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Gas-Fired Absorption Heat Pump: Hybrid System Approach Field Study

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Executive Summary

Beginning in 2009, GTI Energy and its partner Stone Mountain Technologies Inc. (SMTI) have taken a residential-sized gas heat pump water heater from concept to field evaluation, working with major original equipment manufacturers (OEMs) and with support from government, including the U.S. Department of Energy (DOE) and the California Energy Commission (CEC), and support from utilities and utility-facing organizations, such as Utilization Technology Development (UTD) and the Northwest Energy Efficiency Alliances (NEEA). This effort, which culminated in a multi-site demonstration in Southern California for the CEC[1], was eclipsed by an effort to scale-up this technology by a factor of 8 to a gas-fired absorption heat pump (GAHP) for broader applications in residential and commercial buildings. As developed[2] and demonstrated over a range of efforts, these GAHP prototypes were proven in multiple applications, displacing or augmenting existing natural gas-fired heating equipment. This larger GAHP can be coupled with an indirect storage tank and deployed as a commercial water heater and/or paired with hydronic heating equipment (e.g. hot water boilers). This concept, GAHPs operating as a hybrid system, was demonstrated in this project in an extended demonstration of the pre-production prototype hybrid boiler/GAHP system at a multifamily building in the Chicago region, with support from a boiler manufacturer and SMTI, the team extended the monitoring period through the 2023-2024 heating season, with prior phases described under work performed under NEEA Contract 51799 and as published previously[3].

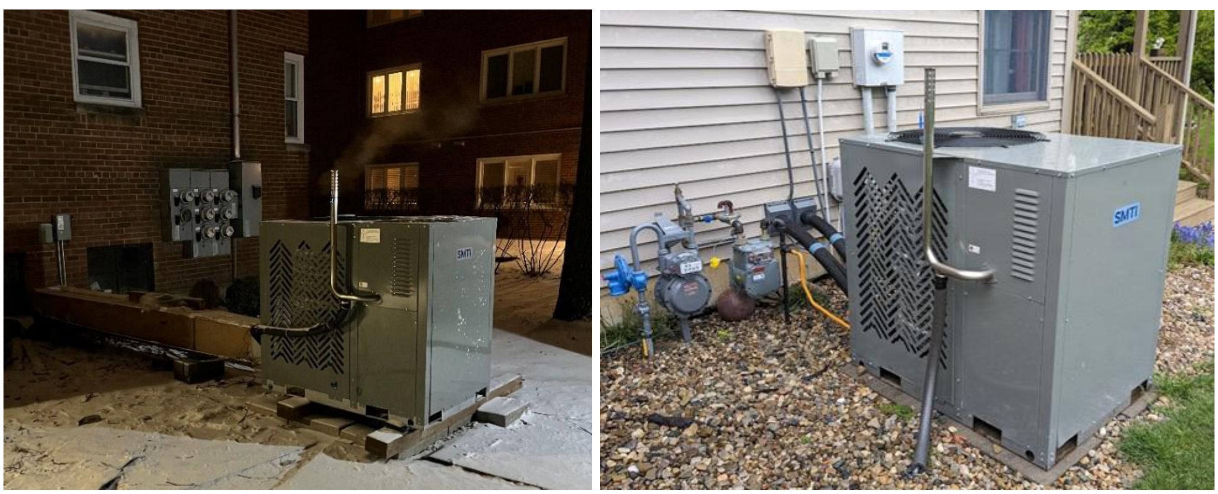


Figure: Multifamily (Left) and Single Family GAHP Installations for this Demonstration

The focus of this effort was the extended monitoring of the GAHP at the multifamily building and explored the "hybrid system" approach with the boiler OEM, in addition to installing and operating two new residential single-family sites. Noted in previous phases, the multifamily site

1 https://www.energy.ca.gov/publications/2023/demonstration-and-assessment-residential-gas-heat-pump-water-heaters-los-angeles

2 https://www.osti.gov/biblio/1328433

3 Glanville, P., Mensinger, M., Blaylock, M., Li, T. and Hardesty, R. (2022) Hybrid Heating and Hot Water in Multifamily Buildings: Demonstration and Analysis of Integrated Boilers and Thermally-Driven Heat Pumps, ASHRAE Transactions, Vol 128, Issue 1.

demonstration required significant installation design and controls development in advance of the commissioning in 2019 and operation through two subsequent heating seasons, which led to several improvements to GAHP design and system operating controls. In this additional extension of this demonstration, through the calendar year 2023, further improvements were made leading to a replacement of the GAHP for improved durability – where operational issues were experienced and addressed with the prototypes. This included replacing the belt drive with a direct drive, changing the bearing drive from slip-fit to press-fit, and improving the integrity of fabrication techniques. In addition, further improvements to the heating system were made, including fully insulating hydronic lines, and installing an On-Demand Recirculation Pump Controller (ODRPC) for the domestic hot water (DHW) loop.

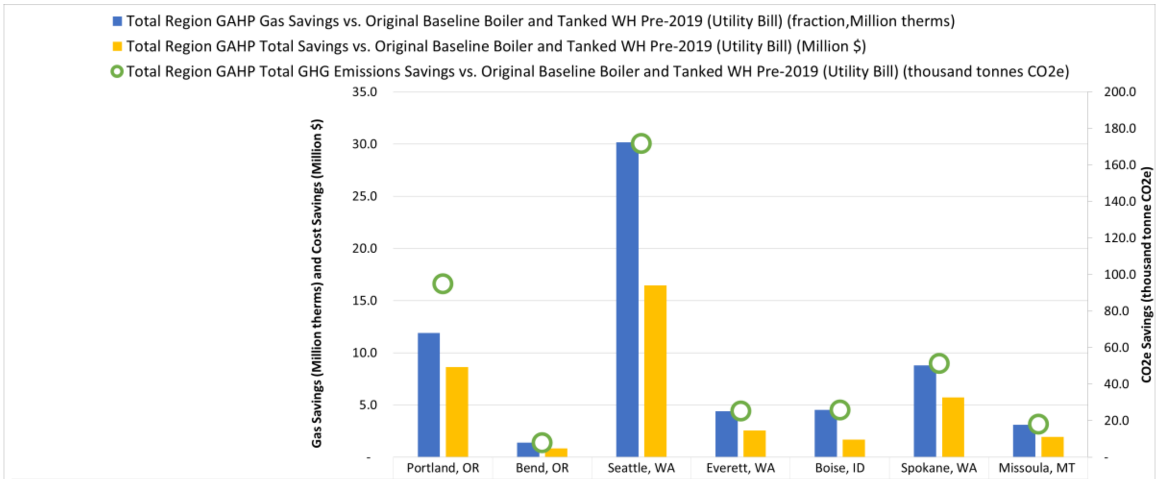
Over the course of the project, the GAHP & boiler systems delivered 744 million Btus (MMBtus) of space heating and 244 thousand gallons of hot water to the three sites, with total operational runtime of 15,183 hours, substantial runtime from which to derive improvements in system design and extrapolate energy and emissions savings as follows:

- **Multifamily Site:** This unique system was installed and operated at an Evanston, IL apartment building from 2019 onwards, allows for a "hybrid" approach, wherein the GAHP component and boiler component can meet the building's space and water heating loads separately or jointly. While challenged by system operational issues and the ongoing COVID-19 pandemic, sufficient data were collected to extrapolate that the system could operate with a net efficiency upwards of 136% and save the building 54% gas consumption for hot water-only mode and up to 55% for combined space heating and water heating mode. When factoring in the added electricity usage of the GAHP and external glycol pump, the total cost savings of the GAHP and boiler system was 47% for hot water-only mode and up to 49% for combined space heating and water heating mode. Lastly, the implementation of On-Demand Recirculation Pump Controls on the DHW loop resulted in annual water savings of 30,845 Gallons or $11,340.

Leveraging the hybrid system platform at the multifamily site, the team additionally made efforts to 1) further optimizing the controls when operating as a hybrid system, for both the specific and general case, 2) extrapolating the findings and optimized controls strategies to other multifamily buildings and commercial applications, and 3) publicizing the results, design guidelines, and other project results in an industry peer-reviewed paper to advance discussions and actions by developers, architect/engineers, and with the boiler OEM partner[4]. While the frequent system servicing had an impact on model development, with alterations to the GAHP system and to its controls over the monitoring period, sufficient data was collected to calibrate models recreating multifamily buildings in the Pacific Northwest. The technical potential for these GAHP-based systems as compared to traditional hydronic boilers was estimated for low-rise and mid-rise buildings in seven regions including OR, WA, ID, and MT. For a single site, the therm savings were estimated as 37%-57% and GHG emissions reduced by 45%-51% over baseline for the seven metropolitan regions considered. Extrapolating to all existing low-rise and mid-rise multifamily buildings the technical potential of the hybrid GAHP/hybrid system was

4 The paper *Hybrid Heating and Hot Water in Multifamily Buildings: Demonstration and Analysis of Integrated Boilers and Thermally-Driven Heat Pumps* was published in the proceedings of the 2022 ASHRAE Winter Conference.

estimated as saving up to 361.1 million therms/year, 2.2 million tonnes (MMT) CO_2/year, and $212 million/year in operating costs, with the breakdown per region in the subsequent figure.



	Portland, OR	Bend, OR	Seattle, WA	Everett, WA	Boise, ID	Spokane, WA	Missoula, MT
Total Region GAHP Gas Savings vs. Original Baseline Boiler and Tanked WH Pre-2019 (Utility Bill) (fraction,Million therms)	11.9	1.4	30.2	4.4	4.5	8.8	3.1
Total Region GAHP Total Savings vs. Original Baseline Boiler and Tanked WH Pre-2019 (Utility Bill) (Million $)	8.6	0.8	16.5	2.6	1.7	5.7	1.9
Total Region GAHP Total GHG Emissions Savings vs. Original Baseline Boiler and Tanked WH Pre-2019 (Utility Bill) (thousand tonnes CO2e)	94.9	8.0	171.9	25.3	25.9	51.4	18.1

Figure: Extrapolated Gas, Operating Cost, and GHG Emission Savings for GAHP & Boiler System in Multifamily Buildings

- **Single Family Hydronic & Forced-Air Heating Sites:** In addition to extending the multifamily demonstration, the project team expanded the application of hybrid GAHP/boiler systems to single family sites. The first of which included a hydronic field site located in La Porte, IN. Another single-family field site was also retrofitted with a GHP Boiler system located in New Carlisle, IN with forced air heating distribution. Like the multifamily site, these sites had a "hybrid" approach, wherein the GAHP component and boiler component can meet the building's space and water heating loads separately or jointly, depending on the operational mode and heating loads. Similarly challenged by the ongoing COVID-19 pandemic, sufficient data were collected to extrapolate system benefits, including estimating net efficiency upwards of 110%-130% and save the home up to 22%-30% (La Porte / New Carlisle) in operating costs for combined space heating and water heating mode, between the sites, depending on baseline. When factoring in the added electricity usage of the GAHP at an incremental 2,193 kWh / 882 kWh (La Porte / New Carlisle) per year, the total cost savings of the GAHP and boiler system was reduced for combined space heating and water heating mode but also driven by observed given controls related issues, and sub-optimized plumbing/sizing for the GAHP – specifically to 15% savings (New Carlisle) and no savings (La Porte). A similar approach to modeling extrapolation for single family detached homes with either furnace forced air systems or hydronic boilers was used for the same seven Pacific Northwest regions. Extrapolating to all existing single-family forced air systems, the technical potential of the hybrid GAHP/hybrid system was estimated as saving up to 436.6 million therms/year, 1.8 MMTCO_2/year, and $324 million/year in operating costs. Meanwhile, the same extrapolation for all single-family hydronic boiler system homes would result in an estimated saving up to 26.3 million therms/year, 29 kTCO_2/year, and $13.0 million/year in operating costs, the smaller value owing to the much larger proportion of homes with forced-air distribution.

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Introduction

Background

Beginning in 2009, GTI Energy and its partner Stone Mountain Technologies Inc. (SMTI) have taken a residential-sized gas heat pump water heater (GHPWH) from concept to field evaluation, working with major original equipment manufacturers (OEMs) and with support from government, including the U.S. Department of Energy (DOE) and the California Energy Commission, and support from utilities and utility-facing organizations, such as Utilization Technology Development (UTD) and the Northwest Energy Efficiency Alliances (NEEA). This effort, which culminated in a multi-site demonstration in Southern California for the CEC[5], was eclipsed by an effort to scale-up this technology by a factor of 8 to a gas-fired absorption heat pump (GAHP) for broader applications in residential and commercial buildings. As developed[6] and demonstrated over a range of efforts, these GAHP prototypes were proven in multiple applications, displacing or augmenting existing natural gas-fired heating equipment as summarized in the 2023 AHRI study[7] performed by GTI Energy, per table below.

Table 1: Summary of GAHP Performance in Prior Studies as Compared to Natural Gas Baseline Equipment

Category		Max. Efficiency Rating[8]	GAHP Field Demo Savings / Performance Target[9]
Residential	Water Heater	0.90 UEF (Storage) 0.96 UEF (Instantaneous)	>50% energy savings over 0.62 UEF baseline, >1.20 UEF target
	Warm-air Furnace	99.0 % AFUE	>45% energy savings over 92% AFUE furnace baseline, >140% $COP_{seasonal}$ target[10]
	Boiler	96.0% AFUE (Water) 83.4% AFUE (Steam)	
Commercial	Water Heater	97% TE (Storage) 99% TE (Instantaneous)	>50% energy savings over 82% TE baseline, >130% TE target
	Weatherized Furnace	>90% TE[11]	>40% energy savings over 80% TE baseline, >1.30 $COP_{heating}$ target
	Boiler	99.4% AFUE (Water) 84.2% TE (Steam)	>40% savings over 80% TE baseline, >130% TE target (N/A for steam)

As summarized, these GAHPs can reliably reduce emissions and improve efficiency over baseline gas-fired equipment by 40%-50%, which can be an attractive strategy for decarbonization efforts. During this period, GTI has successfully characterized the performance of these GAHP systems in a laboratory environment and, increasingly, demonstrated successful operation in

5 https://www.energy.ca.gov/publications/2023/demonstration-and-assessment-residential-gas-heat-pump-water-heaters-los-angeles
6 https://www.osti.gov/biblio/1328433
7 https://www.ahrinet.org/system/files/2023-06/AHRI%208030%20Final%20Report.pdf
8 Maximum efficiencies based on AHRI Certification Directory, inclusive of inactive equipment
9 Sources for savings and targets include: GTI and Brio, 2019; Glanville, 2020; Glanville, 2021, and Glanville 2022
10 Seasonal COP and AFUE metrics are based on the ANSI Z21.40.4 rating method
11 "Condensing RTUs" are commonly rated as industrial-type air heating equipment, thus value is based on recent studies of this category: http://betterbricks.org/uploads/resources/CRTU_pilotSummaryReport_3.23.20.pdf

more than 30 residential and commercial test sites, accumulating > 30,000 hours for these manifold GAHP applications. This collaboration has occurred over a period of RD&D, including development of competing technologies, reducing overall barriers to market adoption, and improving analytical tools to assess their performance, summarized by GTI Energy and NEEA[12].

Figure 1: GAHP Unit Installed at Evanston, IL Multifamily Site

This project builds on these prior efforts with SMTI, leading up to their ramp up in production of GAHP units in 2023-2024, by continuing the partnership with a major boiler manufacturer to:

1) Extend an existing multifamily GAHP & boiler hybrid demonstration at Evanston, IL, from 2022 - early 2024, updating the GAHP unit to the newest design and controls packages.
2) Expanding the demonstration with the boiler partner to include two single family homes, reflecting two different installation types: forced-air heating and hydronic heating, both located in Northern Indiana.
3) Collecting reliability and performance data across the three Midwestern sites over multiple heating seasons, to identify & resolve reliability/servicing issues and extrapolate performance with calibrated modeling.

In the prior phase project with NEEA (multifamily site), under Contract 51799 and summarized in a 2022 publication[13], GTI installed a prototype GAHP at a six-unit multifamily building in the Chicago metropolitan area working with SMTI and the Boiler Manufacturer, integrated with compact boilers to provide space heating and water heating per the above figure. As installed, the GAHP is multifunctional per the diagram below, the GAHP unit is able to serve the space heating and water heating load, with boiler backup in both instances. This flexible site plumbing design was intended to maximize GAHP operation but with redundancy for host site comfort. During this monitoring period, automated system alerts aided in diagnosis and resolution of unit issues, despite challenges brought on by the ongoing pandemic.

During these prior studies at the multifamily site, covering a period from installation in 2019 through the end of 2021, sufficient data were collected to extrapolate that the system would operate with a net efficiency of 136% and save the building 43% gas consumption for hot water-only mode and 41% for combined space heating and water heating mode. Additionally, the retrofit of compact boilers on existing equipment was examined, yielding 24% therm savings for the compact boiler only case. This monitoring period was not without challenges, however,

12 https://www.gti.energy/wp-content/uploads/2021/11/Thermal-Heat-Pumps-The-Time-is-Now-Aug2020.pdf

13 Glanville, P., Mensinger, M., Blaylock, M., Li, T. and Hardesty, R. (2022) Hybrid Heating and Hot Water in Multifamily Buildings: Demonstration and Analysis of Integrated Boilers and Thermally-Driven Heat Pumps, ASHRAE Transactions, Vol 128, Issue 1.

requiring multiple replacements of key components up to and including full swaps of the GAHP units itself, driven by improvements in system design and the challenging nature of this test site.

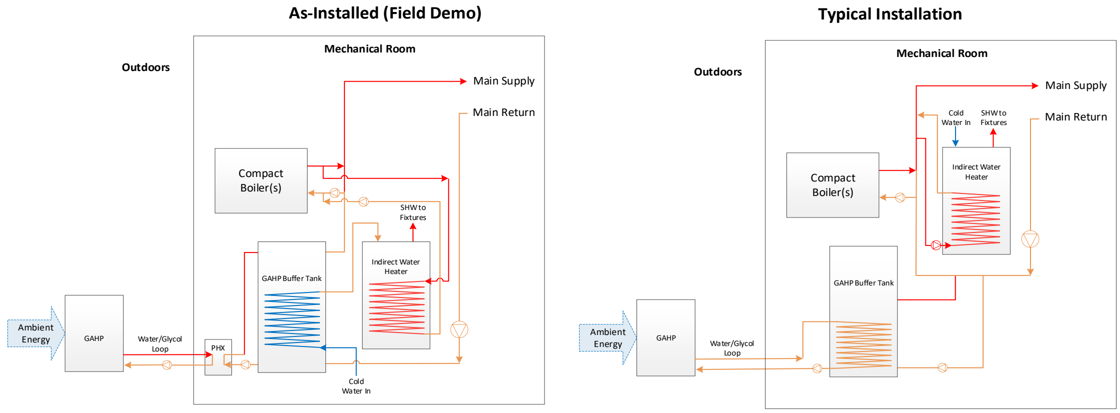

Figure 2: Simplified Diagram of the Multifamily Integrated GAHP Hybrid System

Project Objective & Scope

Currently, SMTI under their "Anesi" brand has refined their path-to-market which focuses on their 80 kBtu/h output air-to-water GAHP (the "80k"), designed to serve both whole-house space/water heating and light commercial heating applications (hydronics, hot water). Under prior R&D efforts, GTI has demonstrated that the 80K can a) achieve an estimated 140% AFUE per the relevant test standard, b) successfully modulate 4:1 and operate dynamically serving space/water heating loads, and c) operate in mild and cold climates, including active defrost models, among other performance elements. SMTI has outlined a path-to-market that is based on a combination of direct-to-market and a "white labeling" approach, achieving initial production in late 2023. With a focus on the partnership with the boiler OEM, this project supports this GAHP technology collaboration in two ways:

1) Measurement and verification of two new field installations at homes in Northwest Indiana, applying the next generation GAHP in single family homes, in direct coordination with the boiler OEM and permitting a more "hands-on" installation and commission for their product teams, and
2) Extension of a multifamily housing site with the same boiler OEM in the Chicagoland area, installing and operating a next generation GAHP at the test site and refining system hardware and controls, building on prior demonstrations at this site from 2019-2021, thus capturing performance operating in 2022-2023 prior to SMTI production ramps up.

With support from NEEA, GTI has extensively reviewed and defined the role that the boiler OEM and their prospective technology vendor, SMTI, will play relative to the project. While defined in greater detail in a document shared confidentially with the team, the broad division of responsibilities for this field demonstration effort are as follows:

<u>GTI is responsible for:</u>

- All aspects of project reporting and team communications
- All aspects of installation, monitoring, removal of instrumentation and data collection hardware, including maintaining databases and analyses of datasets at the three sites

- Retain role as lead coordinator for multifamily housing site, including updating agreements, managing on-site contractor activities (GAHP replacement, decommissioning, etc.)
- Support the boiler OEM in the commissioning, maintenance, and troubleshooting of GAHP systems throughout the project

The Boiler OEM is responsible for:

- Procuring three next gen. GAHPs and, with SMTI support, preparing for field installations
- Recruitment and selection of the two new single family home sites, securing field test agreements with the new sites, and overseeing the GAHP installation at the sites
- Lead role in commissioning, maintaining, and decommissioning GAHP systems, with SMTI support at the two new sites

Through the scope of this demonstration project the effort distinguished between the existing multifamily site and the two new single family sites:

Multifamily Site[14]

Working with the boiler OEM, GTI re-commissioned the multifamily test site for the project period (2022-2023), replacing the GAHP with a next generation version and updating system hardware and controls. As noted, the boiler OEM opted to include this existing test site with the current program as they recognize the site provides an excellent "live test" site to investigate further improvements to system controls, while extending the reliability assessment of the GAHP unit and solicit end user feedback. Noted above, for this site, GTI retained its role as lead site coordinator, including the hiring/supervision of the installation contractor and coordination with the host site supervisor and tenants. Informed by the boiler OEM's approach, the team reviewed, finalized, and documented changes implemented to the data collection hardware, the GAHP/Boiler system design and controls approach, and the GAHP itself. These changes were incorporated into a *Field Demonstration Plan* for this site, summarizing the data collection goals, approach and analytical methods employed.

The replacement GAHP was installed and commissioned, initiating the data monitoring period for a period of more than 24 months, during which GTI provided the team regular data analysis updates, via summary documents and review webinars, and a new web-based portal developed for the project team to review in "real-time". During the monitoring period, GTI coordinated and supported on-site troubleshooting and servicing of both system hardware and data collection equipment. At the close of the monitoring period in early 2024, the data collection system and GAHP itself was decommissioned and the host site was restored to a boiler-only site. Final results were communicated in a final webinar in addition to this reporting.

