2	0.31	0%
3	0.2	0%
4	0.16	0%
5	0.12	0%
6	0.27	0%
7	0.98	2%
8	4.43	7%
9	4.74	7%
10	5.76	9%
11	4.57	7%
12	3.76	6%
13	3.31	5%
14	3.15	5%
15	2.47	4%
16	2.19	3%
17	2.41	4%
18	2.64	4%
19	3.43	5%
20	4.8	8%
21	4.13	7%
22	3.49	6%
23	2.76	4%
24	2.6	4%

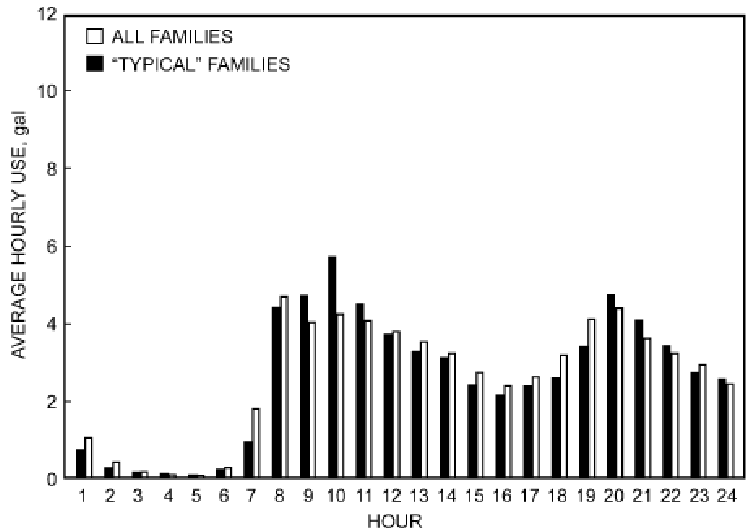
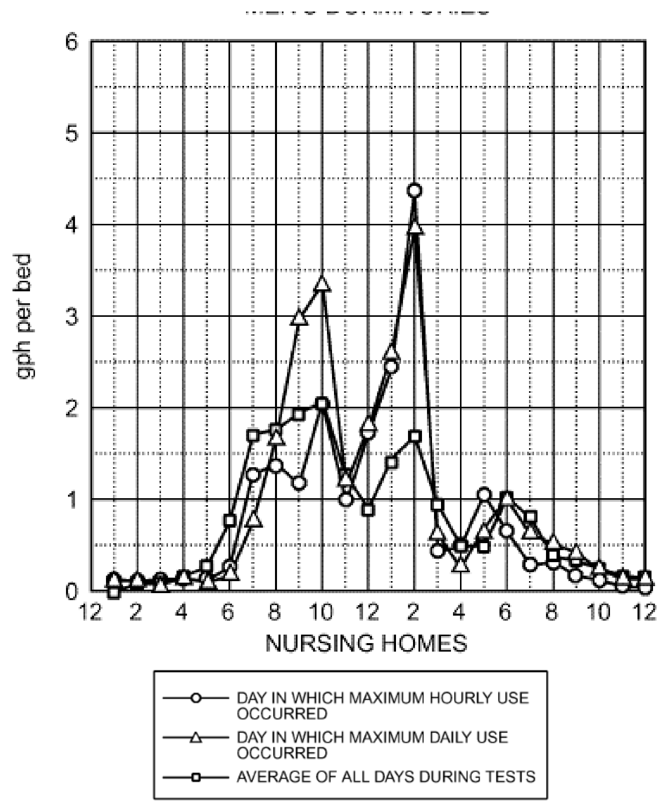


Fig. 11 Residential Average Hourly Hot-Water Use

Figure 27: Nursing Home DHW Daily Load Profile [1]

Total Gallons/day	19.28	
Hour	Avg Hrly Use [gal]	% Daily Usage
1	0	0%
2	0.12	1%
3	0.17	1%
4	0.15	1%
5	0.29	2%
6	0.77	4%
7	1.68	9%
8	1.76	9%
9	1.91	10%
10	2.05	11%
11	1.28	7%
12	0.89	5%
13	1.41	7%
14	1.68	9%
15	0.95	5%
16	0.49	3%
17	0.48	2%
18	1.03	5%
19	0.81	4%
20	0.42	2%
21	0.33	2%
22	0.26	1%
23	0.18	1%
24	0.17	1%



Average Daily DHW Use

The hourly DHW load is calculated using Equation $\dot{q}_{DHW,hourly} = V_{Daily} * \%Daily\ Usage_{hourly}$ (8)

$$\dot{q}_{DHW,hourly} = V_{Daily} * \%Daily\ Usage_{hourly} \tag{8}$$

<u>Where:</u>

$\dot{q}_{DHW,hourly}$ is the hourly DHW load.

V_{Daily} is the total daily average gallons used for that building.

%Daily Usage$_{hourly}$ is the hourly percentage of DHW used for that building type as calculated from the ASHRAE data.

V_{Daily} is entered in the front page and is estimated using the Average Daily Hot Water Demands from Table 6 from the 2015 ASHRAE Handbook – HVAC Applications Chapter 50 Section 9 [1] which is shown again below in

Figure 28.

Figure 28: Hot Water Demand and Use for Various Types of Buildings [1]

Table 6 Hot-Water Demands and Use for Various Types of Buildings*

Type of Building	Maximum Hourly	Maximum Daily	Average Daily
Men's dormitories	3.8 gal/student	22.0 gal/student	13.1 gal/student
Women's dormitories	5.0 gal/student	26.5 gal/student	12.3 gal/student
Motels: Number of units[a]			
20 or less	6.0 gal/unit	35.0 gal/unit	20.0 gal/unit
60	5.0 gal/unit	25.0 gal/unit	14.0 gal/unit
100 or more	4.0 gal/unit	15.0 gal/unit	10.0 gal/unit
Nursing homes	4.5 gal/bed	30.0 gal/bed	18.4 gal/bed
Office buildings	0.4 gal/person	2.0 gal/person	1.0 gal/person
Food service establishments			
Type A: Full-meal restaurants and cafeterias	1.5 gal/max meals/h	11.0 gal/max meals/day	2.4 gal/average meals/day[b]
Type B: Drive-ins, grills, luncheonettes, sandwich, and snack shops	0.7 gal/max meals/h	6.0 gal/max meals/day	0.7 gal/average meals/day[b]
Apartment houses: Number of apartments			
20 or less	12.0 gal/apartment	80.0 gal/apartment	42.0 gal/apartment
50	10.0 gal/apartment	73.0 gal/apartment	40.0 gal/apartment
75	8.5 gal/apartment	66.0 gal/apartment	38.0 gal/apartment
100	7.0 gal/apartment	60.0 gal/apartment	37.0 gal/apartment
200 or more	5.0 gal/apartment	50.0 gal/apartment	35.0 gal/apartment
Elementary schools	0.6 gal/student	1.5 gal/student	0.6 gal/student[b]
Junior and senior high schools	1.0 gal/student	3.6 gal/student	1.8 gal/student[b]

*Data predate modern low-flow fixtures and appliances. [a]Interpolate for intermediate values. [b]Per day of operation.

Total Load

The total hourly load for a combination system is calculated using Equation $\dot{q}_{Total,Combi,hourly} = \dot{q}_{DHW,hourly} + \dot{q}_{heating,hourly}$ (9)

$$\dot{q}_{Total,Combi,hourly} = \dot{q}_{DHW,hourly} + \dot{q}_{heating,hourly} \quad (9)$$

<u>Where:</u>

$\dot{q}_{Total,Combi,hourly}$ is the total hourly space heating and DHW load for the combination system.

Gas Heat Pump Capacity

Gas Heat Pump Capacity

Next, the capacity of the gas heat pump water heater is calculated using an Index-Match function that looks up the hourly capacity based upon the ambient outside air temperature and the hourly water outlet temperature. <u>The capacity data is provided by the manufacturer.</u>

The tool uses an IF statement to determine if the gas heat pump water heater can meet the space heating capacity each hour. The tool then sums up the total number of hours where the gas heat pump water heater can meet the hourly heating load.

Gas Heat Pump Outlet Temperature

If the gas heat pump water heater will only augment the space heating load, the water outlet temperature is calculated as a function of the outdoor air temperature. The maximum water outlet temperature is the water set point temperature at the design outdoor air temperature. The minimum water outlet temperature is the water set point temperature at the maximum ambient temperature for heating. The water outlet temperature is a linear interpolation between these two points.

If the gas heat pump water heater will augment both DHW and space heating, it is assumed that the outlet water temperature is always set to the DHW storage temperature entered on the Front Page.

Appendix II Generic M&V Plan and CO_2 Analysis

This section gives the details of the generic M&V plan and CO_2 analysis that will be used at the sites in Phase 2F and 3F. A site-specific M&V plan will be created for each individual site based upon the generic plan presented in this project.

Technology Intent

The goal of this generic Measurement & Verification (M&V) plan is to,

1. Provide the monitoring deployment and calculation strategy to determine the natural gas energy (therms) savings potential of the GAHP over existing/industry-standard systems across different targeted sites.
2. Additionally, data collection and calculation methodologies will be designed to determine system level operational efficiency improvement at full- and part-load (seasonal) efficiencies (COP), from the GAHP system over an existing boiler/domestic hot water system. Determined efficiency values (COP) will be correlated as a function of the outside air temperature to build System and Unit performance curves under normal operating conditions[3]
3. Quantify the added electrical loads from additional GAHP system components, such as the condenser fan, refrigerant circulation pump, and water/glycol circulation pump that have not been extensively documented for installed gas heat pump systems.
4. Collect site data for further developing and updating Measure Packages. This information will include system costs, as well as design and installation challenges encountered during the project.
5. Collect and analyze the site's load and related outside air temperature to be utilized as a part of a follow-up analysis where the existing system, GAHP and a hypothetical equally sized electric ASHP system source and site carbon-related emissions are analyzed and compared.