During the first phase of this demonstration, the team struggled with two aspects of this system demonstration: a) optimization of system control strategies to effectively balance GAHP energy savings, occupant comfort, and system reliability and separate to this, b) reliability challenges with the GAHP itself, with some of these challenges extending from the prior multifamily site

14 Note that relevant details from the prior phase of this site demonstration are included in this report, leveraging content developed through UTD (1.16.I) and NEEA (51799) project reporting. Where included, this content will be noted for reference. These details include aspects of site selection and recruitment, through system design, installation and commissioning in 2019, and recommissioning in 2022.

monitoring periods. Concerning the former, setback controls for the boilers and GAHP were adjusted on several occasions to seek effective sequencing of the equipment, attempting to balance too little GAHP runtime with optimization of occupant comfort. Concerning the latter, the GAHP and system experienced two sets of reliability challenges, GAHP component failures and site electrical faults. A notable example of these challenges includes a refrigerant leak in the 2021-2022 heating season that required intensive repairs/replacement, which the resolution of this issue spanned most of calendar year 2022. Additionally, the team opted to install a domestic hot water (DHW) recirculation pump to improve system performance.

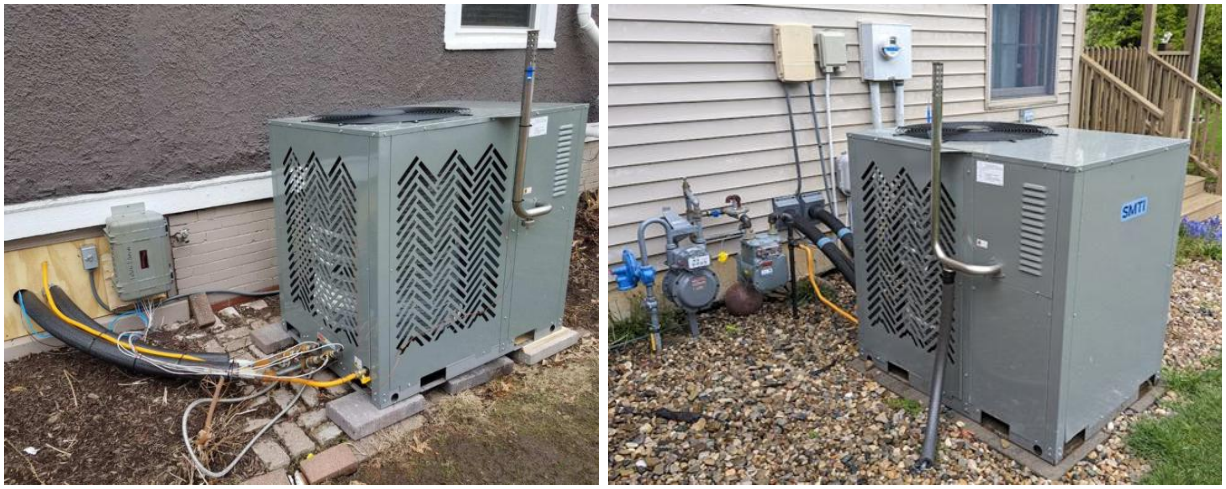

Figure 3: Photos of the Single Family Site Installs – the Hydronic Heating (Left) and Forced-Air Heating (Right) Sites

Single Family Sites

GTI coordinated with the boiler OEM, as they recruited and selected two single family host sites in Northwest Indiana and collected information through site visits to develop and refine a Field Demonstration Plan for these two sites. This effort prior to GAHP delivery and commissioning included: defining data collection and analytical approach, specifying, procuring, and assembling data collection hardware packages, establishing energy use and comfort baseline at sites, and other tasks in advance of the monitoring period. GTI worked closely with the boiler OEM during the planning, installation, and commissioning process to provide assistance as needed and assure that the necessary instrumentation is installed to accurately collect data and monitor the installed system. Once the GAHP units were delivered, GTI installed and commissioned the data collection packages and supported GAHP system commissioning as well. As mirroring the multifamily site task, GTI provided ongoing and coordinated troubleshooting and maintenance support, while providing regular data analysis updates via summary files, webinars, and access to the web-based portal. Upon completion of the monitoring period in early 2024, final results were summarized in a review webinar and site report, in coordination with the multifamily site task. For all sites, the field dataset was used to generate site-specific energy savings, while extrapolating to other building types and climate zones in the Pacific Northwest, via building energy simulation.

At the start of the 2021-2022 heating season, two additional single family residential homes were added as host sites to demonstrate performance of the GAHP "combi", or combined space and water heating, system. While each of these sites would demonstrate combi operation, they differed in that one home was a forced air heating system while the other was a hydronic heating system, providing opportunity for comparative analysis. During installation and commissioning, both GAHP units required additional troubleshooting, repairs, and replacements, which delayed monitoring until late 2022.

Adjustments to Project Scope

Over the course of the project, the team encountered several challenges and setbacks for the GAHP/boiler hybrid demonstrations. Many of these stemmed from on-site complications with the multifamily building – such as an in-unit thermostat being improperly wired prior to this project start and affecting perceived tenant comfort issues, and GAHP system hardware issues experienced at the single family homes, but others were a result of the ongoing COVID-19 pandemic emerging in 2020 and continuing through the duration of this extended project. A quick summary of these complications is:

- Equipment Failures: For reasons described in detail in this report, the GAHP units had limited runtime due to component and/or system failures, resulting in multiple full unit replacements over the course of this three-site demonstration. While the project team continued to learn from these challenges, arising from fabrication issues or other factors, the team did not capture the full performance dataset as intended over the 2021-2022, 2022-2023, and partial 2023-2024 heating seasons. However, certain mechanical issues experienced with the GAHP units did result in timely findings to support late-stage refinement of the product, and the OEM partner remains an unwavering supporter of the technology. With the replacement of multiple GAHP units in late 2022, sufficient data were collected to better understand the combi space heating and DHW heating operation of each single family home. Additionally the multifamily home GAHP was replaced in mid-2022, so there was sufficient data collected to draw conclusions in the DHW-only operation of the unit during this extension project.

- COVID-19 Issues: Kicking off in 2021, this extension continued during a difficult period of the COVID-19 pandemic, with subsequent waves of variants and impacts on both human and hardware resources (e.g. supply chain constraints). This had the primary impact on resource availability (staff and hardware) and site access, at times increasing the level of effort required to perform routine on-site maintenance and troubleshooting. Additionally, the time to perform full system replacements with the manufacturer (SMTI) was also adversely impacted. Finally, and noted in prior monitoring phases at the multifamily site, there was a measurable change in energy use at the host site driven by shifts in occupancy and other behaviors. This did not have an impact on scope, per se, but did limit the general usefulness of the data collected as compared to the pre-pandemic measured baseline. In general, increased unit occupancy drove up overall hot water (mainly) and space heating (somewhat) demands, though load patterns also shifted, driven by increasingly irregular schedules.

Field Test Plan and Demonstration Site Details

The primary goal of this study was to extend the monitoring of both an existing hybrid thermal heat pump/boiler system, with the GAHP component built by SMTI with support from a Boiler OEM, in a hybrid arrangement with conventional gas boilers at a low-rise multifamily building in the Chicago Metropolitan area and install, commission, and operate similar systems at two single family homes. Prior to this effort, baseline monitoring was performed at the multifamily host site following commissioning the GAHP unit in 2019, though multiple unit replacements followed with the most recent recommissioning in mid-2022. At each single family residential site, baseline monitoring was performed in 2021 and GAHPs were commissioned in late 2021, and after issues were resolved, recommissioned in late 2022.

GAHP Technology Review

A detailed review of the GAHP prototype units from SMTI was provided in the previous report under contract 51799, however a brief recap is provided here for convenience. The low-cost GAHP is based on the vapor absorption refrigeration cycle, using the ammonia-water working fluid pair, in which an absorbent (water) is used as a carrier for the refrigerant (ammonia). Commonly, for air-source gas heat pumps, this refrigeration moves heat from ambient air at the evaporator to the recirculating hydronic loop at the condenser.

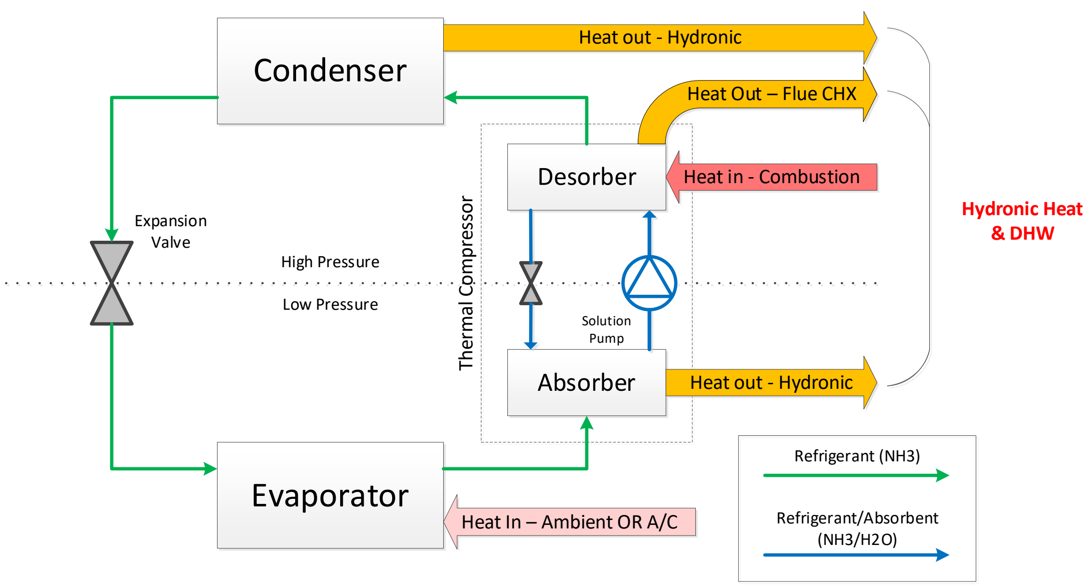

Figure 4: Simplified Diagram of Single-Effect Absorption Cycle

The core GAHP is based on a prototype low-cost design developed and demonstrated in prior R&D efforts as noted in the Introduction, targeting space/water heating. This GAHP has a nominal 80,000 Btu/hr (23 kW) heating output, and full modulation of 4:1, a peak delivered temperature of 150°F, and active defrost. At the core of the GAHP is a thermal compressor, the absorption cycle itself which serves the function of traditional HVAC compressor but with a series of heat exchangers and vessels, driven by thermal energy instead of electricity, the details of which are described in prior reporting [GTI and Brio, 2019], in addition to several publications.

Within this thermal compressor, the compression of the liquid refrigerant/absorbent solution is performed by the solution pump, which requires only about 2% of the total energy input to the heat pump. The thermal energy from the modulating gas burner is required to drive the refrigerant vapor from its absorbed state in the desorber (or "generator"). This desorption process occurs at an elevated temperature - 250-300°F - thus exiting flue gases still have useful heat, which is recovered in a separate condensing heat exchanger (CHX), integrated within the hot water loop. As the ammonia/water pair has a significant heat of absorption, this is recovered at the absorber as well by the same hydronic loop as the condenser. Thus, only approximately 30%-40% of the THP output is the "refrigeration effect" (that is, the evaporator load), and the remainder of heat output and efficiency is effectively independent of operating conditions. This makes THP technologies attractive both for cold climate air-source applications and high temperature lift applications, like water heating. Through prior efforts, GTI and SMTI have demonstrated that this GAHP operates with a projected 140% AFUE, with operating efficiency at or better than existing GAHPs and cold climate electric heat pumps (see figure below). Like existing GAHPs, available in Europe and elsewhere, this GAHP is similar to a boiler, in that it is an air-to-water/brine heat pump supplying heat to a closed hydronic loop, which can independently supply hydronic air coils, indirect tanks for DHW, and other zones (e.g., radiant) as the site requires. Additionally, as required by the South Coast Air Quality Management District (SCAQMD), this GAHP component was certified as "Ultra Low NOx" with an emission rate in compliance with Rule 1146.2 (14 ng NOx/J output).

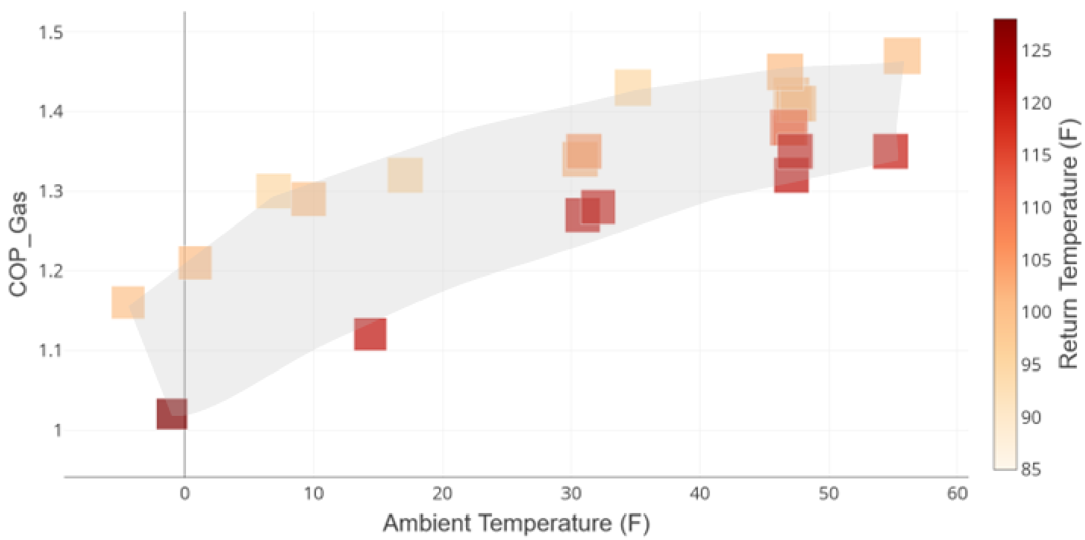

Figure 5: Performance Mapping of GAHP Component in Prior GTI Testing

Figure 6: Photos of Low-Cost GAHPs Operating in Prior/Concurrent Residential Heating Demonstrations

Multifamily and Single family Site Selection

Site 1: Multifamily Site (Evanston, IL)

Similar to the prior section, the demonstration planning and site selection of the multifamily home site was covered in detail in the previous report under contract 51799. A brief review of this is provided here for convenience, with additional information provided in an appendix. The site is a six-unit multifamily building in Evanston, IL, each unit is approximately 1,000 ft^2 and the building is approximately 65 years old. Double-pane windows were installed, and the roof was insulated approximately ~12 years ago, however no further major improvements were made to the building's thermal envelope since then. The details of the original central boiler and central water heater are provided in the figure below. Prior to the 2019 GAHP commissioning, the host site provided access to their past utility bills, for the gas meter that served only the boiler and water heater. From the data (figure below), GTI estimated the following:

- The DHW load was approximately 200-250 gallons/day prior to GAHP installations
- The boiler is significantly over-sized, estimated to have only 6-8 equivalent full load hours (EFLH) during the winter peak billing period for the three years considered.
- With the gas consumption weather normalized, with the space heating isolated from DHW assuming summer months are DHW-only, the building heating load is normalized by heating degree day (HDD). From this analysis:
    - Using the nameplate data on the boiler, the peak load observed is estimated as 3.0 MMBtu/day.
    - If the GAHP installed meets 40% of that load, assuming that the COP_{Gas} of the GAHP at the very cold winter conditions is 1.10, this yields 11 EFLH for the 140 kBtu/h unit and 20 EFLH for the 80 kBtu/h GAHP units, which indicates this GAHP will be well-sized for this application, potentially over-sized with the 140 kBtu/h unit.

Figure 7: Original Boiler and Water Heater at the Multifamily Demonstration Site

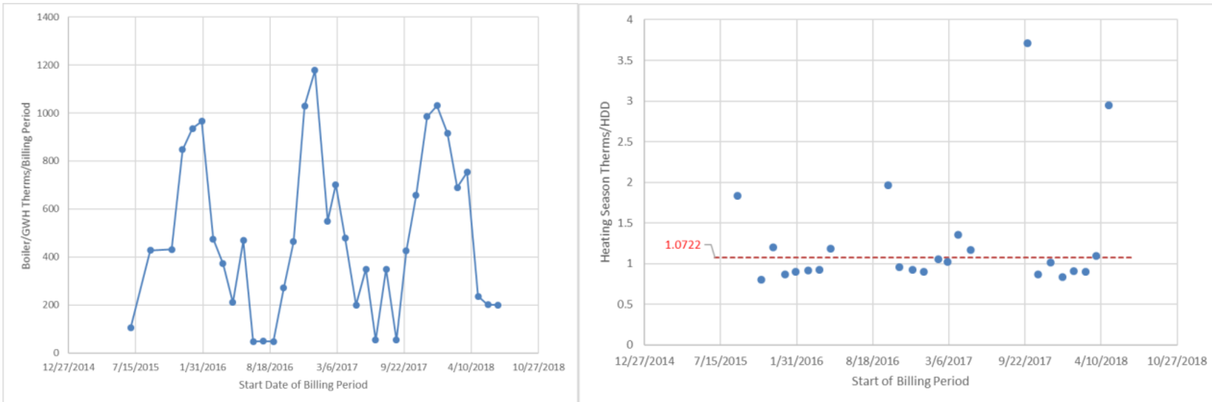

Figure 8: Utility Billing Data from Multifamily Demonstration Site for 2015-2018 – Raw (L) and Normalized (R)

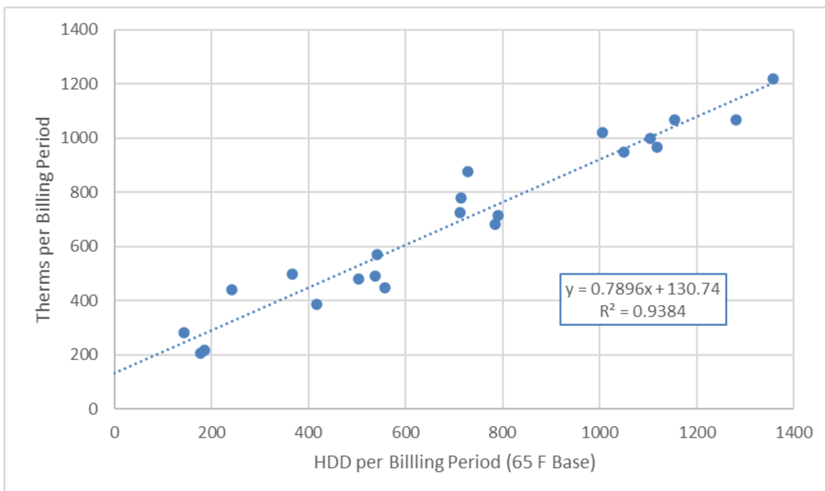

Figure 9: Normalized Site Gas Consumption – Space Heating Only at Multifamily Site (Estimated)

Figure 10: Photo of Demonstration Site in Evanston from Front (Left) and Rear with Notation (Right)

Once this project initiated, the system was installed as described in prior reporting and in publications, including the retrofit of the system to the GAHP / Boiler system as shown in Figure 2, with the following equipment in addition to the GAHP unit:

- The two boilers are 84% AFUE with 200 kBtu/h input each. The boilers are each installed indoors, tied into the main return and supply, with one of the boilers (Boiler #2) able to heat an indirect storage tank for hot water.
- Indirect DHW storage tank, a 111 gallon storage tank designed for 14.0 gallons per minute (GPM) circulation.
- Custom buffer tank and plate heat exchanger model from the boiler manufacturer (largest of the series).

The full instrumentation diagram is shown on the subsequent page for the site as originally commissioned, aside from replacing the 140 kBtu/h GAHP unit with the “80k” during this original monitoring period (through 2020), only minor changes were performed over the prior monitoring periods, such as introducing check valves on the GAHP hydronic loop.

Figure 11: Multifamily Unit Site during Initial GAHP Monitoring Phases (2019-2021)

Outdoor Logger:
- GAHP Hydronic Sup/Rtn Temp. & Flow
- GAHP Gas Flow and Valve Runtime
- GAHP Power Draw
- GAHP Evap In/Out, Des. Shell Temp.
- GAHP Ambient and Flue Gas Temp.
- PHX Hydronic Sup/Rtn Temp.
- DHW Pre-Heat Temp.
- Pump Runtime (Buffer P6)

Indoor Logger:
- Boiler 1/2 Gas Flow
- Boiler 1/2 Sup/Rtn and Flue Temp.
- Pump Runtimes (Boiler P2/P3, Main P4, DHW P5) ***(flow measured one-time)***
- DHW Flow and Outlet Temp.
- DHW Coil Sup/Rtn Temp.
- Main Sup/Rtn Temp.
- Buffer Tank Sup/Rtn Temp.
- Utility Room Temp.

Calculated Metrics:
- Energy Inputs/Outputs for GHP/Boilers
- Cycling Behavior of Equipment
- Energy Flows from GAHP / Boiler Loops to Main Loop & DHW Tank
- DHW Output and Statistics
- GAHP COP_Gas (Daily, Instant),
- GAHP Utilization (GAHP/Total Output)
- System Efficiency (w/ and w/o electricity)
- Summarize weather

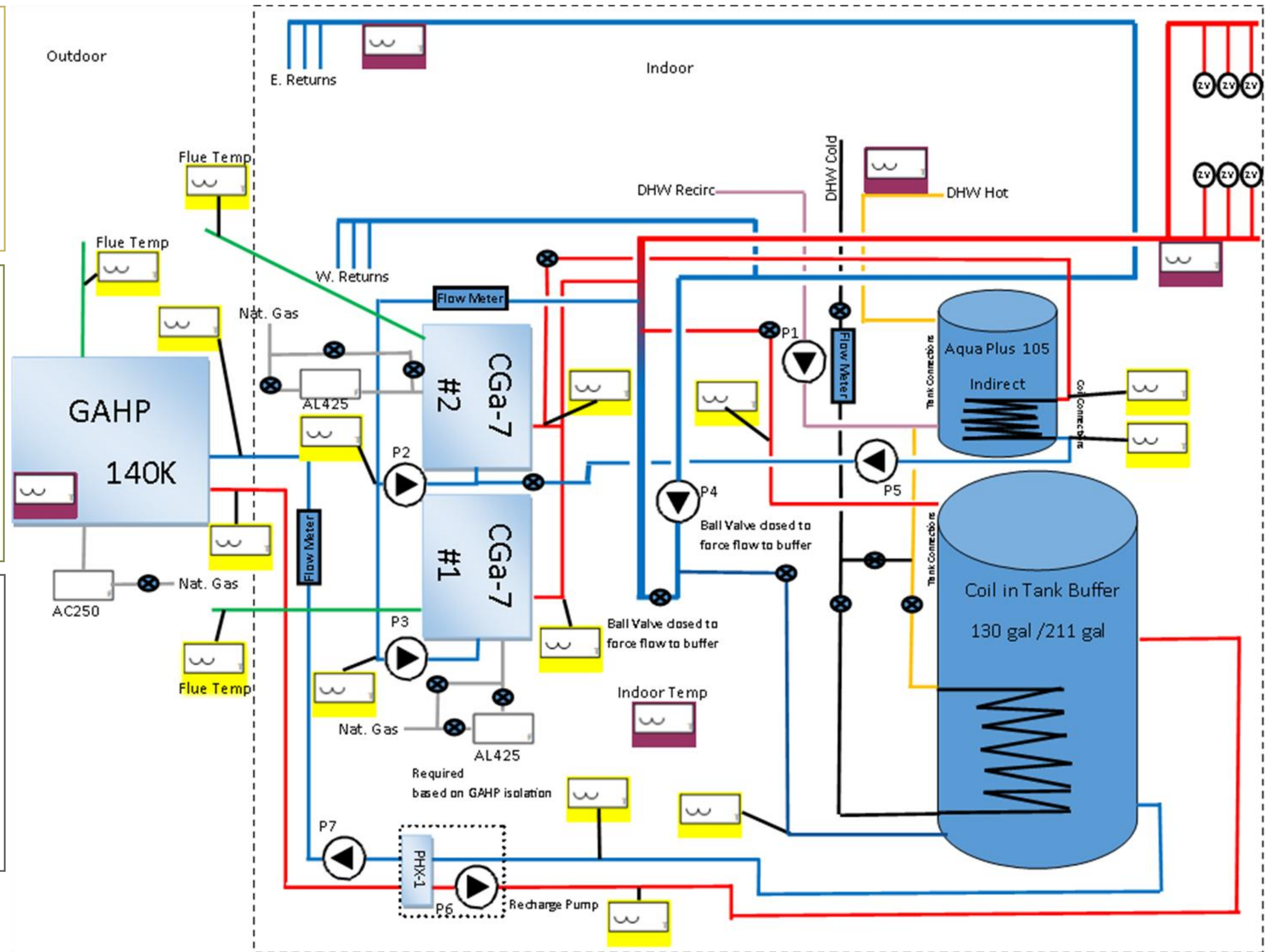

Figure 12: Diagram of the Multifamily GAHP Demonstration Site as Originally Commissioned

Site 2: Single Family Hydronic System (La Porte, IN)

The first of the two new single family host sites are described here, a single family residential home in La Porte, IN. The home is approximately 3,090 ft^2 and the building is approximately 112 years old. No major improvements were made to the building's thermal envelope since construction. The original central boiler was a Burnham 206NC-TEI2, 164,000 BTU/hr gas heating boiler with an AFUE of 82%, while the original tanked water heater was a Bradford White MI40T6FBN, 40,000 BTU/hr gas input, with a UEF of 0.59 with 40 Gal storage. The host site provided access to their past utility bills, for the gas meter that served only the boiler and water heater. From the data (figure below), GTI estimated the following:

- With the gas consumption weather normalized, with the space heating isolated from DHW assuming summer months are DHW-only, the building heating load is normalized by heating degree day (HDD). From this analysis:
    - Using the nameplate data on the boiler, the peak load observed is estimated as .7 MMBtu/day.
    - If the GAHP installed meets 100% of that load, assuming that the COP_{Gas} of the GAHP at the very cold winter conditions is 1.10, this yields 14 EFLH for the GAHP, which indicates this GAHP will be well-sized for this application
- The DHW load was not determined

Figure 13: Original Boiler and Water Heater at La Porte Site

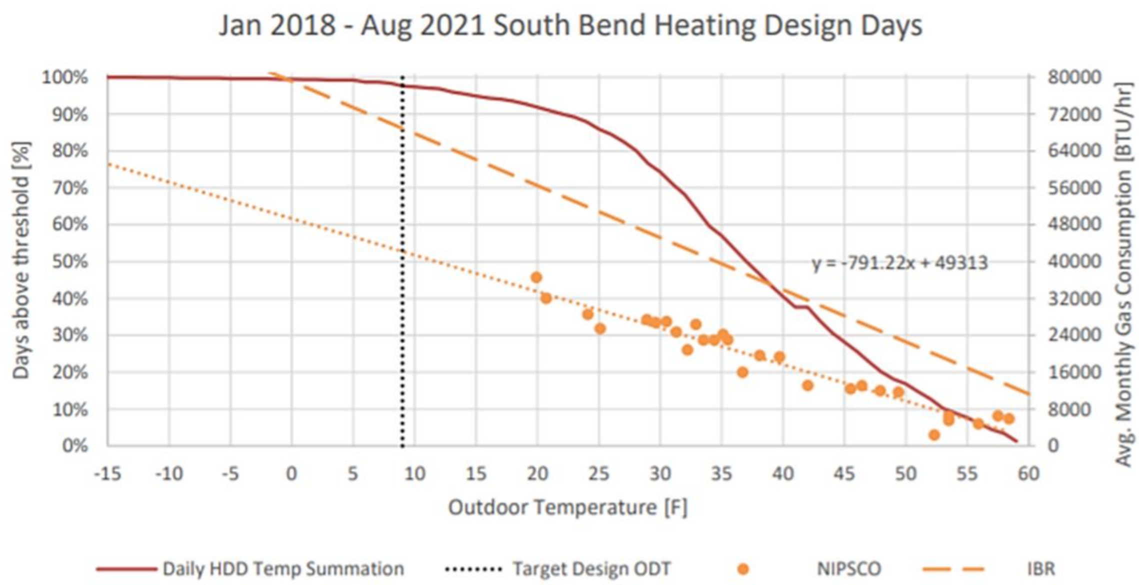

Figure 14: Utility Billing Data from La Porte Demonstration Site from 2018-2021

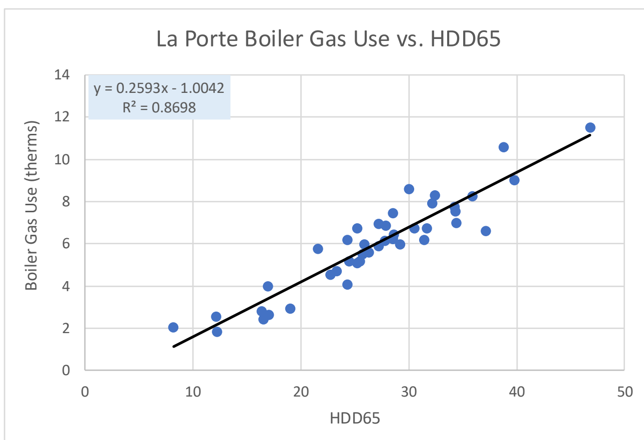

Figure 15: HOBO Logger Normalized Site Gas Consumption – Space Heating Only (Estimated)

In early 2022, the GAHP and backup boiler were installed at the site, replacing the original central boiler and water heater. The backup boiler is 95% AFUE with 110 kBtu/h input, with the boiler installed indoors, while the GAHP was installed outdoors. The heating system loop, per the diagram below, includes the GAHP and boiler in series supplying either the DHW tank or zones with hot water for heating. This allows the heating system to allow the GAHP and boiler to provide heat, and also switch between space heat and DHW heating calls. When active, the GAHP was expected to serve both loads during mild outside air temperatures. At more moderate and severe cold outside air temperatures, this would allow the GAHP to start to heat the hydronic loop to the zones, and for the boiler to further heat and boost the temperature to meet the higher space heating load. The heating zones were kept the same as the baseline plumbing orientation.

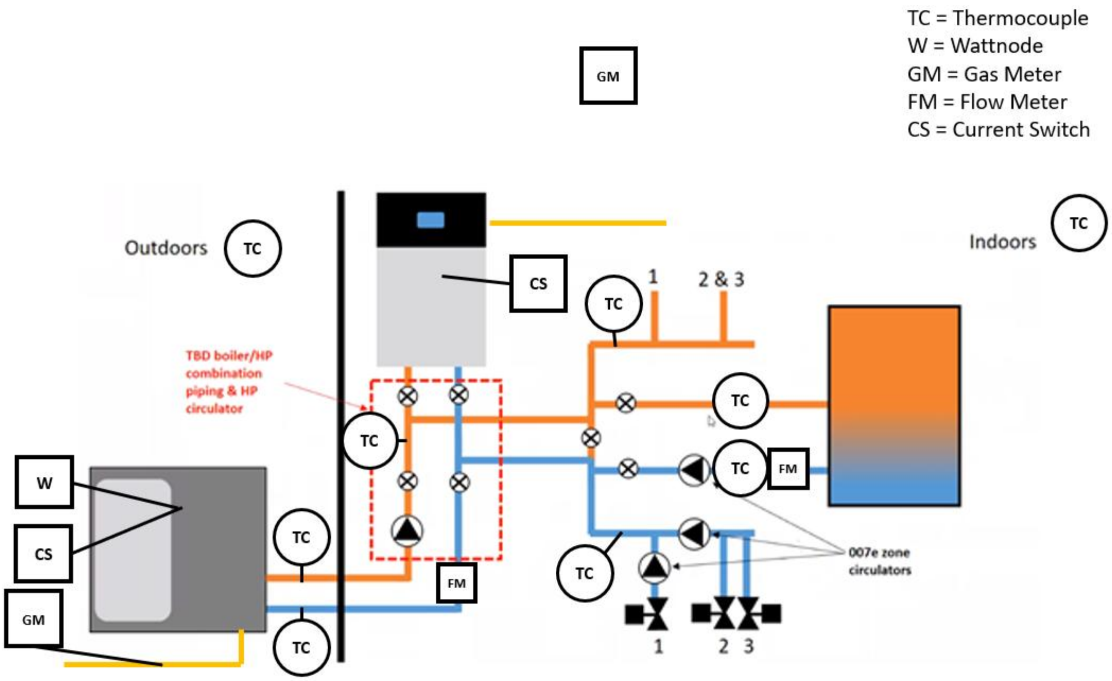

Figure 16: Simplified Diagram of Integrated GAHP System for Hot Water and Space Heating La Porte Site

Site 3: Single Family Forced Air System Site (New Carlisle, IN)

The last single family host site is in New Carlisle, IN with a forced-air heat distribution. The home is approximately 3,470 ft^2 and the building is approximately 22 years old. No major improvements were made to the building's thermal envelope since construction. The original central furnace was a Trane AUD-120C954J1, 120,000 BTU/hr gas heating furnace with an AFUE of 80%, while the original tank water heater was a Rudd PH50, 40,000 BTU/hr gas input, with a UEF of .54 with 50 Gal storage. The host site provided access to their past utility bills, for the gas meter that served only the boiler and water heater. From the data (figure below), GTI estimated the following:

- With the gas consumption weather normalized, with the space heating isolated from DHW assuming summer months are DHW-only, the building heating load is normalized by heating degree day (HDD). From this analysis:
    - Using the nameplate data on the boiler, the peak load observed is estimated as .70 MMBtu/day.
    - If the GAHP installed meets 100% of that load, assuming that the COP_{Gas} of the GAHP at the very cold winter conditions is 1.10, this yields 8 EFLH for the GAHP, which indicates this GAHP may be undersized for this application.
- The DHW load was not determined

Figure 17: Original Boiler and Water Heater at New Carlisle Site

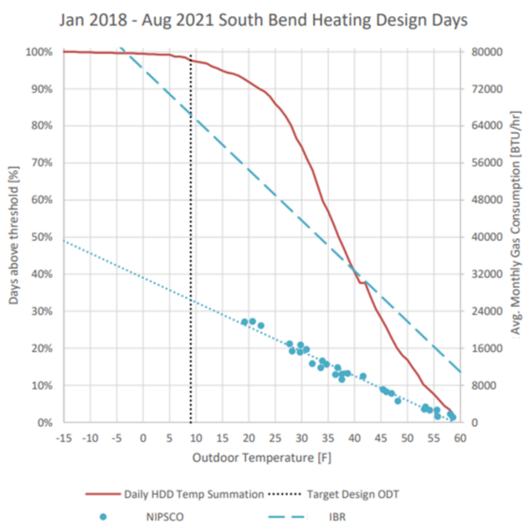

Figure 18: Utility Billing Data from New Carlisle Demonstration Site from 2018-2021

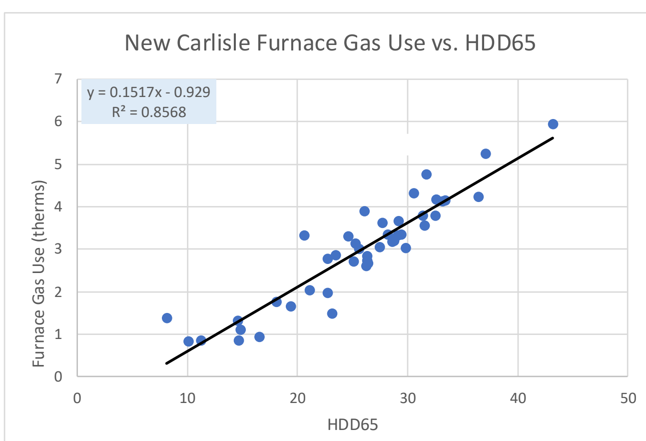

Figure 19: HOBO Logger Normalized Site Gas Consumption – Space Heating Only (Estimated)

In early 2022, the GAHP and backup boiler were installed at the site, replacing the original central furnace and water heater. The new boiler is the same model but a smaller size than Site #2, which is 95% AFUE with 55 kBtu/h input. The boiler was installed indoors, while the GAHP was installed outdoors. The heating system loop, per the diagram below, includes the GAHP and boiler in parallel supplying either the DHW tank or air handling unit (AHU) with hot water. This allows the heating system to quickly switchover to boiler if needed, and also switch between space heat and DHW heating calls. When active, the GAHP was expected to serve both loads while the boiler was expected to provide back-up heat for the GAHP.

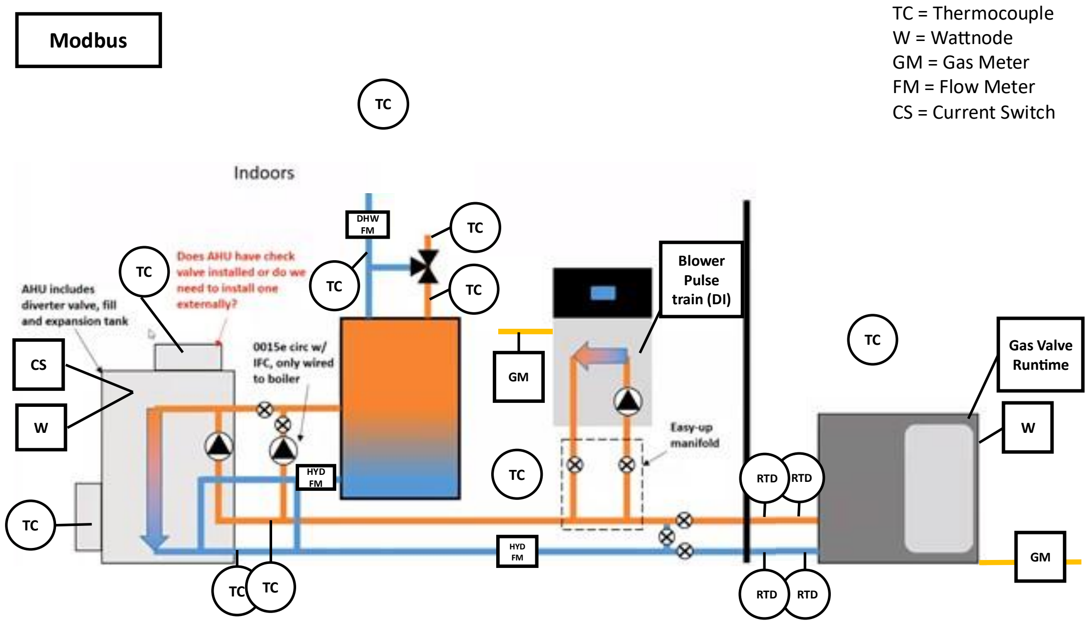

Figure 20: Simplified Diagram of Integrated GAHP System for Hot Water and Space Heating at New Carlisle Site

Monitoring and Methodology

Site 1: Evanston Multifamily Home

The full details of the monitoring and methodology of the multifamily home site was documented in previous reporting under NEEA contract 51799 and are reproduced in an appendix for reference. Minor changes to the plan are documented in this section here.

At the Evanston field demonstration site, several changes were made to the data acquisition and control system (DACS) compared to previous heating seasons. This includes the installation of a check valve in the GAHP hydronic loop (connecting outdoor GAHP to indoor heat exchanger) to reduce the effect of unwanted thermosyphons during periods when the GAHP is offline, 'leaking' heat from the building through the outdoor GAHP passively. This check valve was installed in the hydronic supply line external and close to the GAHP unit.

To improve user satisfaction of the DHW output and further yield energy savings, the DHW recirculation pump (located between potable DHW return to the storage tank) was changed out to provide demand-based actuation of the pump, rather than 24/7 continuous operation.

Through prior field test research, GTI has assessed the impact and reliability of various recirculation control methodologies and recommends this option for the site[15]. This should impose minimal effect on the residents' perceived available hot water, yet impactfully reduce the building's load, subsequently improving the performance of the hybrid GAHP and boiler operation.

Additional onsite changes include the re-plumbing and re-insulating of the condensate drainage line. Due to the updated configuration of the GAHP's design, a remote-controlled heat-trace will be installed along the portion of condensate tubing exposed to the environment. Other control hardware including relays and pumps will be modified as appropriate to communicate with SMTI's new integrated circuit control board.

With the replacement of the heat pump with a more polished, "pre-production", model, the DACS lost the accessibility to measure the GAHP's desorber, evaporator inlet, and evaporator outlet temperatures via test ports external to the unit. In other words, the spare instrumentation ports in prior GAHP unit prototypes were not available in the production-ready model. These temperatures are still monitored by SMTI's control board, however, GTI will not be capturing these data independently. A flue temperature measurement probe will be reversibly installed in the stainless-steel flue pipe used with this pre-production prototype model. Lastly, due to the intricacies of the outdoor temperature reset curve controls and GAHP contributions in space heating, to ensure proper space heating loads are met for each of the six zones, thermocouples were added to monitor the state of the hydronic actuators that control the opening and closing of each zone.

Site 2: La Porte Single Family Hydronic Site

Like the Evanston Multifamily home, the new sites in Indiana were equipped with custom plumbing, ports, and sensors to accommodate the DACS installation for the duration of the field demonstration. During site visits and through solicitation of project partners, GTI captured batch measurements of the following, to be used in model development and analysis:

- True RMS power measurements will be made on existing operating components (e.g. pumps), to estimate pump power consumption
- Natural gas heating value and inlet natural gas pressure (at meters).
- Excess air level in flue gases for GAHP, as measured using a portable combustion analyzer.

15 An example study performed by GTI for the State of Minnesota is found here.

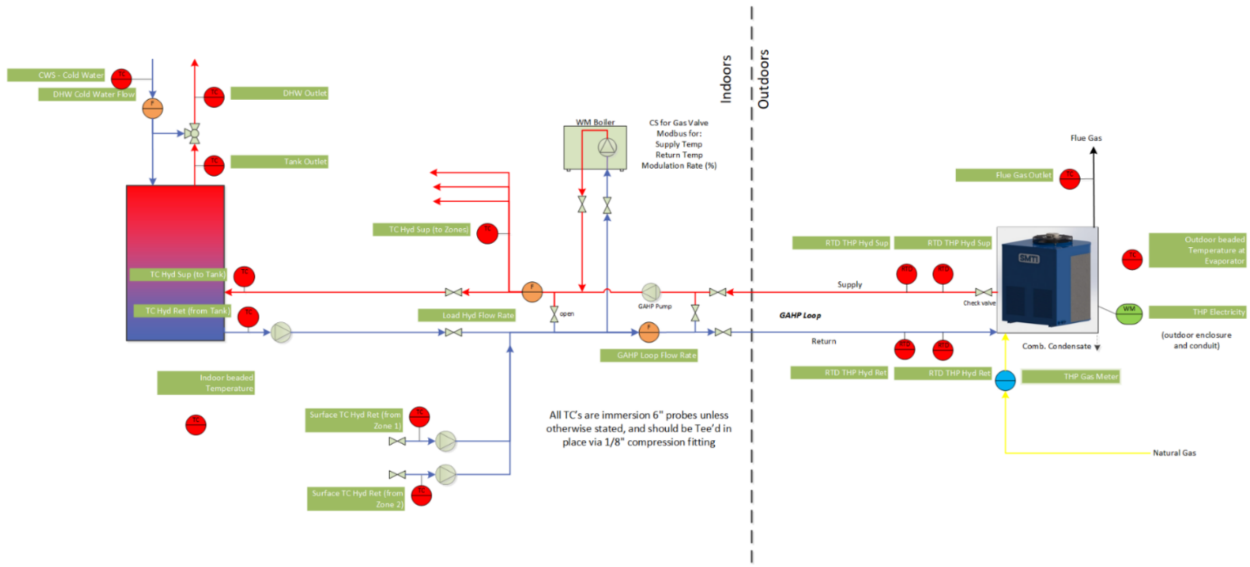

Figure 21: Diagram of Instrumentation during GAHP System Monitoring at La Porte

Table 2: Continuous Measurement Points at La Porte- Overview

Measurement	Method	Accuracy	Measurement Point – Indoors	Measurement Point – Outdoors
Natural Gas Input	Positive displacement diaphragm meter with integrated pulser	±1%, Temperature Compensated	N/A	- GAHP
Electricity Input	True RMS power transducer with split core current transformers (CT)	±0.5% (Meter), ±0.75% (CT)	N/A	- GAHP
Water Flow	In-line turbine flow meter with pulse output	±2% over range or better	- IST Cold Water Inlet	N/A
Recirculating Loop Flow	Magnetic-inductive flow meter	±2% of range or better, effectively ±0.5 GPM or better	-GAHP Hydronic Loop Flow Rate	N/A
Water Temperature (Hot/Cold & Supply/Return) & GAHP Internal Temperatures	Thermocouple Type T	±1.8 °F	- Main Loop Supply/Return to/from Tank - Indirect Storage Tank Outlet - Indirect Storage Tank DHW Supply - Indirect Storage Tank Cold Inlet - Zone 1 Return - Zone 2 Return -GAHP Supply to Zones	N/A
Water Temperature (Hot/Cold & Supply/Return)	RTD sensor	± 0.81 °F	N/A	- GAHP Loop Supply/Return*

Measurement	Method	Accuracy	Measurement Point – Indoors	Measurement Point – Outdoors
Air / Flue Gas Temperature	Thermocouple Type T	±1.5°F	- Mechanical Room	- GAHP Flue Gas - Ambient at GAHP
Ambient Weather Condition	Publicly Accessible Weather Station	N/A	N/A	- Outdoors
Equipment Runtime	Dry contact	N/A	- Boiler Gas Valve On/Off	- GAHP Gas Valve On/Off
Boiler Specific	Modbus	N/A	- Boiler Status - Boiler Gas Valve On/Off - Circulation Pumps - Supply Temperature - Return Temperature	N/A
* These measurements are calibrated in-situ, using a dry-well calibrator				

Site 3: New Carlisle Single Family Forced-Air Site

The New Carlisle forced air system site featured a similar plan to the hydronic system site but was customized to the hydronic zone heating measuring devices with complete air handler monitoring of power consumption, AHU hydronic, and AHU air temperatures – noting that the AHU was from the manufacturer (SMTI) however the measurements were made by the project team. Figure 22 shows a detailed view of the instrumentation and control layout for the New Carlisle forced air system site.