Although the sizing and layout of the different systems may change across sites, the expected baseline and proposed installation systems are described below:

Pre-Installation System: The pre-installation (existing) systems analyzed are expected to be one of the following types and combinations:

[3] Pilot Phase 2L will determine performance curves in more detail with a controlled environment under standard operating conditions.

1) The baseline system is comprised of a combination of solely one or more non-condensing Domestic Hot Water (DHW) heaters/boilers and/or Hot Water (HW) space heating boilers, with at or above code compliant efficiency values and sized for the building's peak DHW load and/or space heating load. These systems may be coupled with constant volume recirculation pumps for DHW and constant volume primary HW pumps for HW heating.
2) The baseline system is comprised of a combination of solely one or more condensing DHW heaters and/or HW space heating boilers sized for the building's peak DHW load and/or space heating load. These systems could be coupled with constant volume recirculation pumps for DHW and constant volume primary HW pumps for HW heating.

Post-Installation System: The post-installation systems analyzed are expected to be one of the following types and combinations, operating in the following operational modes:

1) The new system is comprised solely of one or more GAHPs which are sized for the peak hot water load of the building. The system may cycle one or more units OFF when the difference in supply and return temperature is too low.
2) The new system is comprised of one or more gas heat pump water heaters, in parallel, and integrates with the existing water heaters and/or boilers. If the existing boilers/water heaters are not condensing efficiency boilers, the gas heat pump water heaters do not run at the same time as the boilers. This is due to two main causes,
3) The Gas heat pump water heaters have maximum return/inlet temperature limits (i.e., the maximum inlet water temperature limit is 122°F)
4) The output water temperature of the gas heat pump water heaters is too low to run at the same time as a non-condensing boiler/water heater. Therefore, when the load of the building is higher than the gas heat pump water heater(s) or the required supply water temperature exceeds what the gas heat pump water heater can provide, the controls system shuts down the gas heat pump water heater(s) and turns ON the existing boilers. This integration primarily allows for higher part load efficiencies for the GAHP water heater and to switch to an existing water heater at peak loads.
5) The new system is comprised of one or more gas heat pump water heaters and integrates with new condensing efficiency water heaters and/or boilers. Condensing efficiency water heaters/boilers can run at lower supply water temperatures, so they can run at the same time as the gas heat pump water heaters. In this case, when the hot water load is low and the supply temperature requirements are within the GAHP

supply temperature limits, the control system will turn on the condensing water heater/boiler(s), and both run at the same time.

The tandem system configurations, which may be arranged in series or parallel, depending on the site characteristics, could require additional design and installation requirements, such as integrating the control of the existing DHW and/or space heating recirculation pumps, adding heat exchangers and control valves for fluid mixing prevention and appropriate temperature control, or re-piping to account for the new system layout. During higher load periods, maximum return/inlet temperature limit will be taken into consideration to enable the simultaneous operation of the two (2) systems. This may require additional engineering for space heating systems with supply water temperature advanced controls, such as OAT enabled resets.

Selected IVMVP Option and Testing Details

The selected IPMVP option for this project is Option B – Retrofit Isolation: All Parameter Measurement. For this option, savings are determined by measurement of all performance parameters which define the energy use and efficiency of the measure's affected system.

The seasonal performance and energy consumption values of the GAHP product and baseline existing systems will be characterized during "real world" operation in the sites where installed. During this real load operation, GAHP combination systems are expected to meet space and/or water heating loads, with water heating being the priority. Nevertheless, for each site, a series of operating points established by the standardized testing approach based on the North American rating method (CSA/ANSI Z21.40.4) [6] and on a gas heat pump example laboratory evaluation plan provided by Gas Technologies Institute[4] (GTI) [7] will be identified and used in the system's efficiency and energy consumption calculations. This test method covers a wide range of unitary gas-fired technologies, including engine-driven, desiccant/adsorption-driven, and absorption-driven cycles. Data from these rating points will be used to record seasonal performance metrics, including seasonal efficiency, and estimated annual gas and electric energy consumption at homogeneous conditions across different sites and system layouts. These points will be defined for each installation via a site-specific M&V Plan. The points will depend on the Climate Zone, layout, load, and operation characteristics of each installation.

Although defined as part of this document, the implementation of the data collection and analysis methodology described in the following sections will vary depending on the location and layout of the installed system.

[4] This plan provided by GTI to the Study Team via e-mail. Not a public document.

Baseline and Post: Period, Energy & Conditions

Baseline & Post Data Period

The data logging period is defined to be long enough to represent a full range of operating conditions for both the baseline and installed cases.

The baseline M&V duration has been chosen to at least cover a period of 4 weeks to accurately calculate the in-place system efficiencies, with sufficient data. The post-M&V period will last until the recorded weather factors (dry-bulb temperature) cover 110% of the maximum and 90% of the minimum values of temperature values used to normalize the proposed system model's operational curves (load and efficiency). This is in accordance with ASHRAE Guideline 14 [8]. In combination, the baseline and post-M&V periods will be at least sufficient to fulfill the weather coverage requirements and will be at least 12 months to encompass the yearly fluctuations in hot water demand that may not be captured by the weather coverage factor.

The normalized temperature conditions will be represented by the appropriate CZ2022 Weather data for each specific project's location and utilized to normalize the final energy consumption and efficiency curve values.

Measurement Points and Frequency

Tables 1 and 2 below show the details of the measurement points and the frequency of the measurements. **Error! Reference source not found.** and **Error! Reference source not fo und.** show the prototype schematic of the pre-installation and post-installation combination of DHW and HW systems. A combination heating and domestic hot water system is shown, but if the GAHP system at the actual site will not augment either a HW or DHW loop, no parameters for non-augmented loops will be measured in either pre or post-installation.

Figure 29: Pre-Installation Combination System Prototype Schematic

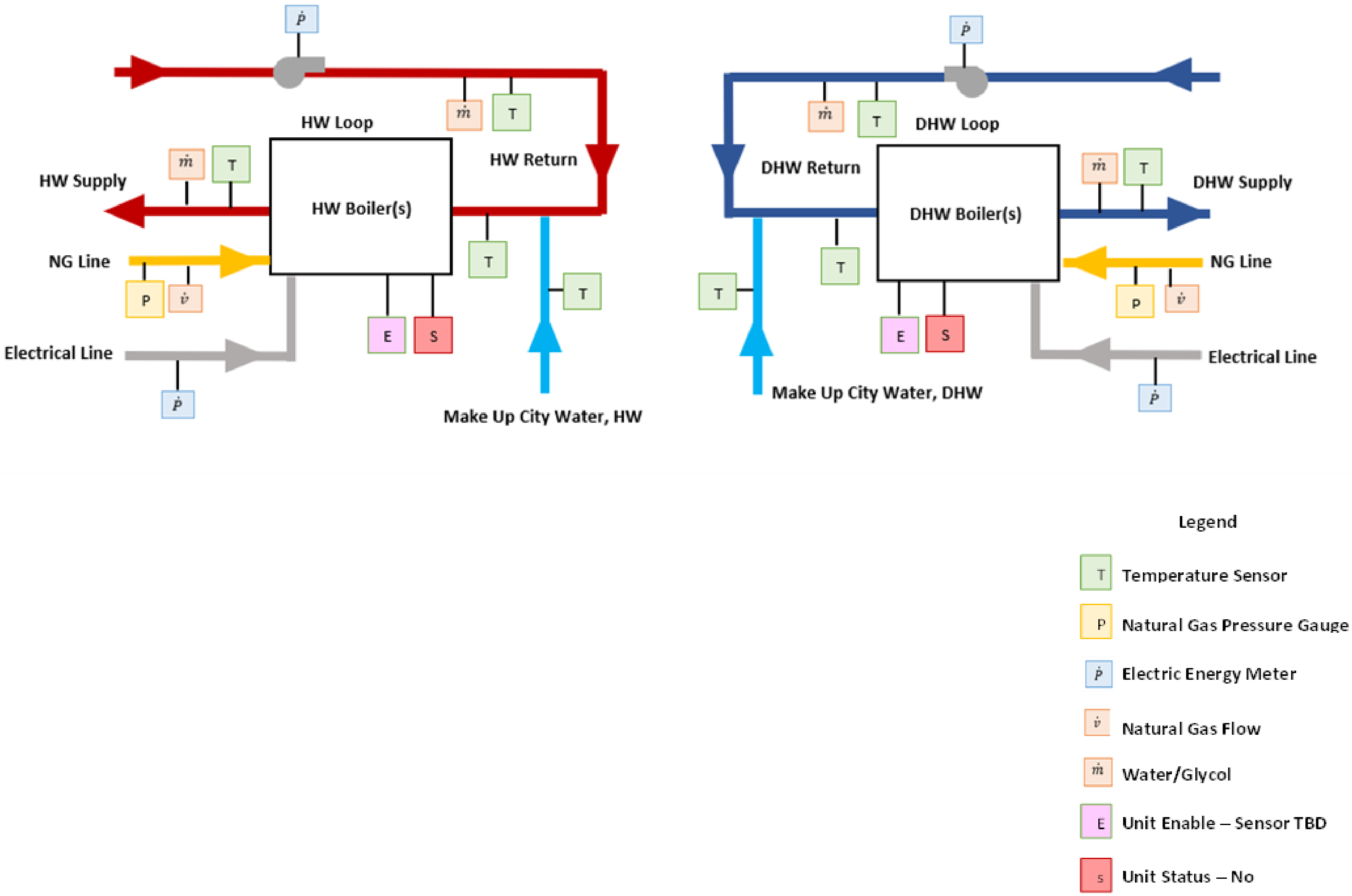


Table 1: Pre-Installation M&V Data

Measurement Type	Measurement Point	Unit	Metering Equipment/Source	Measurement Notes	Interval & Duration
Continuous Measurement	DHW Supply Temp	°F	Omega TJ36 Thermocouple		Interval: minimum of 15 minutes (desired 1- or 5-minute timestamps) Data approach – Timestamp Averaging Duration: minimum of 4 weeks.
	HW Supply Temp	°F	Omega TJ36 Thermocouple		
	DHW Return Temp	°F	Omega TJ36 Thermocouple	Additional measurement points are to be located by Boiler/DHW intake if the Make-up Water System operation is significant or if the system meets both loads.	
	HW Return Temp	°F	Omega TJ36 Thermocouple		
	DHW Supply Water Flow	Gallons	Omega Engineering FTB8020HW-PT + Onset S-UCD-M006 Module		
	HW Supply Water Flow	Gallons	Omega Engineering FTB8020HW-PT + Onset S-UCD-M006 Module		
	DHW Return Water Flow	Gallons	Omega Engineering FTB8020HW-PT + Onset S-UCD-M006 Module	Measurement deployment contingent on if Make-Up Water System operation is significant.	
	HW Return Water Flow	Gallons	Omega Engineering FTB8020HW-PT + Onset S-UCD-M006 Module		
	Make Up Water Temp	°F	Omega TJ36 Thermocouple	Measurement deployment contingent on if Make-Up Water temperature site variance is significant.	
	DHW Natural Gas – Fuel Input	Cubic Feet	AL-425 Natural - Gas Flow Meter (Temperature Compensated) + Onset S-UCD-M006 Module		
	HW Natural Gas – Fuel Input	Cubic Feet	AL-425 Natural - Gas Flow Meter (Temperature Compensated) + Onset S-UCD-M006 Module		
	DHW Circulator Pump Current	Amps	Continental Control Systems CTML-0350-05 Split Core CT + Onset S-FS-TRMSAD Module		

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Measurement Type	Measurement Point	Unit	Metering Equipment/Source	Measurement Notes	Interval & Duration
	HW Circulator Pump Current	Amps	Continental Control Systems CTML-0350-05 Split Core CT + Onset S-FS-TRMSAD Module		
	DHW Power	kWh	WattNode 208/240/480 VAC 3-phase Delta/Wye kWh + Dent CT-HSC-020- U Split Core CTs Onset S-UCC-M006	Measurement deployment contingent on Blower size and operation. If not variable speed operation - Manual measurement during installation of data loggers by a licensed electrician.	
	Boiler Power	kWh	WattNode 208/240/480 VAC 3-phase Delta/Wye kWh + Dent CT-HSC-020- U Split Core CTs Onset S-UCC-M006		
	DHW Status	-	DHW Amp draw captured by DHW Power measurement equipment		
	Boiler Status	-	Boiler Amp draw captured by Boiler Power measurement equipment		
	DHW Enable	-	TBD based on Existing System		
	Boiler Enable	-	TBD based on Existing System		
	Outside Air Temperature	°F	RXW-THC-B-900	To be located as close as possible to a North facing wall or provided with a protective screen	
	Outside Air Humidity	%RH	RXW-THC-B-900		
Batch Measurement	Natural Gas – Line Pressure(s)	Psig	Manual measurement during installation of data loggers by a licensed electrician	Measurement deployment contingent on Natural Gas Meter Location. If located downstream of natural gas regulator, pressure compensation is not required.	
	Circulator pump Voltage(s)	V	Manual measurement during installation of data loggers by licensed electrician or assume based on number of phases		

Measurement Type	Measurement Point	Unit	Metering Equipment/Source	Measurement Notes	Interval & Duration
3rd Party Data	Barometric Pressure	Psia	Nearest Weather Station Data		
	Natural Gas High Heating Value (HHV)	Btu/ft3	Monthly SCG Gas Bills		

Please note the Pre-Installation M&V Data measurement points may be subject to modification based on the existing system layout or observed operation. The site-specific M&V plan for each specific installation will include any potential changes to measurement data points, or measurement equipment in case it is required to be changed due to similar reasons.

Figure 30: Post-Installation Combination Prototype System Schematic

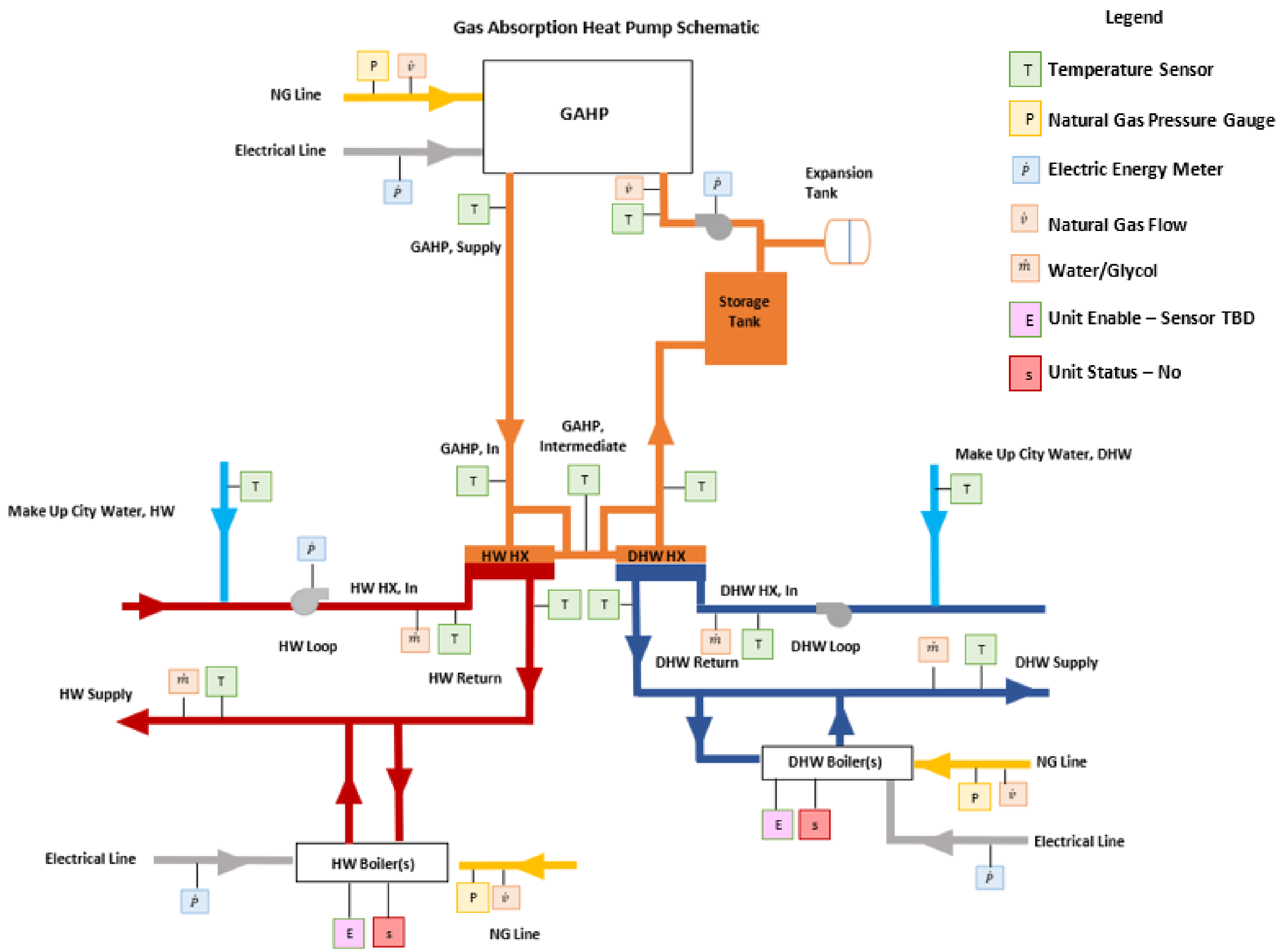


Table 2: Post-Installation M&V Plan

Measurement Type	Measurement Point	Unit	Metering Equipment/Source	Measurement Notes	Interval & Duration
Continuous Measurement	DHW Supply Temp	°F	Omega TJ36 Thermocouple		Interval: minimum of 15 minutes (desired 1- or 5-minute timestamps) Data approach – Timestamp Averaging Duration: minimum of 4 weeks.
	HW Supply Temp	°F	Omega TJ36 Thermocouple		
	DHW Return Temp	°F	Omega TJ36 Thermocouple	Additional measurement points are to be located by Boiler/DHW intake if the Make-up Water System operation is significant or if the system meets both loads.	
	HW Return Temp	°F	Omega TJ36 Thermocouple		
	DHW Heat Exchanger, In Temp	°F	Omega TJ36 Thermocouple		
	HW Heat Exchanger, In Temp	°F	Omega TJ36 Thermocouple	Additional Temperature Measurements will be considered based on the number of HX in the proposed system.	
	HW Heat Exchanger, Out Temp	°F	Omega TJ36 Thermocouple		
	GAHP Supply Temp	°F	ProSense XTP25N-100-0100C	Additional Temperature Measurements will be considered to account for losses due to the length of Supply piping.	
	GAHP Return Temp	°F	ProSense XTP25N-100-0100C		
	GAHP Intermediate Temp	°F	ProSense XTP25N-100-0100C		
	DHW Supply Water Flow	Gallons	Omega Engineering FTB8020HW-PT + Onset S-UCD-M006 Module		

Measurement Type	Measurement Point	Unit	Metering Equipment/Source	Measurement Notes	Interval & Duration
	HW Supply Water Flow	Gallons	Omega Engineering FTB8020HW-PT + Onset S-UCD-M006 Module		
	DHW Return Water Flow	Gallons	Omega Engineering FTB8020HW-PT + Onset S-UCD-M006 Module		
	HW Return Water Flow	Gallons	Omega Engineering FTB8020HW-PT + Onset S-UCD-M006 Module		
	Make Up Water Temp	°F	Omega TJ36 Thermocouple	Measurement deployment contingent on Make-Up Water temperature site variance is significant.	
	GAHP Water/glycol Flow	Gallons	Omega Engineering FTB8020HW-PT + Onset S-UCD-M006 Module		
	DHW Natural Gas – Fuel Input	Cubic Feet	AL-425 Natural - Gas Flow Meter (Temperature Compensated) + Onset S-UCD-M006 Module		
	HW Natural Gas – Fuel Input	Cubic Feet	AL-425 Natural - Gas Flow Meter (Temperature Compensated) + Onset S-UCD-M006 Module		
	GAHP Natural Gas Fuel Input	Cubic Feet	AL-425 Natural - Gas Flow Meter (Temperature Compensated) + Onset S-UCD-M006 Module		