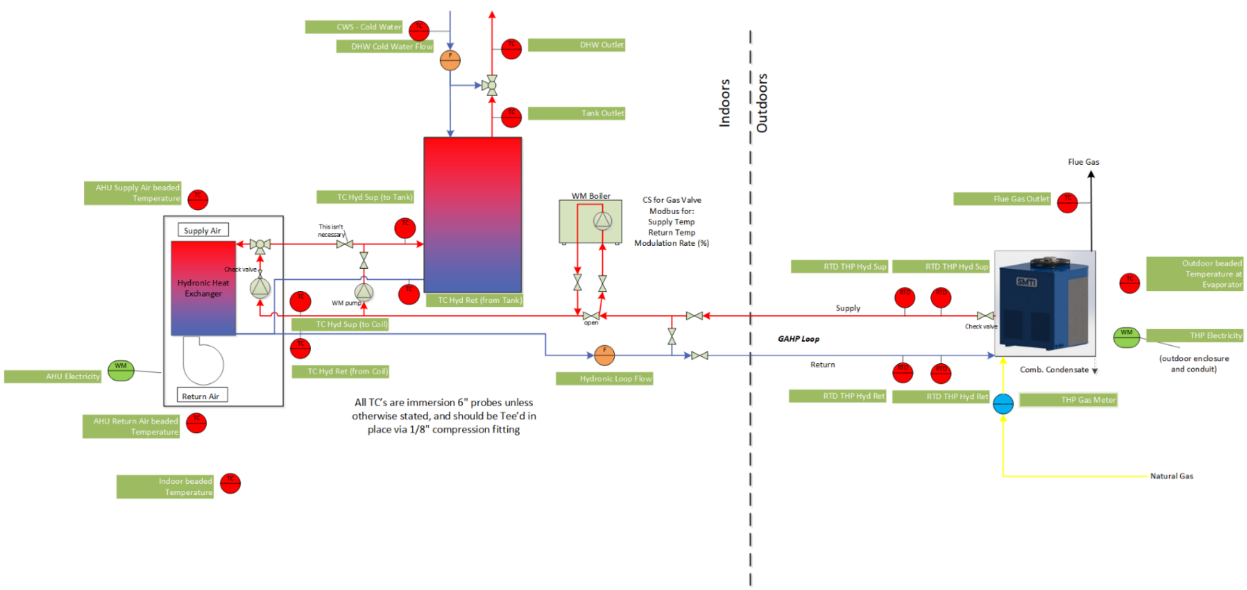

Figure 22: Diagram of Instrumentation during GAHP System Monitoring at New Carlisle

As described in the above monitoring methodology, measurements outlined in Table 3 and Table 2 will be captured on a continuous basis. During site visits and through solicitation of project partners, GTI will capture batch measurements of the following, to be used in model development and analysis:

- True RMS power measurements will be made on existing operating components (e.g. pumps)

- Natural gas heating value and inlet natural gas pressure (at meters).
- Excess air level in flue gases for GAHP, as measured using a portable combustion analyzer.

Table 3: Continuous Measurement Points at New Carlisle - Overview

Measurement	Method	Accuracy	Measurement Point – Indoors	Measurement Point – Outdoors
Natural Gas Input	Positive displacement diaphragm meter with integrated pulse encoder	±1%, Temperature Compensated	N/A	- GAHP
Electricity Input	True RMS power transducer with split core current transformers (CT)	±0.5% (Meter), ±0.75% (CT)	- AHU	- GAHP
Water Flow	In-line turbine flow meter with pulse output	±2% over range or better	- IST Cold Water Inlet	N/A
Recirculating Loop Flow	Magnetic-inductive flow meter	±2% of range or better, effectively ±0.5 GPM or better	-GAHP Hydronic Loop Flow Rate	N/A
Water Temperature (Hot/Cold & Supply/Return) & GAHP Internal Temperatures	Thermocouple Type T	±1.8 °F	- Main Loop Supply/Return to/from Tank - Main Loop Supply/Return to/from AHU - Indirect Storage Tank Outlet - Indirect Storage Tank DHW Supply - Indirect Storage Tank Cold Inlet - AHU Supply/Return	N/A
Water Temperature (Hot/Cold & Supply/Return)	RTD sensor	± 0.81 °F	N/A	- GAHP Loop Supply/Return*
Air / Flue Gas Temperature	Thermocouple Type T	±1.5°F	- Mechanical Room	- GAHP Flue Gas - Ambient at GAHP
Ambient Weather Condition	Publicly Accessible Weather Station	N/A	N/A	- Outdoors
Equipment Runtime	Dry contact	N/A	- Boiler Gas Valve On/Off	- GAHP Gas Valve On/Off
Boiler Specific	Modbus	N/A	- Boiler Status - Boiler Gas Valve On/Off - Circulation Pumps - Supply Temperature - Return Temperature	N/A
* These measurements are calibrated in-situ, using a dry-well calibrator				

Data Quality Control and Analysis

With the data quality control and analysis at the multifamily home site outlined in the appendix, was covered in the previous reporting under project 51799, this section outlines how the same plan was adapted to the two new single family homes in Indiana replacing measurement points and metrics with key components of each of the new systems (AHU, Space heating to zones, etc.). The largest change to the data quality control and analysis was incorporating automated data quality control utilizing automatic daily data file transfers using file transfer protocol (FTP), to designated Azure Blob Storage locations. From these locations, the data was automatically ingested and refreshed in PowerBI where visualizations of measurement values and key performance metrics, were used for quality control and preliminary analysis. This helped GTI identify and resolve issues with data collection and the project team could seek to resolve GAHP system and DACS operational issues to minimize data loss. In addition, data was manually downloaded regularly, analyzed, and reviewed on a weekly basis to spot issues, trends, and identify needs for field servicing of DACS or the GAHP systems.

Demonstration Site Installation, Commissioning, and Servicing

The following sections highlight the various commissioning and services required at the three field sites. For a more detailed and technical description of the issues that occurred, please see the informative final appendix section.

Site 1: Evanston Multifamily Home

Installation and commissioning of the Evanston Multifamily home GAHP-Boiler Combi system prior to 2022 was documented in the prior NEEA reporting under contract 51799, which ran through the end of 2021 and at the end of this project the GAHP at Evanston required replacement. Starting in February, 2022, the project team began making heating system changes to improve system operation and performance. First the contractor installed a check valve on the boiler supply, re-installed the GAHP condensate line, added a flue mount for the GAHP, and prepared the electrical wiring for the upcoming GAHP swap-out – for ease of access and communications, noting that the GAHP units had equivalent power requirements. To prepare for this swap, GTI also helped install a heat trace on the hydronic lines outside and installed a new Wi-Fi access point to be used by SMTI to remote connect to the new GAHP to monitor operation. In addition to these changes and additions to the site, it was observed in 2022 that when the buffer tank was hotter than the GAHP hydronic temperatures, that a thermosiphon was occurring that was pulling heat from the buffer tank back into the GAHP hydronic loop, increasing losses to the colder outdoors. During periods when the GAHP was idle, it was observed that the warmer indoors and the colder outdoors (incl. GAHP) portion of this hydronic water/glycol loop would circulate due to the temperature/density gradient, increasing the apparent heat loss from the GAHP buffer tank and other parts of the system. A check valve was installed in mid-winter to eliminate this backflow, now a standard part in these kinds of installations. Hydronic lines were also fully insulated later in 2022 to minimize thermal losses.

Figure 23: Evanston Multifamily Home Installation of Check Valve 2022

In July 2022 the GAHP was swapped for an updated prototype design. Key differences in this newer GAHP unit include:

- Replacing the belt drive with a direct drive
- Replacing the flue transitions with updated versions.
- Other confidential improvements on design and engineering, some listed in the final appendix

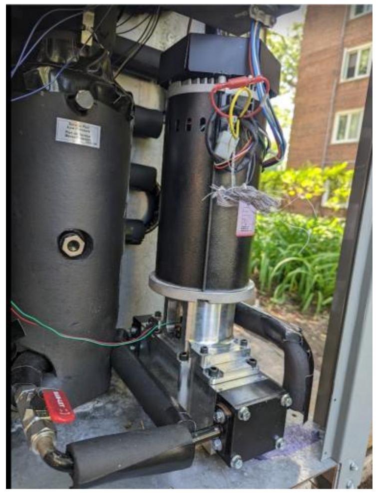

Figure 24: 2022 New Evanston GAHP with Direct Drive

Later after extended operation, the direct-drive solution pump on the GAHP failed. Shortly after, the solution pump was analyzed at SMTI and the failure analysis concluded that the cause of failure was due to the drive train bearing pressing into the housing causing the outer housing to fall down off of the bearing leading to uneven loading. This broke the inner cage in the ball bearing, meaning that it could not move anymore. This failure was not possible in the previous iteration of the solution pump which was a belt drive due to vertical alignment of the bearings. The new direct-drive has bearings that can move, which lead to failure. Future direct-drive solution pumps will now incorporate a design change to prevent the bearings from dropping, a finding that was propagated to other similar direct-drive GAHPs. Several weeks after its discovery, the issue was resolved, and the modified solution pump was installed in the GAHP and it was recommissioned.

In terms of controls and DACS-related matters, there were two major items. In July, 2022 GTI discovered the Boiler 2 Return temperature sensor was not in the correct location (for water heating only), this issue was corrected and affected measurements were compensated for. The second item concerned adjustments to the overall system controls. While initially during the 2022-2023 heating season the heat timer controls were set to a more conservative outdoor setback curve, during an Arctic blast of cold in December 2022, the project team had to adjust the setback curve higher in anticipation of comfort issues, which after feedback from the host site this was further adjusted higher. This issue was driven by a feature of prior monitoring periods wherein the supply water target from the GAHP/boiler system needed to be lower than baseline (180°F) to accommodate the upper return water limitations of the GAHP system (< 160°F). The project team consulted the boiler OEM and elected to operate with this higher target, thus limiting GAHP operation, through this cold snap period. Later the project team discovered and confirmed that the controls for the zone valve serving the unit driving comfort complaints was wired incorrectly, a site issue, not a GAHP/boiler system issue. While the zone control was wired correctly to the in-unit thermostat, and thus could open and close, the wiring to the heat timer was missing.

Outside of changes to the field site relating to the GAHP and its controls, in 2022 and 2023, the project team also installed and commissioned an On-Demand Recirculation Pump Controls (ODRPC) with specifications PT-OD1000[16]. A summary of the ODRPC can be viewed in the informative appendix, along with its impact on energy and water savings.

Site 2 and 3: La Porte Hydronic System and New Carlisle Forced-Air System

In February 2022, with the help of the boiler OEM and SMTI, the project team installed the retrofit GAHP Combi systems at both single family sites. The La Porte hydronic heating site featured a fully hydronic loop that feeds the indirect storage tank for DHW heating, and heats the space heating loops which sends heat to the three zones of the house, seen in Figure 16 and Figure 21, with heat distribution by radiators.

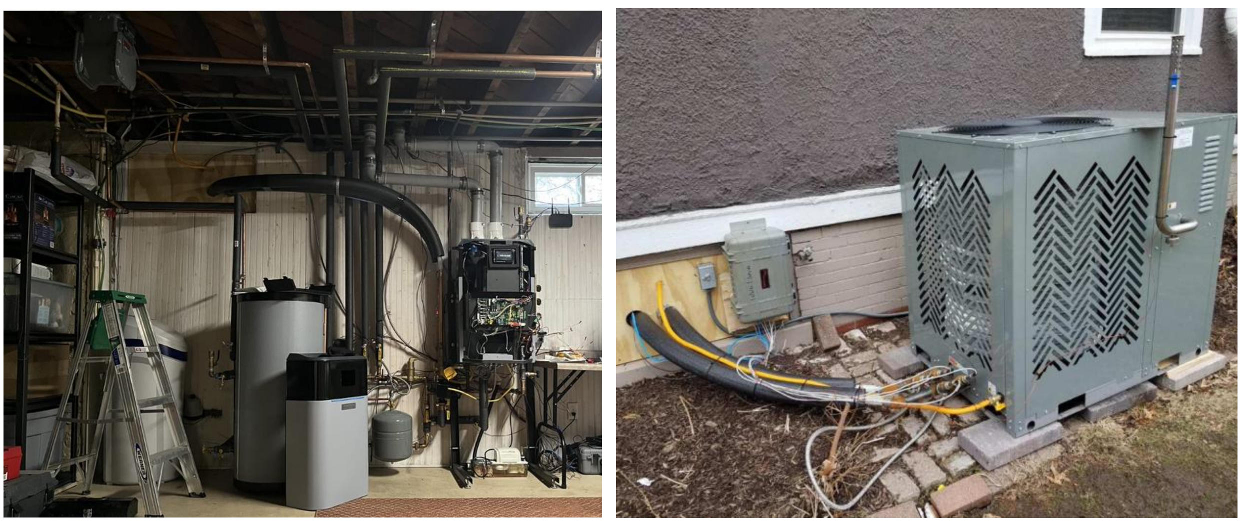

Figure 25: Single family GAHP Combi at La Porte Hydronic Heating Site

The New Carlisle forced air heating site featured a hydronic loop that feeds the indirect storage tank for DHW and heats the hydronic loop of the air handler which sends heat to the house. This house features a higher heating demand than at La Porte, and it was estimated that at peak heating load, the GAHP would require supplementary heat from the compact boiler.

16 https://www.ptelectronicsinc.com/

Figure 26: Single family GAHP Combi at New Carlisle Forced Air Heating Site

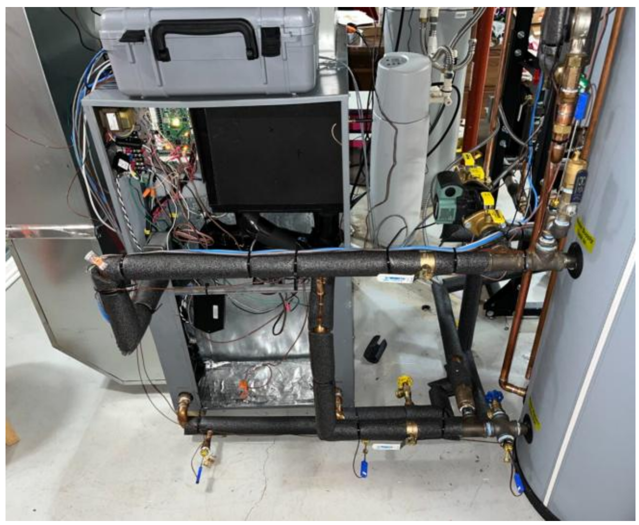

Figure 27: Single family GAHP Combi at New Carlisle Forced Air Heating Site – AHU Focus

Shortly after installation and commissioning, it was observed that the La Porte field site GAHP high temperature alarm continued to alert the project team. As a precaution, the project team shut the unit off in early March, 2022. Several days later the project team investigated the unit, and the likely cause was determined to be the internal temperature sensor (Desorber resistance temperature detectors, or “RTD” and thermistors) wiring on the wire harness. Within a couple weeks, the wire harness was replaced, and the unit was operational once more. The GAHP was operational for several weeks between March and April 2022 when a refrigerant leak was detected and the unit was temporarily disabled to investigate. Meanwhile during the same commissioning period, the New Carlisle GAHP was operational from February through early March, 2022, however this unit also registered a refrigerant leak. After a field site visit to locate the cause for failure, it was determined that the leak was likely caused by a faulty pressure relief valve (PRV), an OEM part for the manufacturer, which was installed on both the La Porte and New Carlisle units. A similar GAHP that was being studied in a parallel project saw similar issues with the same PRV in which it occasionally would release refrigerant well below the set pressure. Despite only recording GAHP operation in 2022 on the order of a few weeks from each single family residential site, the sites did permit collecting a baseline period of the retrofit boiler-only operation. This provided a baseline comparison to compare for the subsequent GAHP combi operating period in the 2022-2023 heating season, in addition to baseline heating data recorded before the initial GAHP commissioning.

In November 2022, with the help of the boiler OEM and SMTI, the project team swapped out the GAHP units with updated models. Key differences in the newer GAHP units include:

- Putting a reinforcement band on both units around the weak joint.
- Replacing the PRVs.
- Replacing the flue transitions with updated versions.
- Adding reinforcement to the evaporator coils that helps keep them in place during transit.

After reconnecting the hydronic lines, controls wiring, and commissioning the units, they operated from November 2022 through December 2023, with an outage in March-April due to the New Carlisle GAHP facing the same solution pump issue that affected the Evanston GAHP in that same March. The solution pump was shipped to SMTI where it was refurbished, and the New Carlisle GAHP was recommissioned in May, 2023.

Finally, in August, 2023, the project team reflashed firmware on the New Carlisle and La Porte GAHPs to update its system controls (e.g. optimized control of the glide). While at the New Carlisle field site, non-condensables were bled, which are a part of the preventive maintenance of the prototype heat pumps to optimize system performance. When non-condensables build up, they lead to poor performance by artificially raising system pressures, among other factors[17]. When servicing, the team replaced a faulty relay that had prevented the evaporator fan from running, limiting performance. From this point forward, both single family GAHP units ran through the remainder of the project monitoring period.

17 https://www.osti.gov/biblio/1886933

Hybrid System Demonstration Results

For the monitoring period in this study, the period of performances differs between the multifamily building and the single family residential sites. This section focuses on the complete space/water heating results for all three sites, while details on the DHW-only operation are descried at length in an informative appendix.

- **Multifamily Site:** At the start of the project, the multifamily site GAHP unit was operational in Combi mode. Prior data collected from the past project of the GAHP operating in DHW-Only mode was also utilized in the analysis.
- **Single Family Sites:** At the single family sites, the period of performance for boiler-only operation began in March 2022, and ended in early October of that same year. The performance of the GAHP units began shortly after in November, 2022 and continued through the end of the project. Therefore, there are distinct periods of performance for each site based on the operating mode being either DHW-only or Combi, and based on the equipment that was operational; boiler/s only or GAHP and boiler/s

Site 1: Evanston Multifamily Site Combined Space/Water Heating ("Combi")

This section will summarize the GAHP and boiler system performance during the 2022-2023 heating season in which the GAHP and boiler system operated in combined space heating (SH) and DHW mode, or "combi" mode. During the previous 2022 DHW-only period a DHW recirculation pump was installed, and later frequent changes were made to the space heating setback and system controls throughout the end of 2022 and beginning of 2023. As mentioned earlier in this report, given a variety of reasons, analysis of this operational period will be brief and GAHP-focused. The figure below illustrates the weather conditions experienced throughout the 2022-2023 heating season in Chicago, IL. Overall, the 2022-2023 heating season accumulated 5,027 HDD65 compared to the 30-Year Normal of 5,753. This equates to a deficit of -726 HDD65, or 87% normal. The subsequent figure reviews the loads during this monitoring period at the site.

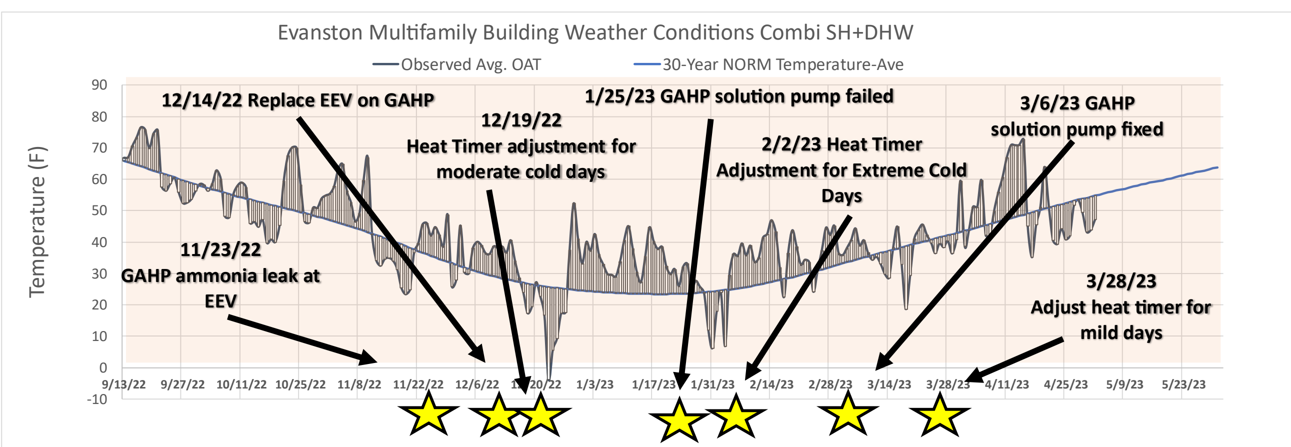

Figure 28: Summary of 2022-2023 Heating Season in Chicago, IL Compared to 30-Year Normals

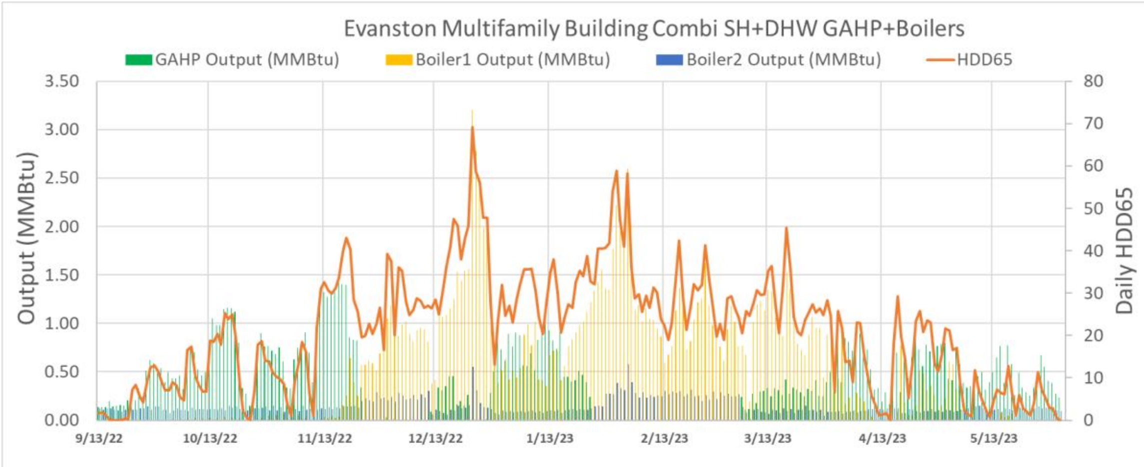

Figure 29: Summary of 2022-2023 GAHP + Boilers Combi SH and DHW Load Profile at Multifamily Site

The above figure illustrates that the GAHP was able to contribute to the space heating load at warmer outside air temperatures during the shoulder season and early heating season. However, as outside air temperatures dipped and heating demand increased, heat timer settings were changed to adjust the outdoor setback curve upwards, resulting in a decrease in GAHP contribution. This is evident in the plot, as well as outages which affected the GAHP.