Measurement Type	Measurement Point	Unit	Metering Equipment/Source	Measurement Notes	Interval & Duration
	DHW Circulator Pump Current	Amps	Continental Control Systems CTML-0350-05 Split Core CT + Onset S-FS-TRMSAD Module		
	HW Circulator Pump Current	Amps	Continental Control Systems CTML-0350-05 Split Core CT + Onset S-FS-TRMSAD Module		
	GAHP Circulator Pump Current	Amps	Continental Control Systems CTML-0350-05 Split Core CT + Onset S-FS-TRMSAD Module		
	GAHP Power	kWh	WattNode 208/240/480 VAC 3-phase Delta/Wye kWh + Dent CT-HSC-020- U Split Core CTs Onset S-UCC-M006		
	DHW Power	kWh	WattNode 208/240/480 VAC 3-phase Delta/Wye kWh + Dent CT-HSC-020- U Split Core CTs Onset S-UCC-M006	Measurement deployment contingent on Blower size and operation. If not variable speed operation – Manual measurement during installation of data loggers by a licensed electrician.	
	Boiler Power	kWh	WattNode 208/240/480 VAC 3-phase Delta/Wye kWh + Dent CT-HSC-020- U Split Core CTs Onset S-UCC-M006		
	GAHP Status	-	DHW Amp draw captured by GAHP Power measurement equipment		
	DHW Status	-	DHW Amp draw captured by DHW		

Measurement Type	Measurement Point	Unit	Metering Equipment/Source	Measurement Notes	Interval & Duration
			Power measurement equipment		
	Boiler Status	–	Boiler Amp draw captured by Boiler Power measurement equipment		
	GAHP Enable	–	Provided by Manufacturer's DDC system		
	DHW Enable	–	TBD based on Existing System		
	Boiler Enable	–	TBD based on Existing System		
	Outside Air Temperature	°F	Onset HOBO MX2302A	To be located as close as possible to a North facing wall or provided with a protective screen	
	Outside Air Humidity	%RH	Onset HOBO MX2302A		
Batch Measurement	Natural Gas – Line Pressure(s)	Psig	Manual measurement during installation of data loggers by a licensed plumber		
	Circulator pump Voltage(s)	V	Manual measurement during installation of data loggers by licensed plumber or assume based on number of phases		
3rd Party Data	Barometric Pressure	Psia	Nearest Weather Station Data		
	Natural Gas High Heating Value (HHV)	Btu/ft3	Monthly SCG Gas Bills		

Please note the Post-Installation M&V Data measure points may be subject to modification based on the final proposed system layout or operation. The site-specific M&V Plan for each specific installation will include any potential changes to measurement data points, or measurement equipment in case it is required to be changed due to similar reasons.

In addition, the GAHP unit(s) will be specified to be provided with a remote monitoring device, which connects to the GAHP's DDC controller, and provides real-time operational data of this system, including:

1. Refrigerant temperatures
2. Water/Glycol GAHP Supply Temperature
3. Water/Glycol GAHP Return Temperature
4. Outdoor Temperature
5. Run time information
6. Burner on-off cycles
7. Error & warning codes

While the objective of the M&V Team is to utilize the information provided by the GAHP DDC system as a redundant data source, in case of a data loss or data communication issues, it is possible that specific installations could use these measurement points as the main source of data, depending on the final cost or installation feasibility of the M&V equipment.

Details of Adjustments Necessary for Gas Input Values

Diaphragm gas meters will be installed to monitor the volumetric gas flow (cubic foot pulses) into the absorption heat pumps, conventional boilers, and water heaters. All meters will be pressure and temperature-compensated and equipped with electronic pulse output. The monthly natural gas High Heating Value (HHV) will be obtained from the gas utility bill and adjusted for line pressure to account for the pressure of the installation gas meters.

Metering Instrumentation Specifications

Meter Specifications

Table 3 includes the meter specifications.

Table 3: Meter Specifications

Metering Equipment	Measurement	Unit	Range	Accuracy
Omega TJ36 Thermocouple	Temperature	°F	32° to 600°F	<±0.4% from -52° to 600°F
ProSense XTP25N-100-0100C	Temperature	°F	-52° to 302°F	±0.81°F
Omega Engineering FTB8020HW-PT + Onset S-UCD-M006 Module	Water/Glycol Flow	GPM	0.22 to 132 GPM 194°F Maximum Operating Temperature	<±1.5% of reading

Metering Equipment	Measurement	Unit	Range	Accuracy
AL-425 Natural Gas Flow Meter + Onset S-UCD-M006	Natural Gas Flow	Cubic Feet	0.25 PSIG – 425 SCGH 25 PSIG – 1462 SCFH	N/A
Onset T-VERE50B2 Real Power Meter + Dent CT-HSC-020-U Split Core CTs Onset S-UCC-M006	Energy Input	kWh	90-600VAC – Wye or Delta configurations	Meter: ±0.5% CTs: <0.5% from 0.25 to 40A
Continental Control Systems CTML-0350-05 Split Core CT + Onset S-FS-TRMSAD Module	Electrical Current	Amps	5 amps to 70 amps	±1% from 10 to 100% Rated Current
Onset HOBO RXW-THC-900	Temperature Humidity	°F %RH	-40°F to 167°F 0–100% RH at 40°F to 167°F	±0.45°F from -40° to 32°F ±0.36°F from 32° to 158°F ±0.45°F from 158° to 167°F) ±2.5% from 10% to 90% RH
Onset RX3000 Remote Monitoring Station	Data Logging Station		15 data sensors -40°F to 140°F	
RX3000 4-channel Analog Module	Data Logging Station Extension			0–25.6 mA DC, ±5 μA ± 0.15% of reading
WebDAQ 316 Internet Enabled Thermocouple Data Logger	Thermocouple Data Logging Station		16 Thermocouple 4 Digital I/O Ethernet communication	

Meter Reading

Data will be automatically transmitted to a cloud server created by a remote data logging station that will be deployed on the site and that will allow for instant access, through the internet, to all sensor values. A scheduled automated delivery of data overnight will be set up, as well as alarm notifications and system status notifications. Connection to this station will be provided through cellular, ethernet, or Wi-Fi-powered networks, depending on each site's connection capabilities. In-person site visits might be exceptionally performed to access and download the data locally due to a major connection loss or any other data connectivity or technical challenge.

Calibration Information

All data sensors that will be used will be provided with original manufacturer calibration certificates.

Lost Data

During the M&V period, all data signals will be checked to ensure they are operating and reporting correctly. Should an alarm appear in the monitoring system that alerts from possible data loss for any measurement point, adequate staff will be deployed on-site to investigate and provide a resolution to the incident, and the following data treatment process will be followed:

1. If the data loss affects measurement values that are not key for the M&V process (i.e., Outdoor Humidity), then no further action will be performed, and the calculation methodology will remain intact.
2. If the data loss affects key measurement values in the Calculation Methodology, then two possible actions may be performed as follows:
    a. If redundancy for these lost measurements exists, either from a redundant or a similar and near sensor, then the compromised data will be replaced by its redundant readings. Appropriate adjustments will be made to ensure the database timestep reference is not at risk during this process.
    b. If redundancy does not exist for these lost measurements, all data from that period will not be used in the data analysis.

In addition, one additional verification will be performed to assure the integrity of the collected data sets. The data will be evaluated to identify and adjust for non-routine events. These events are defined as events within the building, occurring outside of the project's installed energy efficiency measures' scope, that affect the system's load and therefore energy use measured at the meter. If detected, adjustments to baseline energy use are necessary so that the resulting computed normalized savings are due to the project's installed energy efficiency measures, and not due to other events that affect the energy use at the meter.

Monitoring Responsibilities

All data sensors (except temperature sensors) will be installed by a qualified licensed contractor. Data sensor will be hooked up to data logger by the M&V Team, and data logger will be installed by the M&V Team. The logged data will be downloaded and analyzed by the M&V Team by accessing the Data Logging System cloud server. Exceptional site visits shall be performed to download the data locally if necessary due to a major connection loss or any other data connectivity challenge. This will be determined on a site-specific basis.

Analysis Procedure – Energy and Efficiency

Spreadsheet calculations will be performed to calculate the DHW and SHW load of each building where the GAHP will be implemented, as well as pre and post-installation energy usage, and operational efficiency for each case. The annual energy savings are expected to be created from the proportion of SHW and/or DHW loads, depending on the design of the pre-and post-systems, that the GAHP will offset at a higher operational efficiency.