Operating Efficiency

The operating efficiency of the system in combi operation can be broken down into two parts, first is the efficiency of the GAHP itself, which is a function of ambient operating conditions and loading (modulation & loop temperatures), and secondarily the delivered efficiency, which measures the ability for the heating system to distribute heat from the GAHP and boilers to the space and water heating outputs. Compared to the DHW-only operational period (see appendix), the load is significantly greater during the space heating season compared to the DHW load. When it comes to the GAHP's efficiency, the COP_gas was analyzed against its cycling conditions. For this analysis, DHW-only GAHP performance was included as well to compare to the larger output from the GAHP in combi operation.

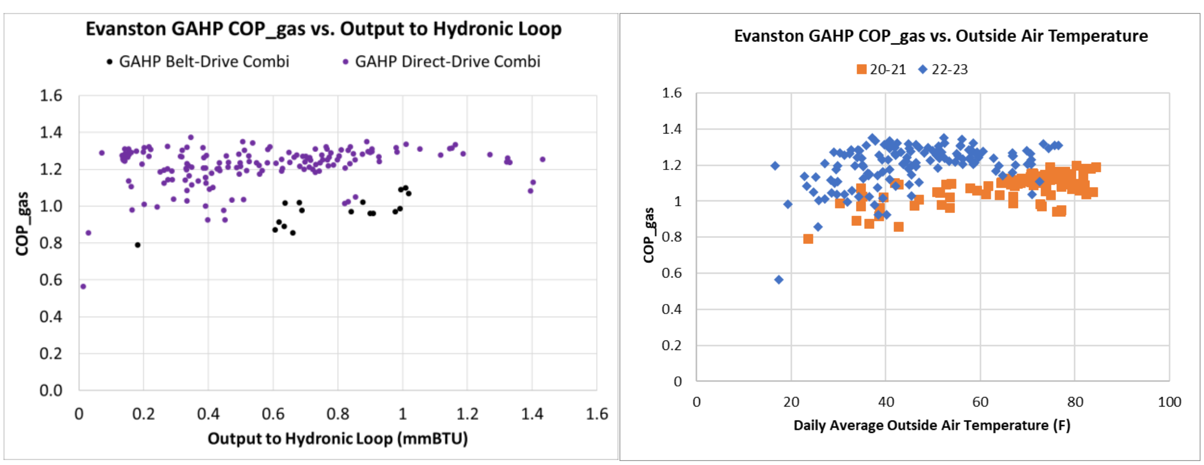

Figure 30: GAHP COP_gas vs. Output to Hydronic Loop and Daily Average Outside Air Temperature

The above figure illustrates that generally, the lower the load (output to hydronic loop), the poorer the performance of the heating system, slight but measurable. It is also seen that there is a modest increase in COP for the direct-drive GAHP compared to the belt-drive GAHP, which is primarily a factor of unit reliability, and system controls issues noted in the appendix. For the full monitoring period, the contributions from the GAHP and Boilers are dependent on outside air temperatures and heat timer controls. The following plot summarizes the gas consumption of the heating equipment on average given all of the daily outside air temperatures observed.

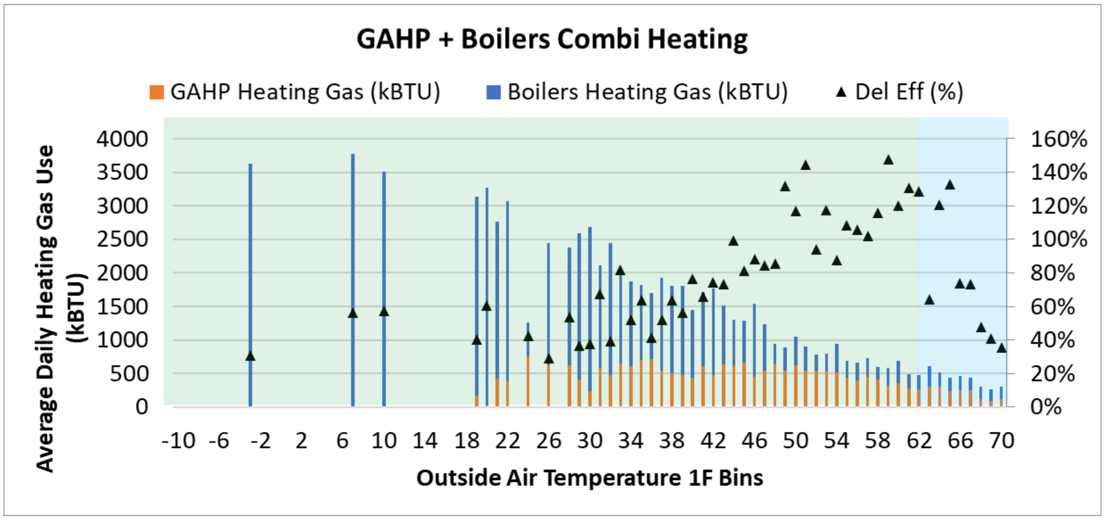

Figure 31: GAHP and Boilers Daily Heating Gas Consumption Contributions and Delivered Efficiency vs. Outside Air Temperature at Multifamily Site

The above figure illustrates that at colder outside temperature conditions, the system relies solely on the boilers – which is a feature of the controls changes noted previously. Representing approximately and effective 12 EFLH at these colder conditions, the GAHP contributes ~700 kBtu/day of output at maximum, independent of outdoor conditions, which is a feature of the staging controls and plumbing for DHW supply[18]. Once the GAHP takes on a larger and larger proportion of total output, from roughly outside air temperature (OAT) of 38°F to 66°F, the GAHP can drive higher system efficiencies (light green region). For warmer OATs above 66°F, the combi system is likely operating in mostly DHW operation (light blue region), leading to lower delivered efficiencies, defined as the total energy delivered by boilers/GAHP as DHW and space heating compared to the total energy input to the same boilers/GAHP, as outlined in the appendix.

Controls Considerations

While the above analysis illustrates that the GAHP integration to the boiler array resulted in greater overall efficiency, something proven in prior reporting periods, it is important to examine the impact of system controls. The space heating system gas consumption was dependent on the heat timer outdoor setback curve, which dictated how much heat was needed to boost the main supply to the zones for space heating, also driving the staging of the boilers

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18 A known issue that arose in the analysis under the prior reporting stage, under NEEA Contract 51799, is that the system plumbing *limits* the GAHP from only serving the **actual** DHW load but only allows Boiler #2 to activate to meet DHW system losses (standby, recirculation, etc.).

relative to the GAHP. The outdoor setback curve was changed frequently throughout the past two years to ensure the comfort of the field site residents, so the following analysis was focused not only how the total gas use was dependent on the heating demand, but also the heating load. To understand the various outdoor setback curves, they were compared in the following plot. Note that the largest constraint to the heating system controls was that the GAHP (and buffer tank) contribution to the space heating loop with a limitation on return temperature, while the boilers could heat the space heating loop more than 180°F. Therefore, for cold enough outside air temperatures, the GAHP could not appreciably contribute to the space heating loop, which was a team decision given the aforementioned comfort challenges, though the perceived comfort issues were misdiagnosed, not attributed to the GAHP supply temperatures but rather found to be an issue with zone valve controls outside of this project's scope and outside of the mechanical room. This served as the basis for why the heat timer settings were frequently changed.

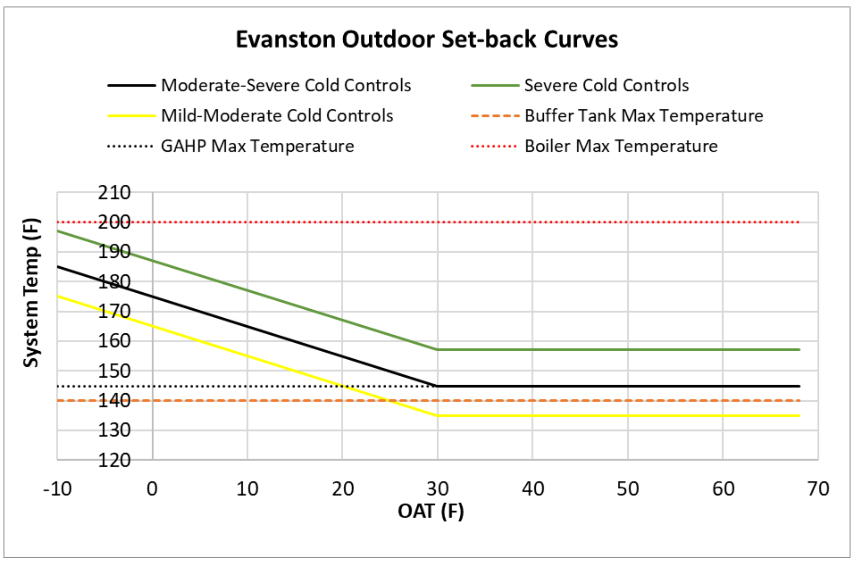


Figure 32: Evanston Outdoor Set-back Curves

Energy Modeling and Extrapolations

Given the timeline of events in Figure 28, and the frequent changes to the outdoor setback curve visualized in Figure 32 above, the following Figure below illustrates the space heating load vs. the heating demand for each general monitoring period.

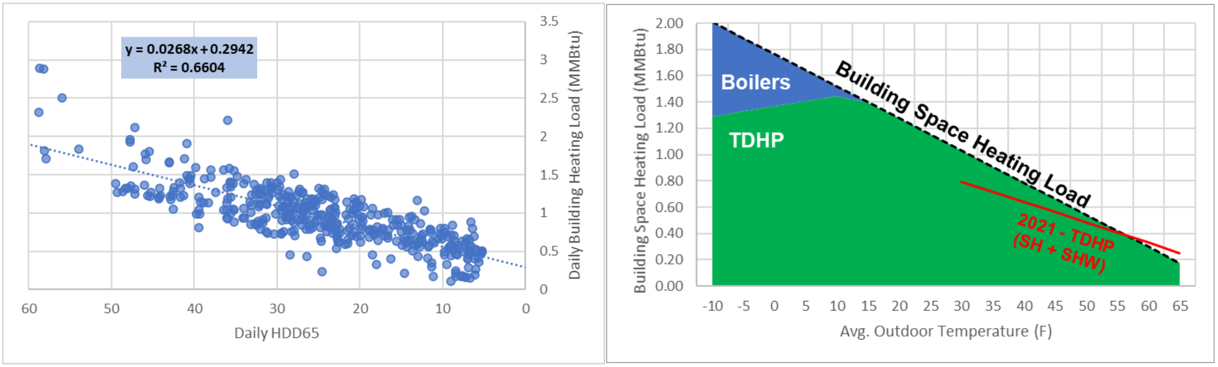


Figure 33: Comparison of Output as Space Heat vs. HDD65 During Combi Operation from 2021-2022 and 2022-2023 Heating Seasons Evanston (Left) and Estimated Capacity Curve from 2019-2020 Initial Study (Right)

During the 2021-2022 heating season, the heat timer settings were held constant with the outdoor setback curve set to the mild-moderate cold curve. This allowed for the greatest GAHP contribution (or load fraction) for OAT > 25°F, but meant that at colder OAT, the units would be at risk of underheating the space. During the 2022-2023 heating season, the heat timer settings started out using the same mild-moderate cold curve, but after reviewing the dataset before forecasted cold weather, the project team adjusted the outdoor setback curve higher, to the moderate-severe cold curve. At this setting, the GAHP could only contribute to the space heating loop when OAT was higher than 30°F, since the heat timer would call for a 145°F main supply temperature.

In January, 2023, the GAHP was put offline, and the project team adjusted the outdoor setback curve higher, to the severe cold curve. At this time, the project team was also able to diagnose a modest amount of heating system related issues that could have contributed to the space heating issues in the unit which gave the complaint. This included the finding of air in the system, an incorrectly specified zone valve/actuator being used for the unit, the wrong relay being used to control the GAHP and main system circulator. It was also no surprise the project team found out that the apartment unit had been using resistance electric heaters to keep their unit warm enough. This contribution of space heating would not be accounted for in the analysis, and if other units were also using similar supplementary heating, it could affect the ability of the project team to analyze the results. By March, the GAHP was fixed, and temperatures had moderated, so that allowed the project team to finally adjust the outdoor set-back curve down to the mild-moderate cold curve, allowing the GAHP to contribute to space heating once again, a process of fine tuning that can be automated.

Figure 33 conveys a story in which the heating system delivered less overall heat in 2021-2022 (GAHP Belt-driven) compared to 2022-2023 (GAHP Direct drive), which perfectly explains the storyline above. It was expected that given the rise in the heat timer outdoor set-back curve for a majority of the 2022-2023 heating season that more heat would be delivered compared to 2021-2022. This also explains why the 2022-2023 "GAHP Direct-Drive and Boilers" dataset showed various clusters of datapoints which coordinated with different heat timer outdoor setback curves. The next figure illustrates the total gas input for the same demonstration periods. In addition, utility bill gas consumption data from October, 2015 to May, 2018 was included in the comparison.

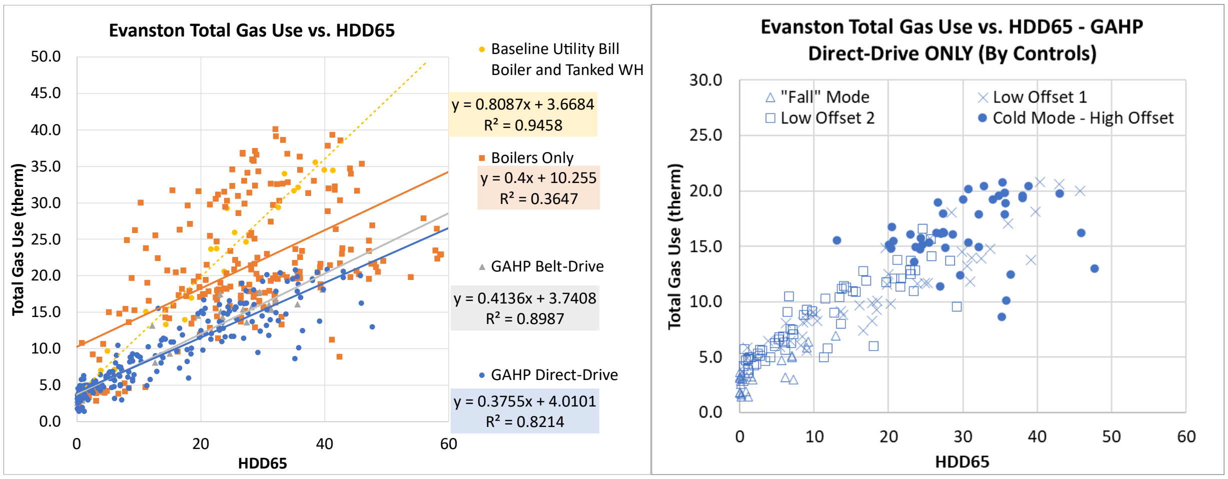


Figure 34: Comparison of Evanston Total Gas Use vs. HDD65 2015-2018 Utility Bill, and Combi Operation from 2021-2022 and 2022-2023 Heating Seasons

Despite delivering greater heating to the building in 2022-2023 for both GAHP inclusive datasets, it was observed that both the GAHP Belt-Drive, and GAHP Direct-Drive operation in 2022-2023 consumed less gas than the Boilers Only period, speaking to the efficiency benefits of the GAHP/boiler hybrid operating periods. In the prior chart, there is significant scatter in the boilers-only operating periods, which was likely affected by the following which occurred during this period:

- Frequent adjustments of the system controls, as noted previously, including the introduction of the ODRPC
- Fully insulating all pipes
- Installation of a check-valve on the Buffer Tank Supply to Main System Supply loop to stop a thermosiphon from occurring which was pulling heat out to the GAHP while it was decommissioned
- Main Supply circulator being hard wired 24/7 due to incorrect relay being installed
- Mis-wired actuator (zone valve) being used for one unit, leading to insufficient heat distribution

Due to the wide variability in heat timer settings and total hydronic heating output vs. HDD65 linearizations, to compare the energy savings of the GAHP + Boiler system, the performance curves were instead made by normalizing total hydronic energy output based on the HDD65 – this allowed for combined DHW and SH outputs to be included together. The following two sets of performance linearizations illustrate the heating appliance specific performances, as well as the combined system performances.

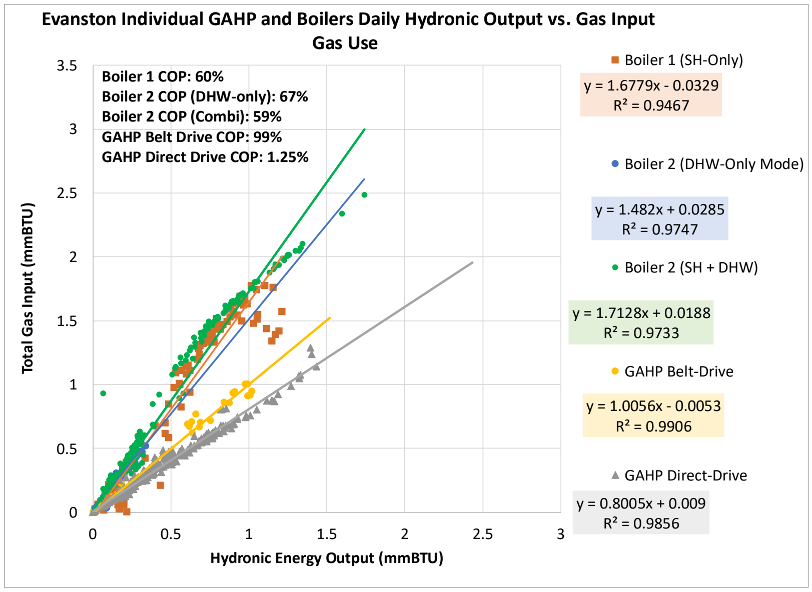


Figure 35: Heating Appliance Performance Curves at Evanston Multifamily Home

By linearizing the individual heating contributions of each heating appliance above and treating "hydronic energy output" as total output from each unit to the hydronic loops (before it is split to space vs. water heating), performance curves were generated to illustrate each appliance's heating gas efficiency. While this gives a non-exact representation of performance, it goes to illustrate the main idea of how well each appliance performed compared to one another. As expected, the best overall efficiency was the GAHP Direct-Drive system, performing modestly better than with the original Belt-Drive solution pump. The following plot illustrates the same performance curves, but for each heating system in specific operating periods, given which appliances were operational during at those times.

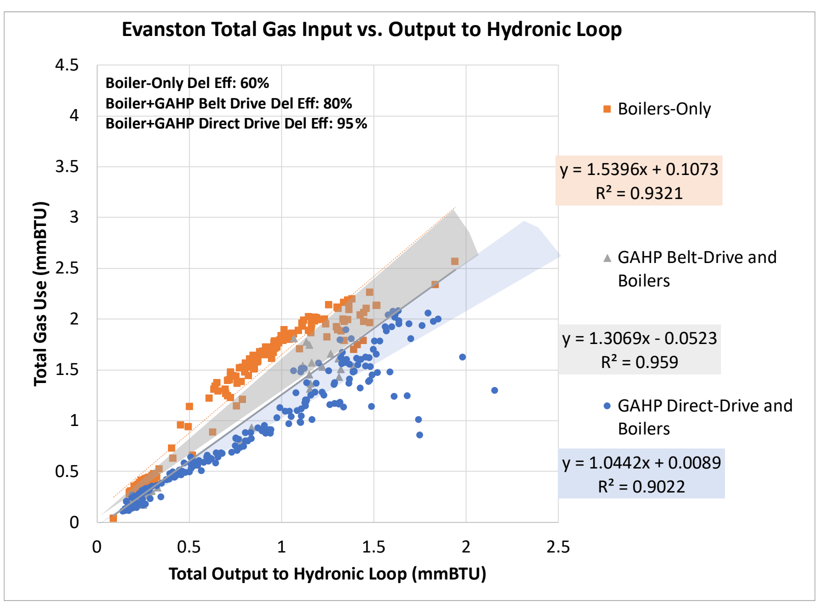


Figure 36: Combined Heating System Performance Curves at Evanston Multifamily Home

As previously explained, at the coldest OAT, the GAHP will only contribute in DHW-operation. Therefore its load fraction at its highest thermal efficiency does not contribute as much as during milder OAT days. However, for the full datasets, the GAHP Direct-Drive and boilers efficiency still operates at a modestly higher efficiency than the GAHP Belt-Drive, and significantly higher efficiency than the boilers only dataset. To model a full year of energy use using the linearizations of Figure 36, combined heating system performance, a building heating curve was also needed comparing the total heat delivered vs. the heating demand.

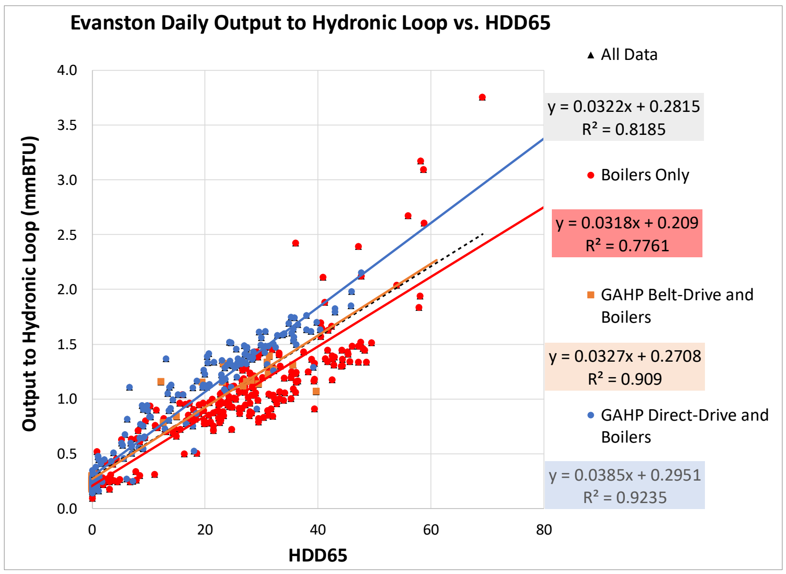


Figure 37: Combined Heating System Total Heating Output vs. HDD65 at Evanston Multifamily Home

Utilizing the heating output and performance curves in Figure 36 and Figure 37 and the National Climatic Data Center (NCDC) 30-Year normal dailies, the full season energy consumption for each monitoring period was calculated. For the extrapolation, DHW-only periods were needed and drawn from the appendix (Figure 71 and Figure 72). The results of the energy savings analysis are seen below. Note that electricity use was calculated for the GAHP & Boilers system since its electricity use is in addition to the baseline consumption.

Table 4: Energy Savings Analysis of Annual Combi and DHW-only Operation at Multifamily Building

	Gas Use (therm)	Electricity Use (GAHP Only) (kWh)	Direct-Drive GAHP Gas Savings Compared to ___ (therm)	Belt-Drive GAHP Gas Savings Compared to ___ (therm)
Direct-Drive GAHP + Boilers + ODRPC	3005	3424	-	-555.5 (-18%)
Belt-Drive GAHP + Boilers + No Recirculation	3561	4658	555.5 (16%)	-
Backup boilers Only + 24/7 Recirculation	4686	N/A	1680.2 (36%)	1124.6 (24%)

Baseline Old Baseline Boiler and Tanked WH Pre-2019 (Utility Bill) Gas (therm)	6601	N/A	3595.9 (55%)	3040.3 (46%)

Note that when the recirculation was utilized, this increases the power consumption of the system, and this was not included in this analysis as it was a feature of the baseline system. For 24/7 operation, the recirculation pump would consume 2,842 kWh and for ODRPC, the pump would consume 1,098 kWh. Compared to the Baseline Old Boiler and Tanked WH via utility bill analysis, the Direct-Drive GAHP & Boilers Combi system saved 54.5% on gas use. When compared to the backup boilers-only system, the savings decreased to 29% since the backup boilers were newer and more right-sized to limit short-cycling compared to the old HVAC equipment. Comparing the Direct-Drive GAHP to the Belt-Drive GAHP, incremental savings of 15.6% were observed for using the more commercial ready GAHP which featured design improvements.

Sites 2 & 3: Summary of Single Family Site Monitoring Results

The Single family residential homes were fully commissioned in November, 2022, and operated through the end of December 2023. Like the multifamily site, the following analysis was broken down into two sections; DHW-only and "Combi" (SH and DHW), with the details of the former in the appendix. In addition, the two periods of performance during 2021 and 2022 of the boiler-only performance was also utilized for all subsequent analyses.

Site 2: La Porte Hydronic System

The observed weather conditions are shown in the figure below for the full Combi periods for the boiler-only and then GAHP and boiler operation at the two single family residential sites in La Porte, IN (same weather data applies to New Carlisle, IN as well). The subsequent chart catalogues the site activity over this period, highlighting the output contributions of the GAHP, the boilers, and the daily HDD. Overall, the 2022-2023 heating season accumulated 5,467 HDD65 compared to the 30-year normal of 6,320. This equates to a deficit of 853 HDD65, or 87% Normal.

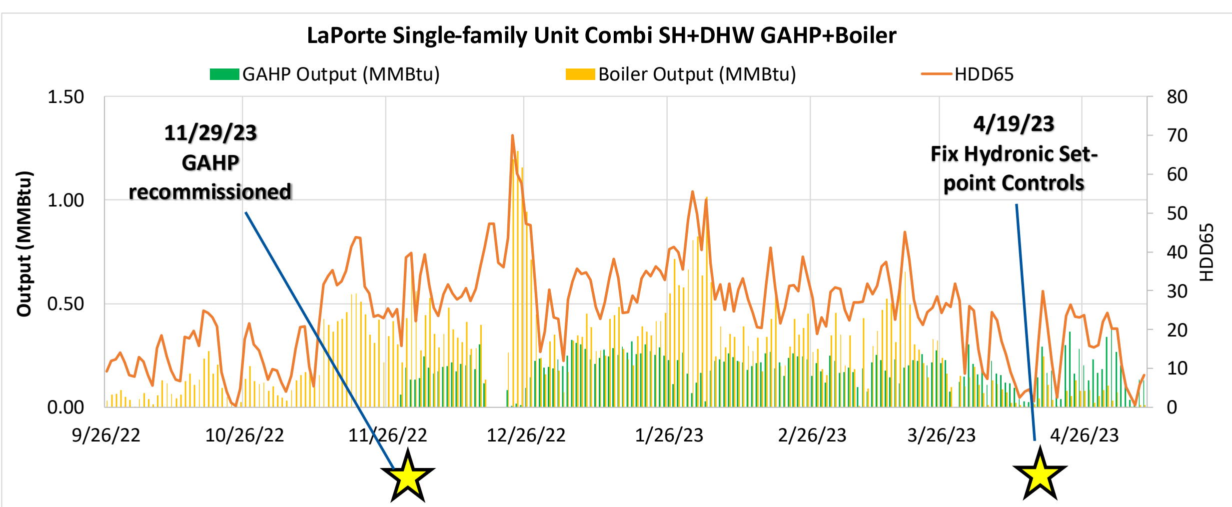


Figure 38: Summary of 2022-2023 GAHP+Boiler Combi Load Profile at Single family Hydronic Site

Comparing the monitoring periods on the above plot to that in the DHW-only period (appendix), the two periods were very similar with respect to the output energy required for space heating and DHW, as well as the daily DHW water use. Given that the DHW setpoint and indoor thermostat likely didn't change dramatically, this is not much of a surprise. However, the significant difference between the two monitoring periods is seen when analyzing the system performance during each monitoring period. Since the baseline boiler, and backup boiler were rated at 80% and 95% AFUE respectfully, and the GAHP could operate with a COP_{Gas} upwards of 1.43 (143%) based on prior laboratory testing, significant gas savings should have been achieved when comparing gas consumption. The following section dives into the system performance.

Controls Considerations
For this single family home, the baseline HVAC system incorporates a heating system that supplies heat to three zones and to a DHW tank. The controls dictating operational modes and setpoint temperatures were based on on-board controllers on each heating appliance, and by an outside air set-back curve. For DHW operation, when there was a DHW call, the system would call for a DHW supply temperature of 145°F from the boiler or GAHP. For space heating calls, supply temperatures followed a system curve seen below.

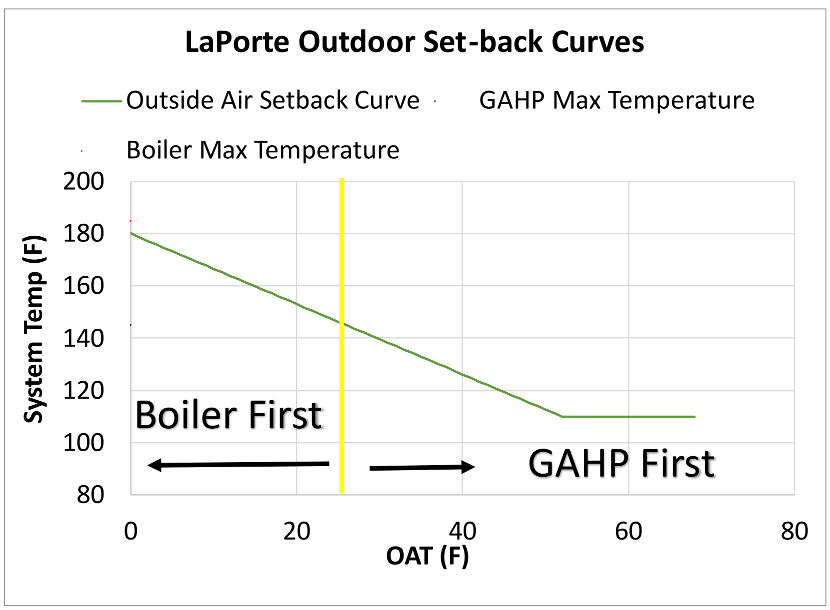


Figure 39: La Porte Field Site Outdoor Set-back Curve

The outdoor set-back curve seen above for OAT above 22°F allows for the GAHP to try to meet the system target temperature first, and then if it is not met, the boiler will provide supplementary heating. For OAT below 22°F, the boiler provides all the space heating. At this field site, the GAHP was designed to be able to partially fulfill the space heating load. There was also a programmed "boost heat" applied to the outdoor set-back curve that would increase the system target temperature by 10°F for each 30-minute period where the system target temperature was not meeting the smart thermostat setpoint. To understand this operation better, snapshots of various days in operation were plotted below illustrating target supply temperatures, and actual observed system temperatures.

The first operational snapshot was taken from a Boiler-only operational period on 11-29-22 when average OAT was near 40°F. During the start of period, OAT hovered around 40°F, and the target supply temperature was 122°F. During the first hour and a half, the boiler was firing and supplying up to 127°F hot water. Then, the system target temperature increased to 133°F, so the boiler modulated to a higher firing rate to supply hot water up to 138°F. After a little over an hour the thermostat setpoint was met, so the boiler stopped firing. This snapshot shows an example of the boiler operating correctly according to its outdoor set-back curve seen in Figure 39, as well as illustrating the boost heating controls.

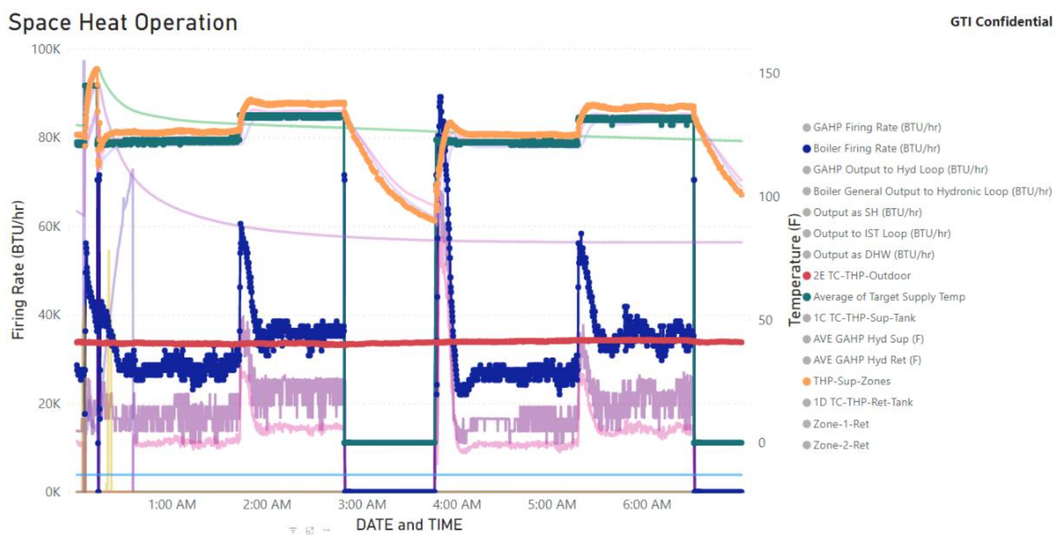


Figure 40: Boiler-Only Combi Snapshot of Operation on Mild Cold Day (11-29-2022)

The next operational snapshot was taken from a GAHP + Boiler operational period on 2-7-23 when average OAT was near 45°F. During the start of period, OAT hovered around 50°F, and the target supply temperature was 145°F. During the first hour, the GAHP was firing and supplying up to 140°F hot water. After 15 minutes of operating at 50 kBTU/hr ,the GAHP hydronic delta-T was sufficient to modulate down to only around 20-30 kBTU/hr to continue to meet the target of 145°F. At around 4am, the target supply temperature rose to 184°F. This substantial increase was due to the required “Boostheat” needed to meet the thermostat demand during this period, and the controls being programmed for a 30-minute lag time (this was found to not be programmed correctly at first). Since the GAHP could not supply hot water temperature this hot, the boiler begins to fire, and after 15 minutes of boiler heating the target supply temperature is met, shutting off the boiler soon after.

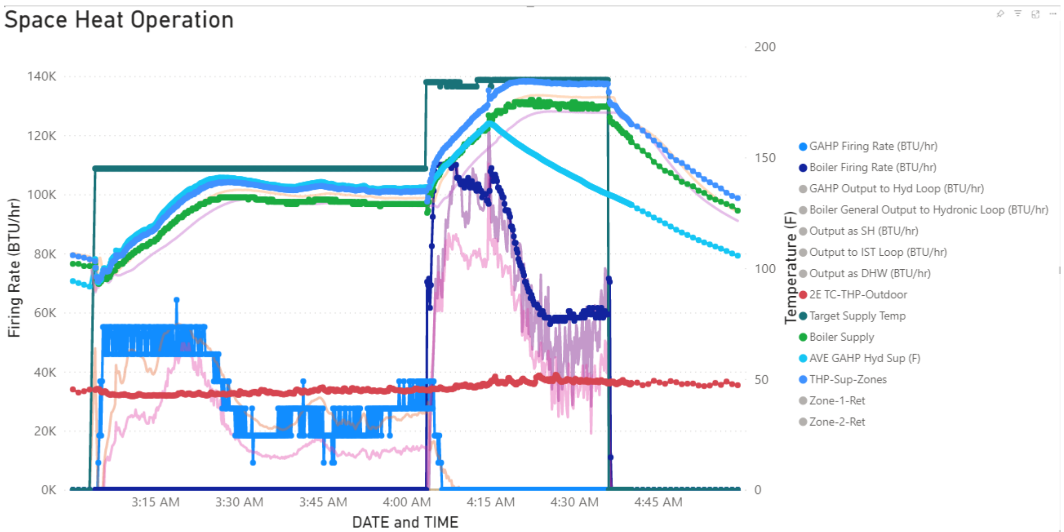


Figure 41: GAHP + Boiler Combi Snapshot of Operation on Mild Cold OAT Day (2-7-2023)

To understand the bigger picture as it pertains to system heating controls due to the outside air temperature and thermostat controls, the figure below illustrates the 20-second datapoint values for system target temperatures given the outside air temperature.

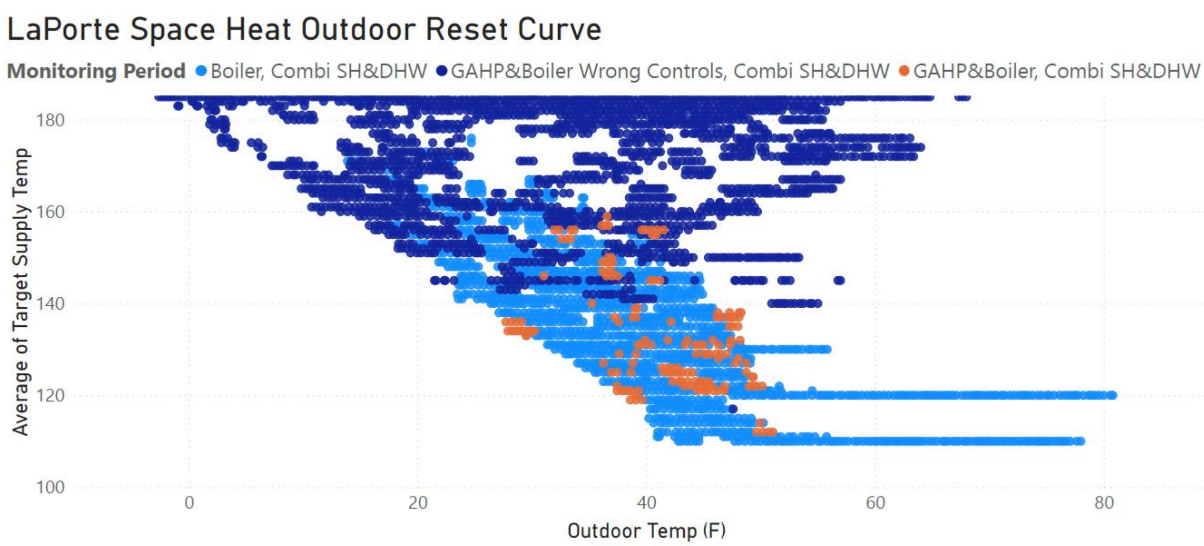


Figure 42: Mapping the Outdoor Temperature Reset Curve – La Porte Site

Observing the figure above, it is seen that during Boiler-only operation, the heating system correctly changed its target system temperature depending on the outside air temperature – shown by the left-hand edge of the rising slope to the left (matching prior controls figure). It is also evident that there were instances of boosting in the target temperature when the thermostat setpoint was not being met. Alternatively, it is seen that for the Boiler + GAHP Wrong Controls (dark blue) operation, the heating system incorrectly followed the outside air setback curve, and mostly called for a 185°F target system temperature, as under these conditions very hot temperatures were called for during a wider range of OAT. This meant that the heating system would not allow for much GAHP contribution to space heat, even at mild outside air temperatures. This also resulted in GAHP operation that did not efficiently contribute to the space heating and would result in gas use from the GAHP that was not being used for space heat.

The project team quickly resolved the issue after its discovery in late April, 2023. The data with the fixed controls (orange) illustrate the correct controlling of target supply temperatures based on the outside air reset curve, with boosting when needed. This optimizing of the boilers and GAHP contribution to space heating, while not sacrificing homeowner comfort is synonymous to the lessons learned with the Evanston Multifamily home heat timer controls and outdoor setback curve optimization.

Operating Efficiency

Noted in prior sections, the operating efficiency of the system in combi operation can be broken down into two parts, the efficiency of the GAHP itself and the delivered efficiency from the full system. Compared to the DHW-only operational period, the load is significantly greater during the space heating season compared to the DHW load. When it comes to the GAHP's efficiency, the COP_gas was analyzed against its cycling conditions. For this analysis, DHW-only GAHP performance was included as well to compare the larger output from the GAHP in combi operation.

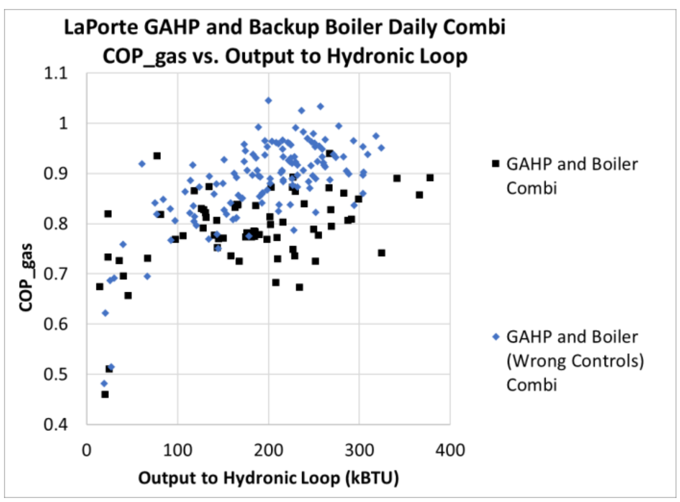


Figure 43: Combi GAHP or Boiler COP_gas vs. Output to Hydronic Loop and Operational Mode at La Porte Site

Overall, in combi operation, GAHP COPs ranging from 0.6 to 1.1 were observed. This is lower than the steady state performance (as expected) and of the higher loaded Evanston site, where having fewer, longer operating cycles shows the benefit of the GAHP's efficiency. As is the case with DHW-only operation, the controls of the GAHP dictating SH or DHW operation result in cycling behavior which can degrade efficiencies. We also see a similar trend as seen in the GAHP COP_gas vs. Output plot above, in that in most cases, the larger the load (output to hydronic loop or output as SH and DHW), the closer the GAHP is to steady-state, and the higher the system efficiency. Nevertheless, there may now be situations where the GAHPs performance is reduced due to the timing and magnitude of the DHW loads. These may focus the GAHPs attention away from steady-state firing to cover the SH load, to cover the intermittent and wide ranging DHW loads. For the full monitoring period, the contributions from the GAHP and Boiler are dependent on the outside air temperatures and configured controls. The following plot summarizes the gas consumption of the heating equipment on average given all the daily outside air temperatures observed.

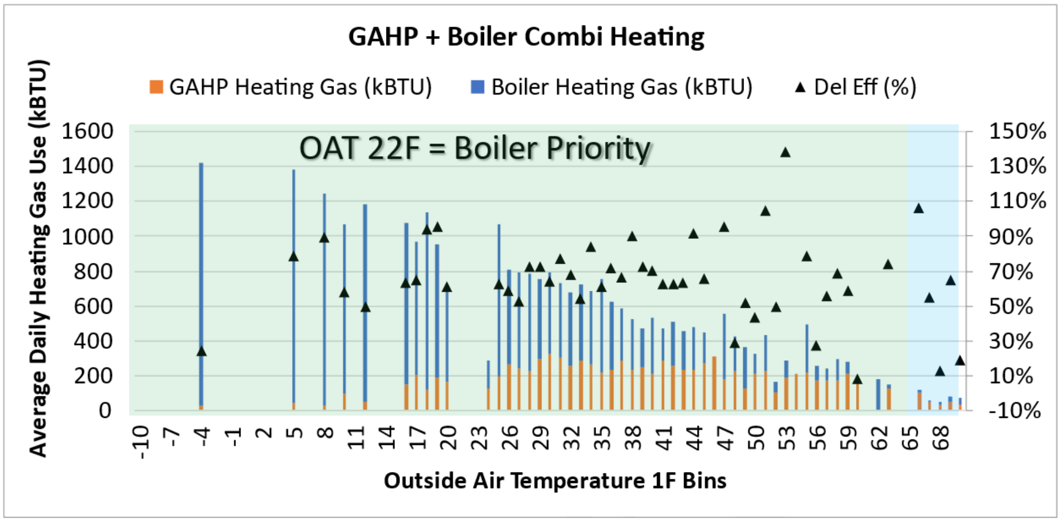


Figure 44: GAHP and Boilers Daily Heating Gas Consumption Contributions and Delivered Efficiency vs. Outside Air Temperature at La Porte Site

The prior figure illustrates that at too cold of OAT, the GAHP does contributes less and less since it cannot heat the hydronic water hot enough for the radiators in the home to deliver space heating. Interestingly, the GAHP contributions levels of ~300 kBTU a day regardless of OAT, but a systematic increase in delivered efficiency (green shading) from OAT of 26°F to 47°F is seen when the GAHP can contribute a greater percentage of the heating load. For warmer OAT above 47°F, the combi system is mostly in DHW operation (light blue shading), leading to lower delivered efficiencies.

Energy Modeling and Extrapolations

While the analysis of the DHW performance could be made by comparing the output energy and input energy, since it is impossible to determine gas consumption in combi mode as either SH or DHW, the following analysis was changed. Instead, the total gas use for SH and DHW was compared to demand each day or HDD65. This is a common analysis to determine the load profile of buildings, and homes, and is how comparisons of energy consumption can be made. The figure below compares this relationship of the boiler-only operational period from late 2022, and the GAHP operation through the end of the 2022-2023 heating season.