The following equations and steps will be used in the calculations, and will assume a combination system:

Existing System:

1) Determine the existing system DHW and SHW system's efficiency using the baseline temperature supply and return, water, flow, and natural gas input on each of the systems. The following parameters will be calculated:

$$HeatOutput_{DHW/Boiler}\left[\frac{BTU}{hr}\right] = \dot{Q}_{DHW/HW\ Boiler} = \dot{Q}_{supply} - \dot{Q}_{Make-Up} - \dot{Q}_{Return} \quad \textbf{(10)}$$

$$\dot{Q}_{supply} = \dot{v}_{water,supply} * \rho_{water} * \bar{c}_{water} * \left(T_{Supply} - T_{ref}\right) \quad \textbf{(11)}$$

$$\dot{Q}_{Return} = \dot{v}_{water,return} * \rho_{water} * \bar{c}_{water} * \left(T_{return} - T_{ref}\right) \quad \textbf{(12)}$$

$$\dot{Q}_{Make-Up} = \dot{v}_{water,make-up} * \rho_{water} * \bar{c}_{water} * \left(T_{make-up} - T_{ref}\right) \quad \textbf{(13)}$$

$$\dot{v}_{water,make-up} = \dot{v}_{water,supply} - \dot{v}_{water,return} \quad \textbf{(14)}$$

$$Gas\ Input\left[\frac{BTU}{h}\right] = \dot{Q}_{in\ DHW/Boiler} = \dot{v}_{NG_{DHW/Boiler}} * HHV * \frac{P_{bar}+P_{line}}{P_s} \quad \textbf{(15)}$$

$$Electricity\ Input_{DHW/HW}\ [kW] = \dot{P}_i + \dot{P}_B = \sum Circulator\ Pumps\ Power\ Input\ +\ \dot{P}_B$$
$$= \sum Amps_{CP} * Volts_{CP}\ +\ \sum Boiler/DHW_{kW} * S_{Boiler/DHW} \quad \textbf{(16)}$$

$$COP_{DHW/Boiler_g} = \frac{Energy\ Output_{DHW/Boiler}}{Energy\ Input_{DHW/Boiler}} = \frac{Heat\ Output_{DHW/Boiler}*\Delta t}{Gas\ Input_{DHW/Boiler}*\Delta t} \quad \textbf{(17)}$$

$$COP_{DHW/Boiler} = \frac{Energy\ Output_{DHW/Boiler}}{Energy\ Input_{DHW/Boiler}} = \frac{Heat\ Output_{DHW/Boiler}*\Delta t}{(Gas\ Input_{DHW/Boiler}+Electricity\ Input_{DHW/Boiler})*\Delta t} \quad \textbf{(18)}$$

$$COP_{Sys} = \frac{Energy\ Output_{DHW} + Energy\ Output_{Boiler}}{Energy\ Input_{DHW} + Energy\ Input_{Boiler}} = \frac{(Heat\ Output_{DHW}+Heat\ Output_{Boiler})*\Delta t}{((Gas\ Input+Electricity\ Input)_{DHW} + (Gas\ Input+Electricity\ Input)_{Boiler})*\Delta t} \quad \textbf{(19)}$$

<u>Where:</u>

$\dot{v}_{water}$ is the volumetric flow of water, in GPM.

ρ_{water} is the density of water in $\frac{lb}{gallon}$, 8.33 $\frac{lb}{gallon}$ at 65°F, 8.22 $\frac{lb}{gallon}$ at 135°F.

$\bar{c}_{water}$ is the specific heat of water in $\frac{BTU}{lb-°F}$, 1 $\frac{BTU}{lb-°F}$ at 65°F, 0.95 $\frac{BTU}{lb-°F}$ at 135°F.

T_{supply} is the water temperature supplied by the DHW heater and/or HW boiler, in °F.

T_{return} is the header water temperature coming into the DHW heater and/or HW boiler, in °F.

$T_{make-up}$ is the water temperature of the incoming city make-up water for the DHW boiler and/or HW boiler, in °F.

T_{ref} is the thermodynamics reference temperature to establish the temperature scale for the system. Usually located at 0° Kelvin and ignored when operating different equations to establish heat gain or loss results.

$\dot{v}_{NG}$ is the volumetric flow of natural gas, in $\frac{ft^3}{h}$

HHV is the high heating value of gas from monthly gas bills in $\frac{BTU}{ft^3}$.

P_{bar} is the barometric pressure from the nearest weather station in psia.

P_{line} is the line pressure of the natural gas pipe in psig, measured once during logger installation.

P_s is standard pressure, 14.696 psia.

$\dot{P}_i$ is the circulator pump measured input power in kW.

$\dot{P}_B$ is the Boiler or Domestic Hot Water Heater power in kW.

$Boiler_{kW}$ is the Boiler or Domestic Hot Water nameplate Power input kW.
S_{Boiler} is a variable that indicates if the Boiler/Domestic Hot Water Heater is enabled or not, as follows,

$$if\ \dot{v}_{NG} > 0\ then\ S_{Boiler} = 1,\ else\ S_{Boiler} = 0 \tag{20}$$

Δt is the timestamp of the reading that will be utilized for the power-to-energy calculation adjustments (preferably hourly).
It is assumed that heat losses in the pipes outside the system boundary in the pre-and post-installation cases are going to be the same. However, as stated in previous sections, additional temperature sensors may be deployed to account for potential heat losses in the piping during the post-installation case. This will be decided depending on the specific site conditions.

2) Utilize measured outdoor air conditions data to determine the site domestic and space heating energy load baseline graphs, as well as each of the systems efficiency parameters as a function of the outdoor conditions.

$$\dot{Q}_{out_{DHW_{BTU/h}}} \& COP_{DHW} = f(OAT) \tag{21}$$

$$\dot{Q}_{out_{HW_{BTU/h}}} \& COP_{HW} = f(OAT) \tag{22}$$

If a regression model based on the Outside Air Temperature does not end up meeting the desired statistical goodness of fit requirements (R^2>0.6), alternative methods, such as manufacturer-published curves; or regressor variables, such as the system load, will be considered to establish a unit's efficiency curve.

Water main temperatures are not expected to change significantly over the course of M&V but will be addressed if they do.

The system's load regression will be further populated with post-verification data if required.

3) Utilize the DHW and HW regressions previously mentioned and utilize the CZ2022 weather data and hourly DHW output and HW output for the site. For each hour of the profile, the baseline total consumption will be calculated using the COP efficiency for each system as follows,

$$EnergyInput_{DHW,hourly}[kBTU] = COP_{DWH_i} * \left(\dot{Q}_{out_{i}}{}_{DHW_{\frac{BTU}{h}}} * \Delta t_i\right) \quad \textbf{(23)}$$

$$EnergyInput_{HW,hourly}[kBTU] = COP_{WH_i} * \left(\dot{Q}_{out_{i}}{}_{HW_{\frac{BTU}{h}}} * \Delta t_i\right) \quad \textbf{(24)}$$

$$EnergyInput_{DHW,Annual}[kBTU] = \sum_{i=1}^{n} Energy\ Input_{DWH,hourly} \quad \textbf{(25)}$$

$$EnergyInput_{HW,Annual}[kBTU] = \sum_{i=1}^{n} EnergyInput_{HW,hourly} \quad \textbf{(26)}$$

Where *i* represents the CZ2022 weather data periods of calculations (expected to be hourly).

Once the baseline of the existing system is defined and the installation of the GAHP is completed and commissioned, the following analysis will be followed after a minimum of two-weeks to determine the operational efficiency and energy consumption for this project.

Measure Case

For simplification and to avoid confusion with the introduction of the GAHP system, the DHW and HW system distinction will not be considered in the proposed analysis equations and will only be referred to in a narrative approach. Please note these equations have been developed based on the system schematic shown in Figure 3. Modifications and simplified methodology may be applied to specific installations and described as such on their M&V report.

1) Calculate GAHP system heat output at timestamp intervals, based on average water flow, supply temperature, and return temperature, as follows,

$$Heat\ Output_{GAHP}\left[\frac{BTU}{hr}\right] = \dot{Q}_{GAHP} = \dot{Q}_{GAHP,supply} - \dot{Q}_{GAHP,Return} \quad \textbf{(27)}$$

$$\dot{Q}_{GAHP,supply} = \dot{v}_{water/glycol} * \rho_{water/glycol} * \bar{c}_{water/glycol} * \left(T_{GAHP\ HX\ In,glycol} - T_{ref}\right) \quad \textbf{(28)}$$
$$\dot{Q}_{GAHP,return} = \dot{v}_{water/glycol} * \rho_{water/glycol} * \bar{c}_{water/glycol} * \left(T_{GAHP\ HX\ Out,glycol} - T_{ref}\right) \quad \textbf{(29)}$$

Where:

$\dot{v}_{Glycol}$ is the volumetric flow of glycol water solution, in GPM.

ρ_{Glycol} is the density of glycol solution, in $\frac{lb}{gallon}$, 8.505 $\frac{lb}{gallon}$ for 20% glycol solutions at 120°F.

$\bar{c}_{Glycol}$ is the specific heat of glycol solution, in $\frac{BTU}{lb-°F}$ 0.928 $\frac{BTU}{lb-°F}$ for 20% glycol solutions at 120°F.

Please note, in the event that GAHP water loop piping and storage tank losses will be significant in the system, the temperatures at the GAHP supply and inlet may be used to additionally calculate the Heat Output of the GAHP before losses using equations 24 – 26. However, it is not expected that these losses will be significant enough to call for this approach.