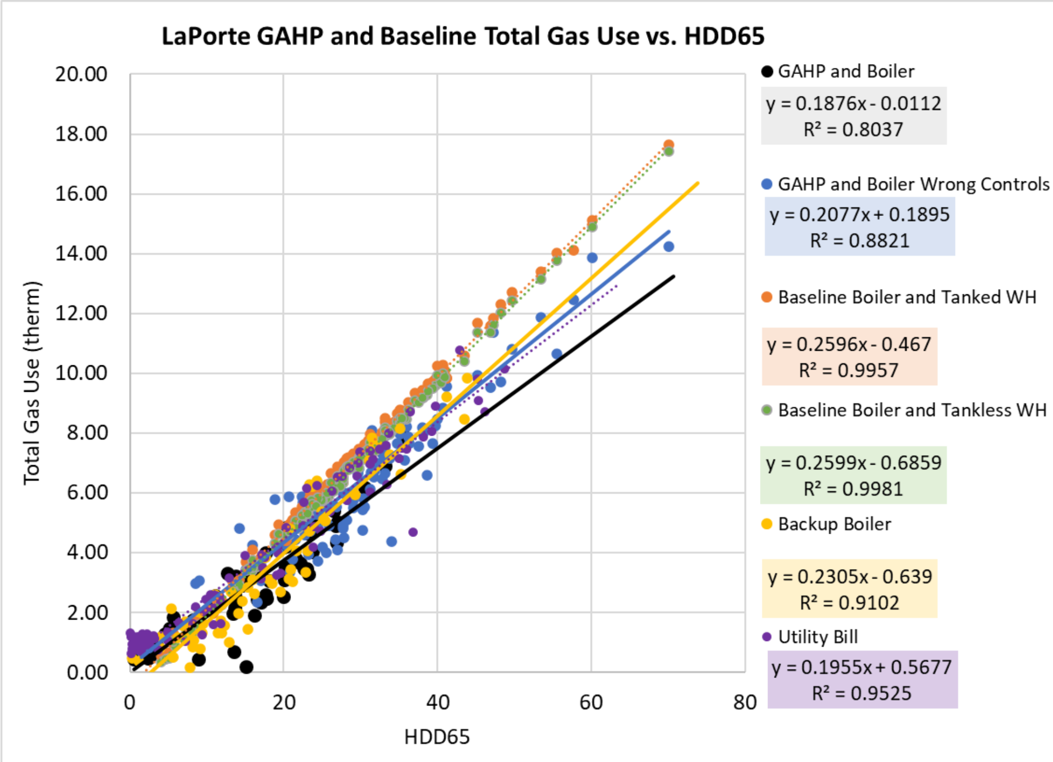


Figure 45: Comparison of Total Gas Input vs. HDD65 During Combi Operation from 2021-2022 (baseline) and 2022-2023 Heating Seasons (GAHP periods) La Porte

We see from the above Figure that for boiler-only operation, the backup boiler operated like the baseline boiler and modeled tankless WH. However, for the GAHP & Backup boiler operation, system inefficiencies led to a performance like that of the baseline boiler and tanked WH. Knowing that there was an issue with the Boiler & GAHP controls at the end of March, the project team adjusted the controls, and the total gas use vs. HDD65 linearization was plotted separately from the rest of the Boiler & GAHP dataset. Given the smaller dataset in this configuration, these datapoints were not used for the full season extrapolations. Utilizing a comparison of operational modes for the full demonstration period as seen in Figure 45, it was seen that the Boiler & GAHP operation on average consumed less gas than the backup boiler-only operation (blue vs. yellow lines). It was also seen that the backup boiler operated like the baseline boiler and modeled tankless WH. It is also clear that the GAHP was able significantly reduce the gas consumption compared to each of the compared baselines.

To extrapolate the previous figure into full year energy consumption for SH and DHW loads, the linear regression developed between HDD65 and total gas use were utilized with the NCDC 30-Year Normal Dailies for the Combi period, while the linearizations in Figure 76 and Figure 77 were used for the DHW-only period. The results of the energy savings analysis are seen below. Note that electricity use was calculated for the GAHP & Boiler system since its electricity use is in addition to the baseline consumption.

Table 5: Energy Savings Analysis of Annual Combi and DHW-only Operation at Single Family Residential Site La Porte

	Gas Use (therm)	Electricity Use (GAHP Only) (kWh)	Direct-Drive GAHP Gas Savings Compared to ___ (therm)	Belt-Drive GAHP Gas Savings Compared to ___ (therm)
GAHP+Boiler Combi	1129	2193	-	-
GAHP+Boiler Combi Bad Controls	1277	2448	148 (12%)	-
Backup boiler	1255	N/A	126 (10%)	-
Baseline Boiler and Modeled Tanked WH	1440	N/A	310 (22%)	184 (13%)
Baseline Boiler and Modeled Tankless WH	1362	N/A	233 (17%)	107 (8%)
Baseline Utility Bill	1331	N/A	202 (15%)	76 (6%)

The above table illustrates that the highest energy savings occurred for the GAHP & Boiler operation, which compared the baseline utility bill saved 15.2%, compared to the baseline boiler and modeled Tanked WH saved 21.6% and compared to the baseline boiler and modeled tankless WH saved 17.1%. This illustrates that the GAHP & Boiler system can save energy, but there is room for optimization.

Site 3: New Carlisle Forced Air System

The same weather conditions are used between the two single family sites, which are within range of the same weather station. As noted for the La Porte site, overall the 2022-2023 heating season accumulated 5,328 HDD65 compared to the 30-Year Normal of 6,298. This equates to a deficit of 970 HDD65, or 85% of normal. The next plot illustrates the energy flow and DHW water consumption of the heating system during the 2022-2023 heating season during boiler-only and GAHP-only operation.

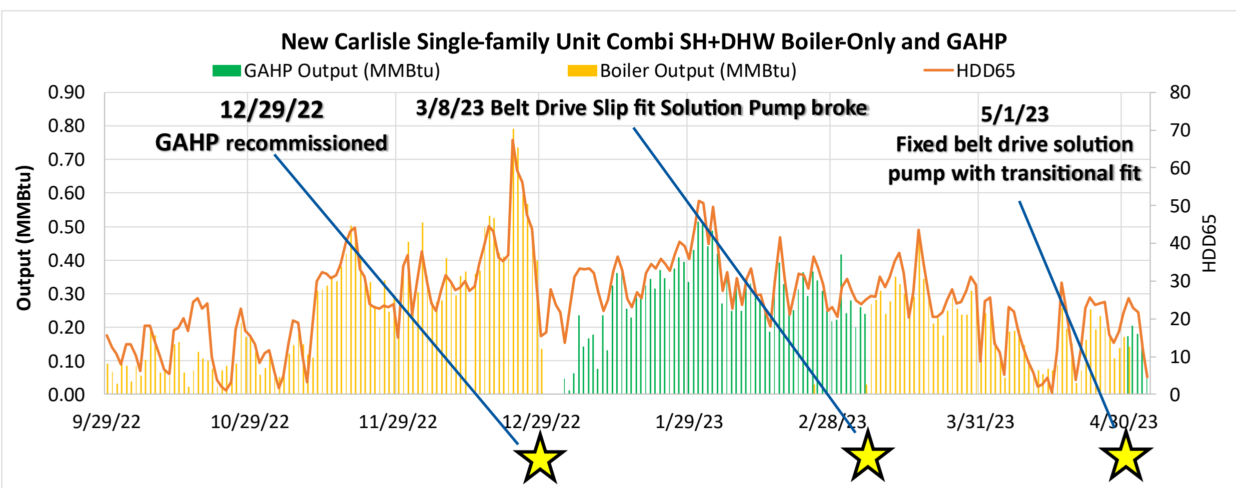


Figure 46: Summary of 2022-2023 GAHP+Boiler Combi Load Profile at Single family Forced Air Site

Comparing this monitoring period to the DHW-only period (in the appendix), the two periods were very similar with respect to the output energy required for SH and DHW, as well as the daily DHW water use. Given that the DHW setpoint and indoor thermostat likely didn't change dramatically, this is not much of a surprise. However, the significant difference between the two monitoring periods is seen when analyzing the system performance during each monitoring period. Like the La Porte site, given the increase in rated efficiency of the GAHP, significant savings were expected.

Controls Considerations

For this single family home, the baseline HVAC uses a standard thermostatic controller for the baseline furnace. The controls dictating operational modes and setpoint temperature schedules were left as-is from the point of the of the occupant, who were free to make changes. Once the GAHP system was installed, when there was a DHW call, the system would call for a DHW supply temperature of 145°F from the boiler or GAHP. For space heating calls, supply temperatures did not follow an outdoor reset curve like the La Porte site. Instead, a 145°F supply temperature was targeted for space heating.

For Boiler-only operation when the GAHP is locked out, the heat demand comes out of the AHU to drive the boiler. Both the DHW and space heat demands still run through the AHU, so we have the boiler operate at a 140°F system target to respond to the AHU demand. 150°F is the Boiler Max temp, so occasionally when the system flow is lower than the boiler loop flow (e.g. if the AHU is running), the main supply temperature may reach 150°F. When the heating system is operating in GAHP-only mode, the GAHP will supply up to 145°F hydronic supply temperatures to meet the space heating demand.

Operating Efficiency

The operating efficiency of the system in combi operation can be broken down into two parts, as noted in prior sections, the GAHP efficiency and that of the full system. Compared to the DHW-only operational period, the load is significantly greater during the space heating season compared to the DHW load. When it comes to the GAHP's efficiency, the COP_gas was analyzed against its cycling conditions. For this analysis, DHW-only GAHP performance was included as well to compare the larger output from the GAHP in combi operation.

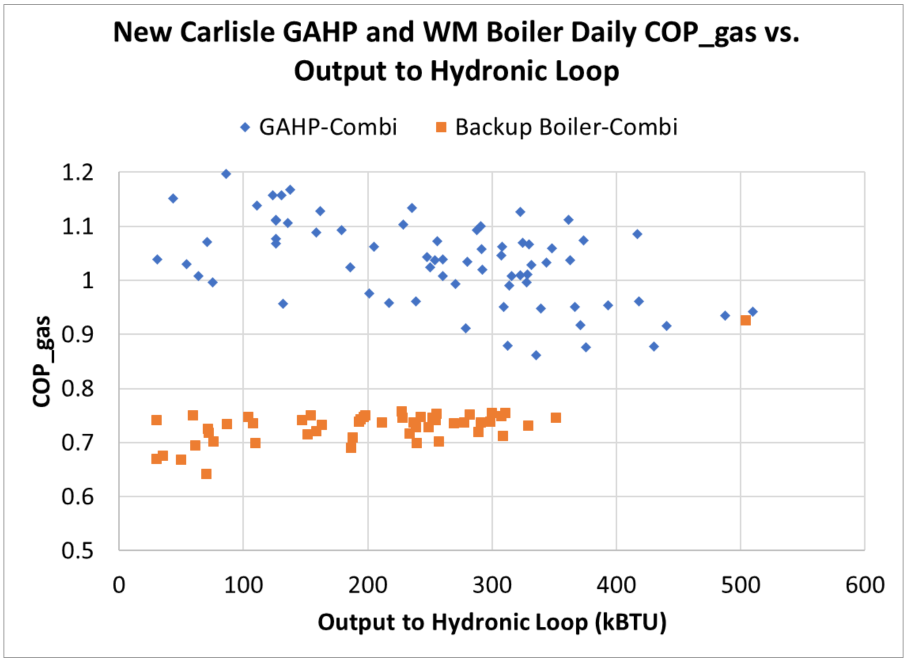


Figure 47: Combi GAHP or Boiler COP_gas vs. Output to Hydronic Loop and Operational Mode at New Carlisle Site

Generally, in combi operation, GAHP COPs ranging from 0.8 to 1.2 were observed, slightly lower than the laboratory tested steady state, comparable to the La Porte site and higher than the DHW-only operation. As is the case with DHW-only operation, the controls of the GAHP dictating SH or DHW operation result in some less-than-ideal cycling behavior. There is a similar trend as seen in the GAHP COP_gas vs. Output plot above, in that in most cases, the larger the load (output to hydronic loop or output as SH and DHW), the closer the GAHP is to steady-state, and the higher the system efficiency.

Energy Modeling and Extrapolations

While the analysis of the DHW performance could be made by comparing the output energy and input energy, since it is impossible to determine gas consumption in combi mode as either SH or DHW, the following analysis was changed. Instead, the total gas use for SH and DHW was plotted against the heating demand each day or HDD65. This is a common analysis to determine the load profile of buildings, and homes, and is how comparisons of energy consumption can be made.

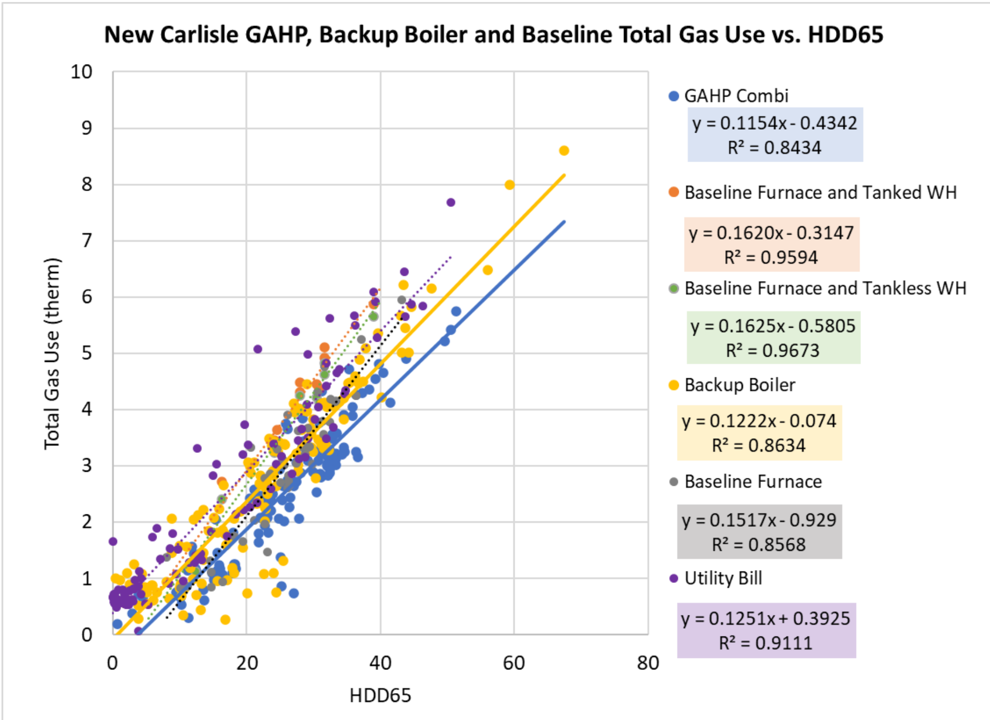


Figure 48: Comparison of Total Gas Input vs. HDD65 During Combi Operation from 2021-2022 (Baseline) and 2022-2023 (GAHP Period) Heating Seasons New Carlisle

Utilizing a comparison of operational modes for the full demonstration period as seen in Figure 48, it was seen that the GAHP-only operation on average consumed less gas than the backup boiler-only operation (blue vs. yellow lines). It was also seen that the Backup boiler operated like the baseline boiler and modeled tankless WH. It is also clear that the GAHP was able significantly reduce the gas consumption compared to each of the compared baselines. To extrapolate the previous figure into full year energy consumption for SH and DHW loads, the linear regression developed between HDD65 and total gas use were utilized with the NCDC 30-Year Normal Dailies for the Combi period, while the linearizations in Figure 81 and Figure 82 were used for the DHW-only period. The results of the energy savings analysis are seen below. Note that electricity use was calculated for the GAHP+Boiler system since its electricity use is in addition to the baseline consumption.

Table 6: Energy Savings Analysis of Annual Combi and DHW-only Operation at Single Family Residential Site New Carlisle

	Gas Use (therm)	Electricity Use (GAHP Only) (kWh)	Direct-Drive GAHP Gas Savings Compared to ___ (therm)	Belt-Drive GAHP Gas Savings Compared to ___ (therm)
GAHP Combi	652	882	-	-
Backup boiler	794	N/A	142 (18%)	-
Baseline Furnace and Modeled Tanked WH	933	N/A	281 (30%)	139 (15%)

Baseline Furnace and Modeled Tankless WH	846	N/A	194 (23%)	51 (6%)
Baseline Utility Bill	852	N/A	200 (24%)	58 (7%)

The prior table illustrates that the highest energy savings occurred for the GAHP operation, which compared the baseline utility bill saved 23.5%, compared to the baseline furnace and modeled Tanked WH saved 30.1% and compared to the baseline furnace and modeled tankless WH saved 22.9%.

Extrapolating Annual Performance

Through prior data analysis under NEEA contract 51799, the project team measured performance curves in the savings analysis sections for the multifamily residential building and two single family residential homes. These same performance curves which relate the total system output to total system input can be used to approximate total system input for other potential field sites. For this analysis, the regions of the Pacific Northwest are broken up per the *RBSA II*, as follows in the table below[19]. Here each region is assigned its climate zone, per DOE designation, representative city, and the building population is shown per region, as total population.

For the multifamily home hydronic site, these are broken out by those that are low/mid-rise with central gas boilers assuming that the overall fractions are uniformly applied throughout. With the gas consumption estimated via modeling for Hybrid GHP + Boilers and Boiler-only case, the low-rise and mid-rise buildings are assumed to be 3 units and 6 units respectively. When applied, utility rates are assumed to be “all-in” annualized values, ignoring demand charges, time-of-use (TOU) rates, or other schemes. With the focus of this analysis on annual fuel savings, the project team made this simplification for modeling efficiency, however future analyses that incorporate complex control strategies and/or electrically-driven hydronic heat pump solutions (hybrid or primary), this simplification will have to be revisited.

Table 7: Regional Breakdown for Technology Assessment for MF Home

NEEA Region	Climate Zone	Rep. City	MF Building Population - Total	MF Building Population - Low-Rise w/ Central Boiler	MF Building Population - Mid-Rise w/ Central Boiler
Western MT	6B	Missoula	28,914	520	116
Idaho	5B	Boise	54,782	986	219
Eastern WA	5B	Spokane	80,772	1,454	323
Western WA	4C	Everett	56,321	1,014	225
Puget Sound	4C	Seattle	423,507	7,623	1,694
Eastern & Central OR	5B	Bend	17,835	321	71
Western OR	4C	Portland	252,581	4,546	1,010

For the single family home hydronic site, these are broken out by those that are single family detached with natural gas boilers assuming that the overall fractions are uniformly applied throughout. With the gas consumption estimated via modeling for Hybrid GHP + Boilers and Boiler-only case.

19 https://neea.org/resources/rbsa-ii-combined-database

Table 8: Regional Breakdown for Technology Assessment for SF Home Hydronic

NEEA Region	Climate Zone	Rep. City	SF Building Population - Total	SF Building Population – Detached with NG Boiler Hydronic
Western MT	6B	Missoula	28,914	7,585
Idaho	5B	Boise	54,782	10,920
Eastern WA	5B	Spokane	80,772	13,059
Western WA	4C	Everett	56,321	15,676
Puget Sound	4C	Seattle	423,507	36,293
Eastern & Central OR	5B	Bend	17,835	5,294
Western OR	4C	Portland	252,581	30,297

Lastly, for the single family home forced air furnace site, these are broken out by those that are single family detached with natural gas furnaces assuming that the overall fractions are uniformly applied throughout. With the gas consumption estimated via modeling for Hybrid GHP + Boilers and Boiler-only case.

Table 9: Regional Breakdown for Technology Assessment for SF Home Forced Air

NEEA Region	Climate Zone	Rep. City	SF Building Population - Total	SF Building Population – Detached with NG Furnace Forced Air
Western MT	6B	Missoula	28,914	116,098
Idaho	5B	Boise	54,782	239,947
Eastern WA	5B	Spokane	80,772	199,896
Western WA	4C	Everett	56,321	167,158
Puget Sound	4C	Seattle	423,507	555,537
Eastern & Central OR	5B	Bend	17,835	81,035
Western OR	4C	Portland	252,581	463,767

Site 1: Evanston Multifamily Home Combi

First, for the multifamily residential home in DHW-only mode, the daily average DHW water consumption was used for the modeling to determine the DHW water usage. Then, the output as DHW heating vs. DHW water use linearization was utilized to determine the daily average DHW load. By then utilizing the performance curve of the GAHP combi system with respect to total gas input vs. output as DHW heating, the team could extrapolate the DHW gas consumption for the GAHP Combi. Like the DHW focused analysis above, to determine the appropriate space heat loads, the measured output as space heat load vs. HDD65 was utilized from the forced air single family residential and hydronic single family residential homes. Utilizing the NCDC 30-Year Normal Daily HDD65 values for a wide variety of cities lying in varying climate zones within the Pacific Northwest, estimated space heating loads were determined. By then utilizing the performance curve of the GAHP combi system with respect to total gas input vs. output as space heating, the team could extrapolate the SH gas consumption for the GAHP Combi. Similarly, utilizing the same daily average SH load, the baseline hydronic boiler and furnace gas consumption could be determined.

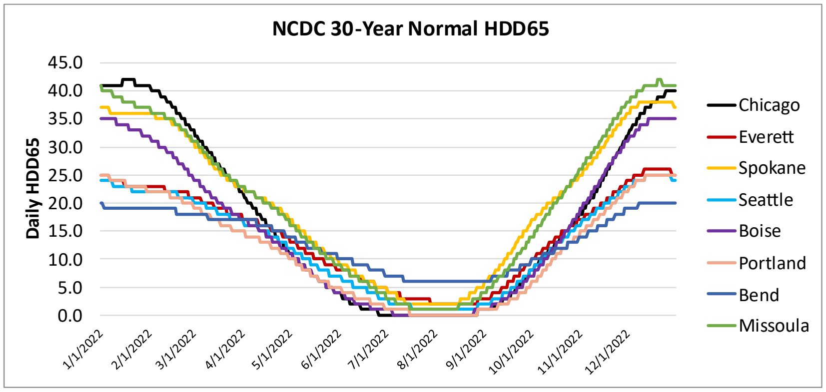


Figure 49: Pacific NW, USA Daily HDD65

Table 10: Pacific NW, USA Annual HDD65

Chicago, IL	Missoula, MT	Seattle, WA	Boise, ID	Everett, WA	Spokane, WA	Bend, OR	Portland, OR
6362	7380	4715	5529	5121	7351	4852	4284

With the complete modeling results below, the therm, GHG emission (as CO_2), and operating cost savings are annualized per site extrapolated to a full year of Combi and DHW-only operation. For each case, the GAHP + boiler system is compared to the measured boiler-only baseline and the original site baseline (utility bill analysis), whereas the single family sites take a similar approach but have a modeled conventional boiler/furnace and modeled low UEF tanked water heating system using site data, if sites could retrofit such a system in place. For utility costs, the 2021 EIA statewide pricing is used for multifamily and single family analyses. Additionally, for more accurate CO_2e emissions estimates, Residential 2021 Non-Baseload Composite Emissions Factors for the Pacific NW Sub-region of NWPP was utilized.