2) Calculate the total DHW and HW loads using equations 11 to 15 but locating the return temperature measurement reference to the value prior to the HXs, as well as the heat added to HW and DHW loops and the percentage of load distribution between both, as follows,

$$\dot{Q}_{GAHP,HX-DHW/HW} = \dot{v}_{water} * \rho_{water} * \bar{c}_{water\ HW/DHW} * \left(T_{HX,In-HW/DHW} - T_{HX,Out-HW/DHW}\right) \quad \textbf{(30)}$$

$$\%_{HHW} = \frac{\dot{Q}_{GAHP,HX-HW}}{\dot{Q}_{GAHP,HX-DHW} + \dot{Q}_{GAHP,HX-HW}} \quad \textbf{(31)}$$

$$\%_{DHW} = 1 - \%_{HHW} \quad \textbf{(32)}$$

3) Calculate heat pump gas input energy, based on temperature-corrected natural gas flow meter and utility-provided gas heat contents,

$$Gas\ Input\left[\frac{BTU}{h}\right] = \dot{Q}_{in_{GAHP}} = \dot{v}_{NG_{GAHP}} * HHV * \frac{P_{bar}+P_{line}}{P_s} \quad \textbf{(33)}$$

4) Convert heat outputs and gas input to hourly energy totals. – as shown in the calculation of Equation 18.
5) Calculate electrical pump input energy, using Equation 17 and replicate to calculate the GAHP Input Source.

$$Electricity\ Input_{\ GAHP}[kW] = \dot{P}_{CP} + \dot{P}_{GAHP} = \sum Circulator\ Pumps\ Power\ Input + \dot{P}_{GAHP} = \sum Amps_{CP} * Volts_{CP} + \dot{P}_{GAHP} \quad \textbf{(34)}$$

6) Calculate hourly $\boldsymbol{COP_{GAHP,g}}$ and $\boldsymbol{COP_{GAHP}}$ and using the ratio of Energy output to Energy input.

$$COP_{GAHP,g} = \frac{Energy\ Output_{GAHP}}{Energy\ Input_{GAHP}} = \frac{Heat\ Output_{GAHP} * \Delta t}{(Gas\ Input_{GAHP}) * \Delta t, measured} \quad \textbf{(35)}$$

$$COP_{GAHP} = \frac{Energy\ Output_{GAHP}}{Energy\ Input_{GAHP}} = \frac{Heat\ Output_{GAHP} * \Delta t}{(Gas\ Input_{GAHP} + Electricity\ Input_{GAHP}) * \Delta t} \quad \textbf{(36)}$$

7) Calculate relationships of the different heating loads, and $\boldsymbol{COP_{GAHP}}$, compared to hourly dry-bulb temperature reported by the Ambient conditions data –

$$\dot{Q}_{GAHP}, COP_{GAHP}\ \&\ COP_{GAHP,g} = f(OAT) \quad \textbf{(37)}$$

$$Electricity\ Input\ _{GAHP}[kW] = f(OAT) \quad \textbf{(38)}$$

$$\dot{Q}_{DHW/HW} = f(OAT) \quad \textbf{(39)}$$

$$\dot{Q}_{GAHP,HX-DHW/HW}\ \&\ \%_{HHW} = f(OAT) \quad \textbf{(40)}$$

8) Apply the calculated heat output and energy input relationships to the hourly temperature from CZ2022 weather data to calculate normalized hourly heat output and electric energy input.
9) Apply efficiency relationships to hourly temperature from CZ 2022 weather data to calculate hourly GAHP and Existing Boilers and DHW performance, as follows.

$$EnergyInput_{GAHP,hourly}[BTU] = COP_{GAHP,hourly} * \left(\dot{Q}_{out\,GAHP_{\frac{BTU}{h}}} * \Delta t\right) \quad \textbf{(41)}$$

$$EnergyInput_{DHW,hourly}[BTU] = COP_{DWH} * \left(\dot{Q}_{out\,DHW} - [(1 - \%_{HHW}) * \dot{Q}_{GAHP,HX-DHW}] * \Delta t\right) \quad \textbf{(42)}$$

$$EnergyInput_{HW,hourly}[BTU] = COP_{HW} * [\dot{Q}_{out_{i\,HW}} - (\%_{HHW} * \dot{Q}_{GAHP,HX-HW}) * \Delta t] \quad \textbf{(43)}$$

$$EnergyInput_{Sys,Hourly}[BTU] = EnergyInput_{GAHP,hourly} + EnergyInput_{DHW,hourly} + EnergyInput_{HW,hourly} \quad \textbf{(44)}$$

$$EnergyInput_{GAHP,Annual}[BTU] = \sum_{i=1}^{n} EnergyInput_{i,GAHP,hourly} \quad \textbf{(45)}$$

$$EnergyInput_{DHW,Annual}[BTU] = \sum_{i=1}^{n} EnergyInput_{i,DHW,hourly} \quad \textbf{(46)}$$

$$EnergyInput_{HW,Annual}[BTU] = \sum_{i=1}^{n} EnergyInput_{i,HW,hourly} \quad \textbf{(47)}$$

$$EnergyInput_{Sys,Annual}[BTU] = \sum_{i=1}^{n} EnergyInput_{i,Sys,hourly} \quad \textbf{(48)}$$

Where *i* represents the CZ2022 weather data periods of calculations.

The COP efficiencies curves for the DHW and HW Boiler defined during the baseline period will be utilized to account for the possible energy input of these systems in the combined installation.

10) Sum/project the hourly normalized system heating outputs and gas energy input for 8760 hours and calculate the ratio of overall heat output to gas and electricity input to obtain annual $\boldsymbol{COP_{Sys}}$

$$COP_{Sys} = \frac{\sum_{i=1}^{n}\left(\dot{Q}out_{i_{DHW}} * \Delta t_i\right) + \sum_{i=1}^{n}\left(\dot{Q}out_{i_{HW}} * \Delta t_i\right)}{Energy\ Input_{GAHP} + Energy\ Input_{HW} + Energy\ Input_{DHW}} \quad \textbf{(49)}$$

Because the GAHP may only displace a portion of the system's total DHW and HW loads, the annual energy savings will be calculated by measuring the portion of energy output delivered to the respective hot water loops at different hourly weather conditions. The annual energy savings will be calculated by subtracting the total post-installation energy consumption (boiler(s) & GAHP) from baseline energy consumption.

If there are multiple sites being monitored simultaneously, the M&V Team will consider calculating daily COPs and cycle averaged COP may be a better assessment of energy efficiency, since the total useful heat output through the ramp-up and wind-down stage will be considered.

All system's load and performance-derived equations, as well as related outside air temperature information and correlations will be utilized as part of a follow-up analysis where the GAHP and a hypothetical equally sized EHPWH system source and site carbon related emissions are analyzed and compared.

CO2 Analysis Background

The purpose of the CO_2 analysis is to estimate hourly and annual GHG emissions for:

- Baseline SHW boiler(s) and DWH boiler(s)
- GAHP measure case system
- Theoretical electric heat pump water heater system (EHPWH)

GAHP vs. EHPWH Design Considerations

GAHP

The GAHP adds heat to the SHW loop and/or DHW loop via a double-walled heat exchanger (*Potable water cannot go through the GAHP*). The GAHP may be the only device adding heat to the HW loop and/or DHW loop, or there may be additional SHW/DHW boiler(s) in those loops to handle peak water demands. See **Error! Reference source not found.** for an e xample. The peak water loads are addressed by:

- Sizing the GAHP to meet the peak loads; or
- A control strategy that turns ON additional SHW/DHW boiler(s) during peak loads

EHPWH

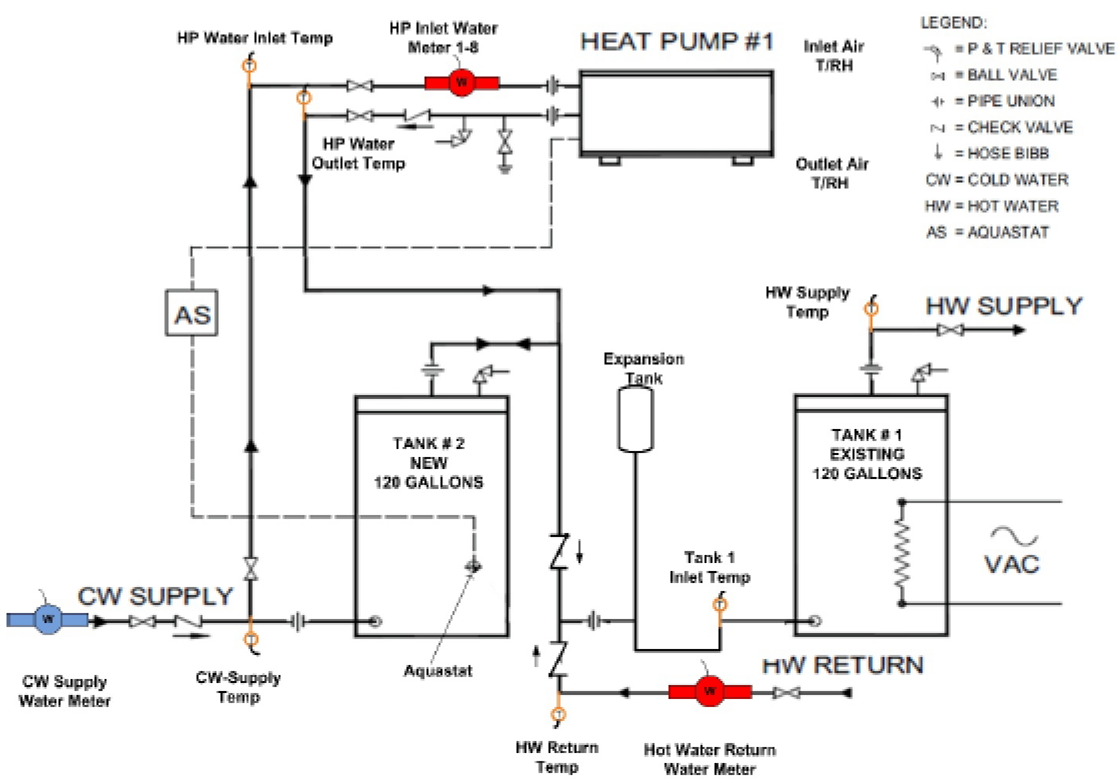
On the other hand, an EHPWH can add heat to the HW loop and/or DHW loop via

- A double-walled heat exchanger; or
- It can completely replace the existing DHW boiler(s)

In either case, an EHPWH generally does not have back up gas-fired DHW boiler(s) and instead relies on additional potable water storage tanks and/or internal electric resistance heating to handle peak DHW loads. EHPWHs can also utilize additional electric instantaneous water heaters for DHW loop temperature maintenance.

An example design of an EHPWH system is shown in **Error! Reference source not found.** b elow from a study done by the Electric Power Research Institute (EPRI) [9].

Figure 31: Example EHPWH Schematic [9].



This system has an additional 120-gallon storage tank and an external electric resistance water heater to serve peak loads.

An additional design consideration is that an EHPWH is generally only used for DHW purposes and not for space heating purposes. When a facility desires to electrify an existing hydronic space heating system, the space heating system is usually switched to an HVAC electric heat pump.

Assumptions

Since the GAHP and EHPWH system designs are different, some assumptions have to be made to compare their source CO_2. Those assumptions are:

1) The hourly EHWPH load is the same as the combined hourly DHW and HW loop heat output

   This means that the load on the EHPWH is based upon the supply, return and make-up city water temperatures and flow rates for the DHW and HW loops. In an actual EHPWH system, those supply/return temperatures might be different when the additional hot water storage tanks are included. However, this was not considered in this calculation since there will be no monitored data to calculate theoretical water temperatures with additional storage capacity in the SHW/DHW loop(s).

2) The EHPWH only serves a HW loop

   As aforementioned, EHPWHs do not typically serve hydronic heating systems. However, calculations to convert from a hydronic heating system to an HVAC heat pump system were also not considered because no other monitored information about building load is being captured to model theoretical HVAC consumption.

3) The EHPWH does not load shift

   Some EHPWHs have the ability to load shift so they only heat water during certain times of the day. This was also not considered in this calculation.

4) The EHPWH does not use additional electric resistance or electric resistance water heaters

   In a typical EHPWH system, the EHPWH has an internal electric resistance element or there is an additional electric resistance water heater to handle periods when the heating load exceeds the EHPWH capacity and the storage tanks have been depleted. However, it is assumed that the EHPWH system would have been designed with sufficient storage tank capacity so this would not happen. As a result, the EHPWH capacity is not taken into account in this tool. It is assumed that the EHPWH can serve any hourly load.

5) EHPWH is designed with additional potable hot water storage which loses energy to the surrounding environment

As stated above, the EHPWH will be designed to have additional storage capacity above what the existing system already has. This additional storage tank will lose heat to the surroundings. The total size of the storage tank will be determined by putting the site characteristics into the EcoSizer Tool [10] with the selected EHPWH capacity. This tool sizes the storage tank capacity (in gallons) based upon the site characteristics and EHPWH capacity. It will be assumed that the new storage tank(s) have an insulation R-value that meets the minimum requirements in Title 24 2019 [11]. The new storage tank(s) will be assumed to store hot water at the same temperature as the existing storage tank(s). The heat loss to the surrounding environment for the new storage tank(s) will be calculated and added to the total heating load that the EHPWH needs to meet each hour.

Analysis Procedure – CO2 Emissions

Overall Summary

The analysis for energy and efficiency will provide heat output from and total energy into the SHW Boiler(s), DHW Boiler(s), and GAHP on an hourly and annualized basis.

The CO_2 emissions for the baseline and post-installation systems are estimated using:

- Hourly gas input as a function of outdoor air temperature into:
  - GAHP (Equation **Error! Reference source not found.**)
  - DHW boiler(s) (Equations**Error! Reference source not found.** and **Error! Reference source not found.**)
  - SHW Boiler(s) (Equations **Error! Reference source not found.** and**Error! Reference source not found.**)
- Natural gas CO_2 emission factor from U.S. EPA [12]
- Monthly High Heating Value (HHV) of natural gas (Obtained from site natural gas bills)
- Gas leakage rate from source to site from the Avoided Cost Calculator (ACC) documentation published by California Public Utilities Commission (CPUC) [13]

The theoretical EHPWH emissions are estimated using:

- Calculated hourly heating load (Equation**Error! Reference source not found.**)
- EHPWH COP as a function of outside air temperature [9]

- Average hourly emissions value (AHE) from California Independent System Operator (CAISO) data [14] or CPUC Avoided Cost Calculator (ACC) values for hourly emissions per kWh [13]

Analysis Steps

The following is the analysis procedure:

1) Calculate electricity input as a function of outside air temperature for baseline & post-installation:

$$ElectricInput_{DHW,hourly}[kWh] = f(OAT) \quad \textbf{(50)}$$

$$ElectricInput_{HW,hourly}[kWh] = f(OAT) \quad \textbf{(51)}$$

$$ElectricInput_{GAHP,hourly}[kWh] = f(OAT) \quad \textbf{(52)}$$

Where:

$ElectricInput_{DHW}$ and $ElectricInput_{HW,hourly}$ come from Equation 17.

$ElectricInput_{GAHP,hourly}$ comes from Equation 35.

2) Calculate natural gas COP[5] as a function of OAT for baseline and post-installation:

$$COP_{DHW_{g,hourly}} = f(OAT) \quad \textbf{(53)}$$

$$COP_{HW_{g,hourly}} = f(OAT) \quad \textbf{(54)}$$

$$COP_{GAHP_{g,hourly}} = f(OAT) \quad \textbf{(55)}$$

Where:

COP_{DHW_g} and COP_{HW_g} come from Equation **Error! Reference source not found.**.

COP_{GAHP_g} comes from Equation **Error! Reference source not found.**.

Note that the variables COP_{DHW_g}, COP_{HW_g}, and COP_{GAHP_g} all consider:

- Pressure and temperature correction for natural gas
- Natural gas HHV

3) Calculate hourly natural gas input for baseline and post-installation:

$$GasInput_{DHW,hourly}[kBTU] = COP_{DWH_{g,hourly,i}} * \left(\dot{Q}out_{i_{DHW_{\frac{BTU}{h}}}} * \Delta t_i\right) \quad \textbf{(56)}$$

$$GasInput_{HW,hourly}[kBTU] = COP_{WH_{g,hourly,i}} * \left(\dot{Q}out_{i_{HW_{\frac{BTU}{h}}}} * \Delta t_i\right) \quad \textbf{(57)}$$

[5] This COP only includes natural gas and does not include electricity

$$GasInput_{GAHP,hourly}[kBTU] = COP_{GAHP_{g,hourly,i}} * \left(\dot{Q}_{out_{i}}{}_{HW_{\frac{BTU}{h}}} * \Delta t_i\right) \quad \textbf{(58)}$$

4) Calculate baseline system CO_2:

$$GHG_{Base,hourly} = \left(GasInput_{DHW,base,hourly} + GasInput_{HW,base,hourly}\right) * GHG_{NG} * C_1 + \left(ElectricInput_{DHW,base,hourly} + ElectricInput_{HWbase,,hourly}\right) * AHE_{hourly} \quad \textbf{(59)}$$

$$GHG_{Base,Annual} = \sum_{i=1}^{8760} GHG_{Base,hourly,i} \quad \textbf{(60)}$$

Where:

GHG_{NG} is the CO_2 emission from natural gas combustion in $\frac{kg\ CO_2e}{MMBtu}$, 53.06 $\frac{kg\ CO_2e}{MMBtu}$ [12], based on the Environmental Protection Agency's (EPA) emission factor for natural gas.

C_1 is a constant to consider the assumed 2.4% natural gas leakage rate from source to site from the Avoided Cost Calculator (ACC) documentation, 1.024 [13].

i is the hour, ranging from 1 to 8,760

5) Calculate post-installation system CO_2

$$GHG_{Base,hourly} = \left(GasInput_{DHW,post,hourly} + GasInput_{HW,post,hourly} + GasInput_{GAHP,post,hourly}\right) * GHG_{NG} * C_1 + \left(ElectricInput_{DHW,post,hourly} + ElectricInput_{HWpost,hourly} + ElectricInput_{GAHP,post,hourly}\right) * AHE_{hourly} \quad \textbf{(61)}$$

$$GHG_{Post,annual} = \sum_{h=1}^{8760} GHG_{post,hourly} \quad \textbf{(62)}$$

6) Calculate theoretical EHPWH system CO_2

A theoretical EHPWH model with publicly available performance map data will be selected that serves the entire load (or multiples of it) of the DHW and/or HHW system. For this generic plan, the performance data from an EPRI study of an EHPWH was selected. Performance data must have EHPWH COP as a function of the outside air temperature.

The source CO2 of the EHPWH will be calculated using the following equations:

$$Load_{Sys,hourly} = [\dot{Q}_{Out,DHW,hourly} + \dot{Q}_{Out,HW,hourly} + \dot{Q}_{Out,GAHP,hourly} + \dot{Q}_{STloss}] * \Delta t \quad \textbf{(63)}$$

$$\dot{Q}_{STloss} = UA_{Tank} * (T_{tank} - T_{amb}) \quad \textbf{(64)}$$

$$UA_{Tank} = SA_{Tank} * HeatLoss_{Tank} \quad \textbf{(65)}$$

$$ElectricityInput_{EHPWH,hourly} = \frac{Load_{Sys,hourly}}{COP_{EHPWH}} \quad \textbf{(66)}$$

$$GHG_{EHPWH,hourly} = ElectricityInput_{EHPWH,hourly} * AHE_{hourly} \quad \textbf{(67)}$$

$$GHG_{EHPWH,Annual} = \sum_{i=1}^{8760} GHG_{EHPWH_i} \quad \textbf{(68)}$$

Where:

$Load_{Sys,hourly}$ is the hourly heating load for the entire system (DHW only, SHW only, or combination DHW/SHW).

$\dot{Q}_{Out,DHW,hourly}$, $\dot{Q}_{Out,HW,hourly}$, and $\dot{Q}_{Out,GAHP,hourly}$ come from Equations 38, 40 and 41.

$\dot{Q}_{STloss}$ are the thermal losses from the additional hot water storage tank(s).

UA_{Tank} is the heat transfer coefficient of the additional storage tank.

T_{tank} is the temperature of the stored water in the tank, assumed to be the same as the stored water in the existing storage tank.

SA_{Tank} is the surface area of the additional storage tank.

$HeatLoss_{Tank}$ is the maximum allowable heat loss from the additional storage tank based upon Title 24 requirements [11].

$ElectricityInput_{EHPWH,hourly}$ is the hourly electricity input to the EHPWH to serve the total hourly heating load.

$GHG_{EHPWH,hourly}$ is the theoretical hourly source CO2 emissions from the EHPWH.

COP_{EHPWH} is the COP as a function of ambient outside air temperature for the EHPWH.

AHE_{hourly} is the average hourly emissions. The preferred source of this data will be from CAISO [14]. This data is available until the last day of monitoring for this project. If additional AHE data is desired or required, it will come from the avoided cost calculator [13]. The ACC AHE is dependent upon the year selected and the CAISO market. The ACC has two (2) CAISO markets:

1) SP15 for SDG&E and SCE
2) NP15 for PG&E

The applicable market will be selected for the site based upon which IOU's territory it is located in. If it is located in an SCG territory that is outside of the electric IOUs, the closest IOU will be selected for CO_2 calculations.

The year selected and sources for the AHE values will be specified when the site-specific M&V plan is created.

$GHG_{EHPWH,Annual}$ is the annual source CO_2 for the theoretical EHPWH

3) Compare typical year annual GHG for baseline system, post system, and theoretical EHPWH system.
4) Calculate Seasonal Hourly GHG Profiles.

Hourly GHG profiles are constructed using the average hourly emissions for each hour over a specified time period. The periods used in this analysis are separated by season and by weekday/weekend. Specifically, a profile is made for both the weekday and weekend for Summer, Winter, and shoulder seasons. The exact days included in each season are to be determined but will be symbolized by the range $\{d_s, D_s\}$, where d_s and D_s are the first and last day of the season, respectively. The day number, n, will determine if the day is a weekday or weekend, with (1) representing Monday, and (7) representing Sunday. The equation for calculating any system's average hourly emissions profile is shown below.

Weekday:

$$GHG_{s,h} \sum_{d_s}^{D_s} \sum_{n=1}^{5} GHG_{h,n} \tag{69}$$

Weekend:

$$GHG_{s,h} \sum_{d_s}^{D_s} \sum_{n=6}^{7} GHG_{h,n} \tag{70}$$

Where:

$GHG_{s,h}$ is the average hourly CO_2emissions for a given season, s, and hour, h, in $metric\ tons\ CO_2$.

$GHG_{h,n}$ is the hourly GHG emissions for either baseline, post-installation GAHP, or theoretical EHPWH system, specified by hour and day number, n.

Twenty-four hour (24-hr) weekday and weekend profiles for each season will be created for the baseline, post-installation GAHP and theoretical EHPWH systems to determine how many hours the EHPWH has lower CO2 emissions than the post-installation GAHP system in each season.

Quality Assurance Procedures

M&V Team will process, check, and analyze all data to ensure all anomalies have been considered and reasonably addressed. The energy input (kWh) data from the GAHP, power input of all circulation pumps (kW), temperature supply and return measurements from each water and glycol loop, water, and natural gas flow values, and outside conditions (temperature and humidity) data will be checked for consistency and errors. The report and calculations will also be reviewed by another staff member for quality control.

As stated in previous sections, if there appears to be any data loss for any measurement point, adequate staff will be deployed on-site to investigate and provide a resolution to the incident, and an appropriate data loss procedure will be followed to minimize the impact of such a loss.

During the Pre- (baseline) and Post- (Measure case) installation periods, system performance data will be methodically reviewed to detect anomalous values and to ensure that the operational variables fall within the ranges specified for the developed COP and Consumption Weather based models. The generally acceptable values for each variable will be the maximum of $\pm 3\sigma$ (σ refers the standard deviation of the model set) or the range used in the model.

In the case of the baseline or Pre-Installation scenarios, outlier data will be reviewed within the M&V team, and consulted with a site representative, and may be removed from the data series if determined to be erroneous. All excluded data will be documented in the Final M&V report for each specific site.

When quantifying how the Baseline or Post-installation periods are impacted by a non-routine event (NRE), the following methodologies will be considered:

1) Removing data from the short period during which the NRE occurred, developing a post-installation period model with the remaining data, and using it to quantify savings for the project. The NRE impact may be determined from the difference in actual energy use and the performance period model prediction during the time the NRE occurred.
2) Using an indicator variable in the energy consumption model for the period when the NRE occurred. A simple indicator variable may be appropriate for an NRE that creates a constant addition or removal of energy. More sophisticated variables may be used when the NRE has variable energy use impacts.

Any updates to the energy model used to calculate savings must be documented in the Final M&V report for each specific site.

This process will adhere to the guidelines and recommendations issued in the *IPMVP – Application Guide on Non-Routine Events & Adjustments* [15].

Design Considerations

Although this M&V plan does not directly consider the mechanical design required to achieve the proposed implementations, the following considerations should be considered to achieve successful installation and operation:

1) Return temperature limitation: One of the primary challenges with finding a suitable application for this technology is locating a site that requires a consistent and significant HW load and sufficiently low-temperature heat sink. The GAHP typically requires a maximum return temperature of around 120°F. As discussed, many SHW and DHW heating applications have return temperatures that consistently exceed

122°F. Without a lower-temperature heat sink, the GAHP lacks the means to add useful heat to the system, thus its utilization and resulting energy savings may be lower than expected. During GAHP integration with a WH/Boiler, a control strategy is required to switch operation from GAHP to WH/Boiler when system return water temperatures are above GAHP limits. Additionally, a GAHP should not be integrated into a DHW recirculation loop that has constant volume recirculation since these loops often have return water temperatures that exceed 122°F.

2) Limited maximum supply temperature: The maximum water/glycol temperature at the outlet of the commercially available GAHP unit is typically around 140˚F. Due to the lack of modulation control, in practice, this outlet temperature varies between 130˚F and 140˚F. If an additional layer of heat transfer is added with a heat exchanger, the range of GAHP outlet temperatures results in a maximum DHW and SHW delivery temperature from the heat exchangers of only 125˚F to 135˚F. Careful consideration of the existing required heating design coil temperatures should be considered based on this limitation.

3) Lack of modulation: Some GAHPs do not have modulation. Although manufacturers provide a direct digital controller (DDC) which can control multiple heat pumps as a hot water plant, the lack of modulation and return temperature limitation could be a challenge to maintain a high hot water supply temperature or operate in periods of low load. Integrating a buffer tank may be critical.

4) Need for additional storage: One manufacturer of GAHP units recommends additional hot water storage of about 50-80 gallons to prevent large temperature swings in the DHW loop that will cause the GAHP to cycle more.

5) Building Codes: In the northwest region of the United States, building codes typically require that larger equipment receive a structural engineering stamp of approval and is seismically secured. Typically, this means that the equipment would have to be bolted in place with seismic bolts. One manufacturer's GAHP units come on rails that do not allow enough room for an easy installation of seismic bolts. There are two primary challenges in bolting the modules. The first is the rail height is 3.75 inches, which is less than a typical 4-inch seismic bolt. The second is that typically to seismically secure equipment, the equipment would be set on the pad, while the installer drills into the pad and then installs the bolts through the drilled holes. For ease of seismic installations, it is recommended to include anchor points on the sides of the modules with access from above to allow installers to first set the modules, and then drill and bolt them with free access from above [16].

References

[1] ASHRAE, "Chapter 50: Service Water Heating," in *2015 ASHRAE Handbook Heating, Ventilating and Air-Conditioning APPLICATIONS*, Atlanta, GA, 2015, pp. 50.2 - 50.36.

[2] Database for Energy Efficient Resources, "DEER Water Heater Calculator," August 2022. [Online]. Available: https://cedars.sound-data.com/deer-resources/tools/water-heaters/. [Accessed October 2022].

[3] DNV GL Energy Insights USA, Inc, "2019 California Residential Appliance Saturation Study (RASS)," California Energy Commission, 2021.

[4] Heschong Mahone Group, "Multifamily Central Domestic Hot Water Distribution Systems," California Energy Commission, 2013.

[5] Energy 350, "Robur Heat Pump Field Trial," Northwest Energy Efficiency Alliance, 2020.

[6] American National Standards Institute, *ANSI Z21.40.4-1996 (R2017)/CGA 2.94-M96 (R2017) - Performance Testing And Rating Of Gas-Fired, Air Conditioning And Heat Pump Appliances,* American National Standards Institute, 2017.

[7] Gas Technologies Institute, *GTI Energy GHP and GHP-Combi Example Laboratory Evaluation Plan,* Gas Technologies Institute.

[8] American Society for Heating, Refrigeration, and Air-Conditioning Engineers, *ASHRAE Guideline 14-2014 - Measurement of Energy,Demand, and Water Savings,* American Society for Heating, Refrigeration, and Air-Conditioning Engineers, 2014.

[9] Electric Power Research Institute, "Commercial Heat Pump Water Heaters - Evaluation of Field Performance for San Diego Gas & Electric (SDG&E)," Electric Power Research Institute, 2015.

[10] EcoTope, "EcoSizer," 2020-2023. [Online]. Available: https://ecosizer.ecotope.com/sizer/. [Accessed January 2023].

[11] California Energy Commission, *2019 Building Energy Efficiency Standards for Residential and Nonresidential Buildings,* California Energy Commission, 2019.

[12] Environmental Protection Agency, *Table C-1 to Subpart C of Part 98,* Environmental Protection Agency.

[13] California Public Utilities Commission, *2022 Distributed Energy Resources Avoided Cost Calculation Documentation,* California Public Utilities Commission, 2022.

[14] California Independent System Operator, "California ISO - Today's Outlook," [Online]. Available: http://www.caiso.com/TodaysOutlook/Pages/emissions.html. [Accessed January 2023].

[15] Efficiency Valuation Organization, *IPMVP Application Guide on Non-Routine Events & Adjustments,* Efficiency Valuation Organization, 2020.

[16] Northwest Energy Efficiency Alliance, "Robur Heat Pump Field Trial," 2020.

[17] California Public Utilities Commission, "2021 PG Study Results Viewer," 2021. [Online].

[18] Northwest Energy Efficiency Alliance, "Non-Powered Damper Gas Storage Water Heater Lab Testing," 2021.

[19] Brio, Gas Technologies Institute, "The Gas Heat Pump and Technology Market Roadmap," 2019.