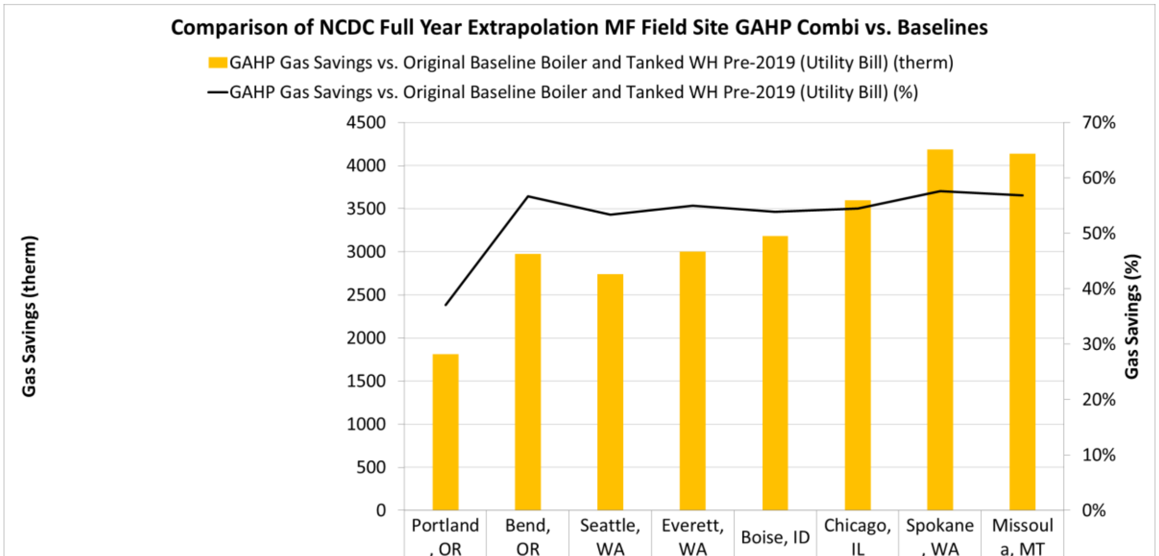
Table 11: EIA Utility Costs for Technology Assessment

Region	Natural Gas ($/therm)	Electricity ($/kWh)
Western Montana	1.08	.0914
Idaho	.72	.0914
Eastern WA	.72	.0914
Western WA	1.10	.0914
Puget Sound	1.10	.0914
Eastern/Central OR	1.09	.0914
Western OR	1.09	.0914

Table 12: Carbon Management Information Center NW Power Pool Residential 2021 Non-Baseload Composite Emissions Factors

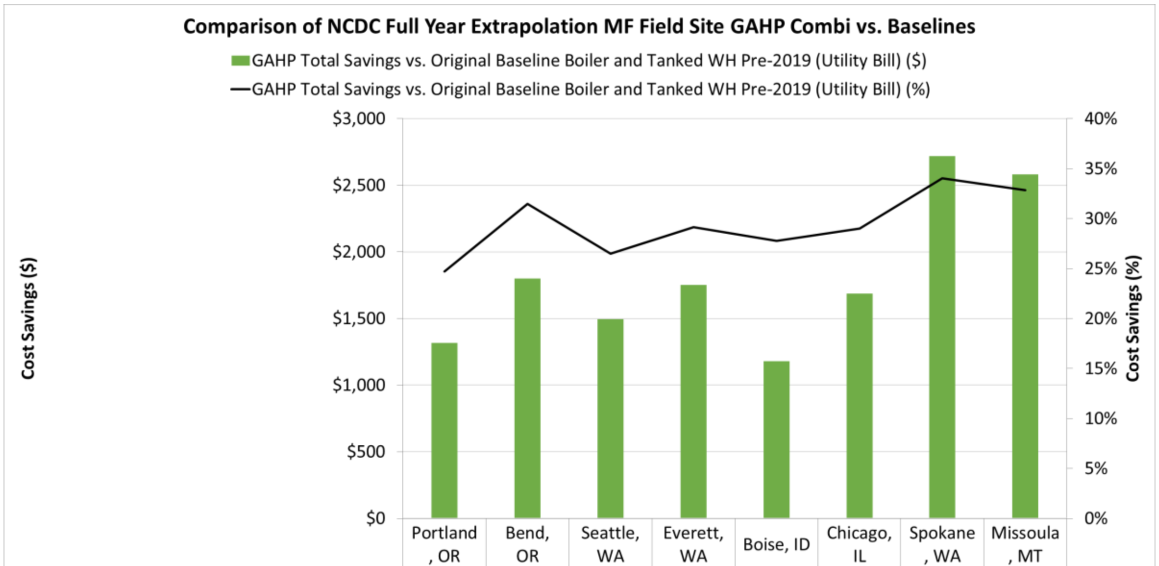
Natural Gas (CO2e lb/MMBtu)	Electricity (CO2e lb/MWh)
145.66	1745.2

With the complete modeling results below, the figures summarize the therm, GHG emission (as CO_2), and operating cost savings annualized per site extrapolated to a full year of Combi and DHW-only operation. For each case, the GAHP + Boiler system is compared to a conventional Boiler and Water Heater system using the utility bill analysis from the Evanston field site, if sites could retrofit such a system in place. Therm savings per region/climate zone ranges from 37% to 58%, with the colder climates seeing larger savings due to longer runtime of the GAHP, despite the loss of GAHP capacity in colder peak conditions. This analysis does not include any water savings from utilizing the ODRPC.



	Portland, OR	Bend, OR	Seattle, WA	Everett, WA	Boise, ID	Chicago, IL	Spokane, WA	Missoula, MT
GAHP Gas Savings vs. Original Baseline Boiler and Tanked WH Pre-2019 (Utility Bill) (therm)	1813	2974	2741	3004	3183	3596	4185	4138
GAHP Gas Savings vs. Original Baseline Boiler and Tanked WH Pre-2019 (Utility Bill) (%)	37%	57%	53%	55%	54%	54%	58%	57%

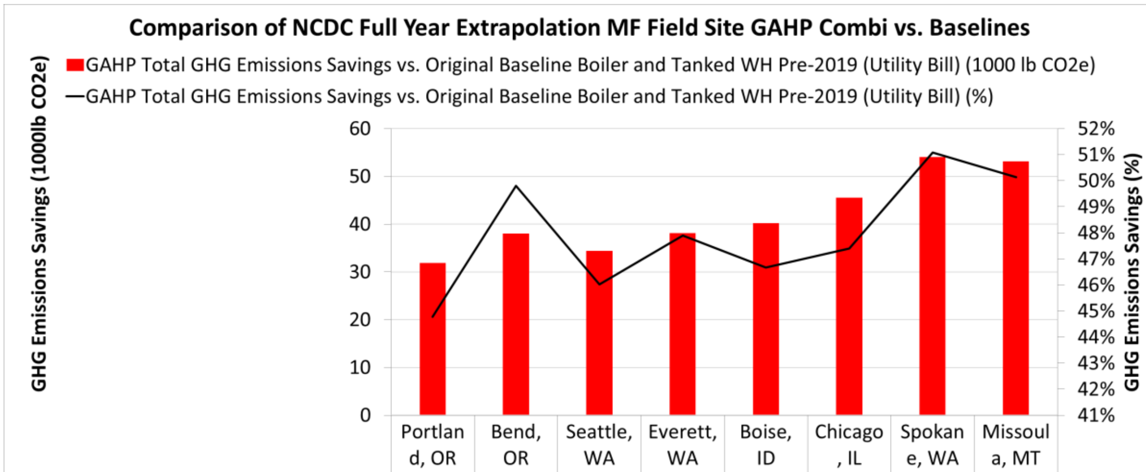
Figure 50: Gas Savings – Multifamily Home Hydronic Site



	Portland, OR	Bend, OR	Seattle, WA	Everett, WA	Boise, ID	Chicago, IL	Spokane, WA	Missoula, MT
GAHP Total Savings vs. Original Baseline Boiler and Tanked WH Pre-2019 (Utility Bill) ($)	1316	1801	1496	1751	1181	1686	2719	2582
GAHP Total Savings vs. Original Baseline Boiler and Tanked WH Pre-2019 (Utility Bill) (%)	25%	31%	26%	29%	28%	29%	34%	33%

Figure 51: Cost Savings – Multifamily Home Hydronic Site

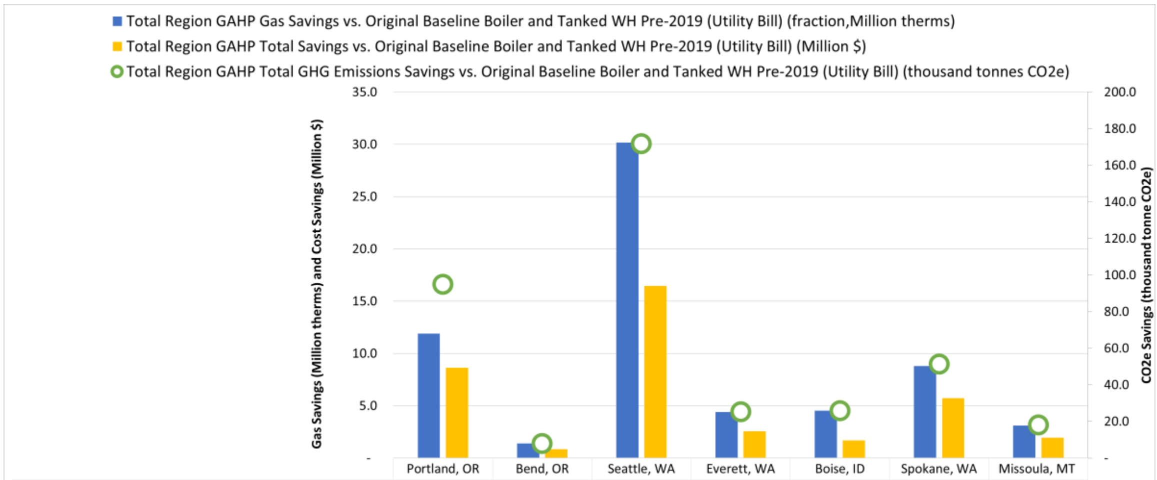
When electricity costs are included with regional rates all the modeled field sites see a reduction in overall energy savings percentages compared to the gas savings percentages due to an increase in electricity use for operating the GAHP and its pumps. However, all the locations see a total cost savings for utilization of the GHP Combi system compared to the modeled conventional HVAC equipment. As expected, with the greatest loads the highest total cost savings occur at the coldest modeled locations. This is despite the GAHP providing a reduced contribution to the total heating demand at the coldest outside air temperatures, but still illustrates that an overall higher heating demand also includes days with small to medium heating demand in which the GAHP can contribute space heating contributions at efficiencies much higher than conventional boilers.



	Portland, OR	Bend, OR	Seattle, WA	Everett, WA	Boise, ID	Chicago, IL	Spokane, WA	Missoula, MT
GAHP Total GHG Emissions Savings vs. Original Baseline Boiler and Tanked WH Pre-2019 (Utility Bill) (1000 lb CO2e)	32	38	34	38	40	46	54	53
GAHP Total GHG Emissions Savings vs. Original Baseline Boiler and Tanked WH Pre-2019 (Utility Bill) (%)	45%	50%	46%	48%	47%	47%	51%	50%

Figure 52: GHG Savings – Multifamily Home Hydronic Site

Like the total cost plot above, the GHG emissions savings plot tells a similar story. In all cases, despite an increase in electricity-based source emissions, large enough natural gas consumption savings resulted in significant GHG reductions at all locations. Unlike the single family homes in which the added electricity-based source emissions take a greater bite out of total GHG reductions, at the multifamily site, gas use takes up a much larger percentage of energy use, so there still exists substantial GHG reductions. The previous analysis for a like for like home in each region was then extrapolated using Table 7 to determine the savings for a full-scale implementation of a GHP + Boiler Combi System across the Pacific NW region in replace of central boiler hydronic heating systems in multifamily homes.



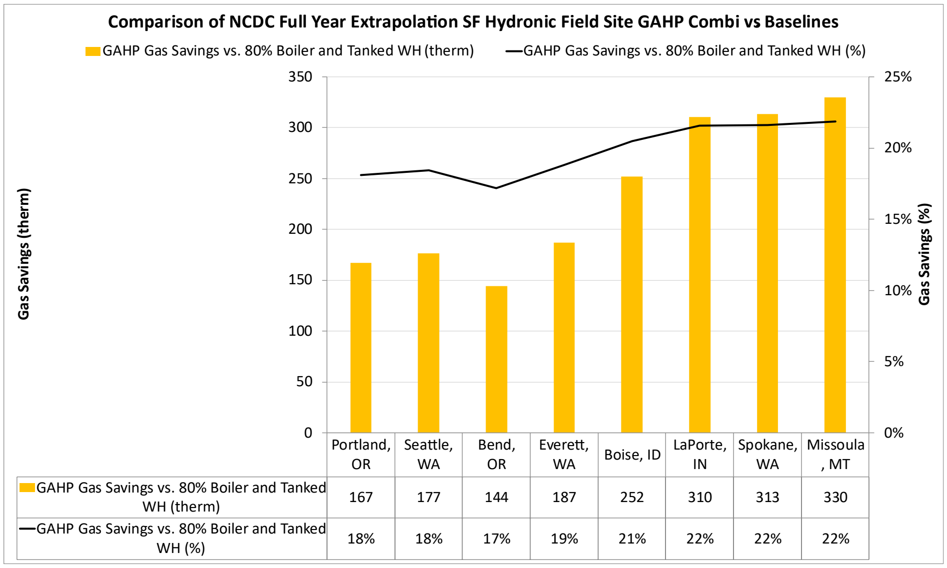
	Portland, OR	Bend, OR	Seattle, WA	Everett, WA	Boise, ID	Spokane, WA	Missoula, MT
Total Region GAHP Gas Savings vs. Original Baseline Boiler and Tanked WH Pre-2019 (Utility Bill) (fraction,Million therms)	11.9	1.4	30.2	4.4	4.5	8.8	3.1
Total Region GAHP Total Savings vs. Original Baseline Boiler and Tanked WH Pre-2019 (Utility Bill) (Million $)	8.6	0.8	16.5	2.6	1.7	5.7	1.9
Total Region GAHP Total GHG Emissions Savings vs. Original Baseline Boiler and Tanked WH Pre-2019 (Utility Bill) (thousand tonnes CO2e)	94.9	8.0	171.9	25.3	25.9	51.4	18.1

Figure 53: Energy, Cost, and GHG Savings –Multifamily Site Annual Combi and DHW-Only

The above plot incorporates data from the previous three plots and scales the magnitude savings by the amount of population that could potentially retrofit their multifamily homes with a GHP combi system. As was expected, significant gas savings and total cost savings are possible in the larger population centers with the higher heating demand. Additionally, retrofitting a GHP Combi system across all locations would lead to significant reductions in GHG emissions.

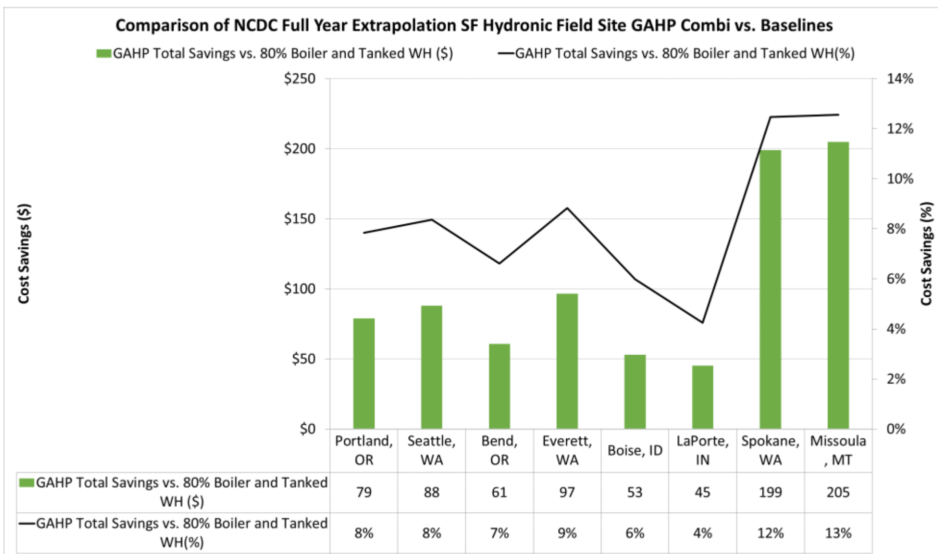
Site 2: La Porte Hydronic System Combi

Like the previous section which estimated annual savings for the multifamily home field site, this section compares the consumption and savings for the single family hydronic field site. The methodology to determine SH and DHW loads was kept consistent for this field site. The following plots illustrate the total savings for each climate zone assuming complete replacement of heating systems to the GHP combi system.



	Portland, OR	Seattle, WA	Bend, OR	Everett, WA	Boise, ID	LaPorte, IN	Spokane, WA	Missoula, MT
GAHP Gas Savings vs. 80% Boiler and Tanked WH (therm)	167	177	144	187	252	310	313	330
GAHP Gas Savings vs. 80% Boiler and Tanked WH (%)	18%	18%	17%	19%	21%	22%	22%	22%

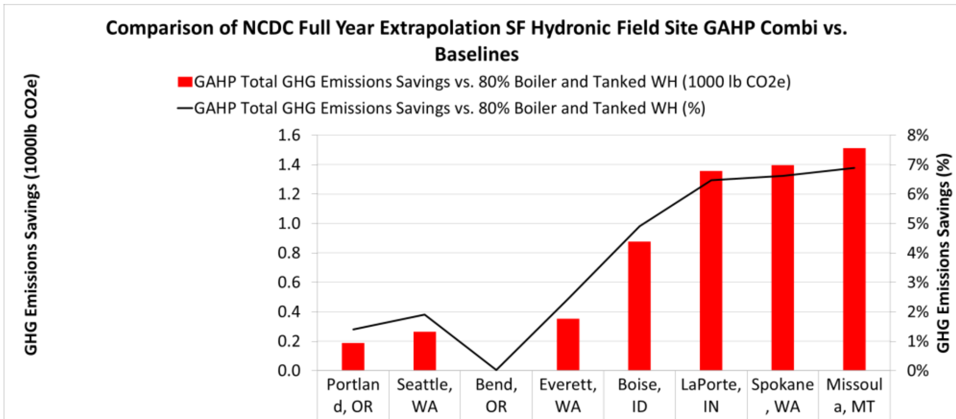
Figure 54: Gas Savings – Single Family Home Hydronic Site



	Portland, OR	Seattle, WA	Bend, OR	Everett, WA	Boise, ID	LaPorte, IN	Spokane, WA	Missoula, MT
GAHP Total Savings vs. 80% Boiler and Tanked WH ($)	79	88	61	97	53	45	199	205
GAHP Total Savings vs. 80% Boiler and Tanked WH(%)	8%	8%	7%	9%	6%	4%	12%	13%

Figure 55: Cost Savings – Single Family Home Hydronic Site

When electricity costs are utilized with regional rates most of the modeled field sites modest cost benefits, however this is muted due to the larger relative consumption of power from the GAHP system relative to the baselines and the higher costs of electricity vs. gas in certain regions. For colder climate sites, the frequent operation with modulation of the unit incurs high kWh consumption which when compared to the reduced therm savings, due to the overall lower demand at this site, *can* impact the cost effectiveness adversely. It is also important to note that this site had issues with system controls as noted before, which adversely impacted runtime controls. Also note that for this extrapolation, the power consumption of the GAHP versus total fuel consumption/runtime is based on the New Carlisle unit (an identical unit), due to certain measurement issue noted previously.

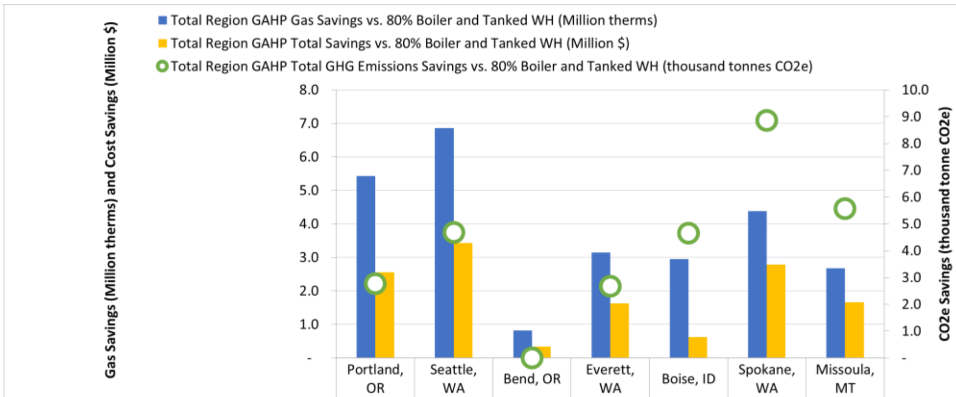


	Portland, OR	Seattle, WA	Bend, OR	Everett, WA	Boise, ID	LaPorte, IN	Spokane, WA	Missoula, MT
GAHP Total GHG Emissions Savings vs. 80% Boiler and Tanked WH (1000 lb CO2e)	0.2	0.3	0.0	0.4	0.9	1.4	1.4	1.5
GAHP Total GHG Emissions Savings vs. 80% Boiler and Tanked WH (%)	1%	2%	0%	2%	5%	6%	7%	7%

Figure 56: GHG Savings – Single Family Home Hydronic Site

Like the total cost plot above, the GHG emissions savings plot tells a similar story. In most cases, an increase in natural gas usage based CO2e emissions is similar in magnitude to the electricity use sourced emissions at modeled sites, this is due largely to the *poor system controls* during the monitoring period. The previous analysis for a like for like home in each region was then extrapolated to determine the savings for a full-scale implementation of a GHP + Boiler Combi System for across the Pacific NW region in replace of boiler hydronic heating systems in single family homes. An optimized system control is necessary to improve the on the savings.

The subsequent plot incorporates data from the previous three plots and scales the magnitude savings by the amount of population that could potentially retrofit their homes with a GHP combi system. As it was expected, significant gas savings are possible in the larger population centers with the higher heating demand; however, poor performance and a higher relative electricity cost rate meant that total cost savings are not as attractive as other sites, also limiting the GHG benefits on a relative basis to other sites.

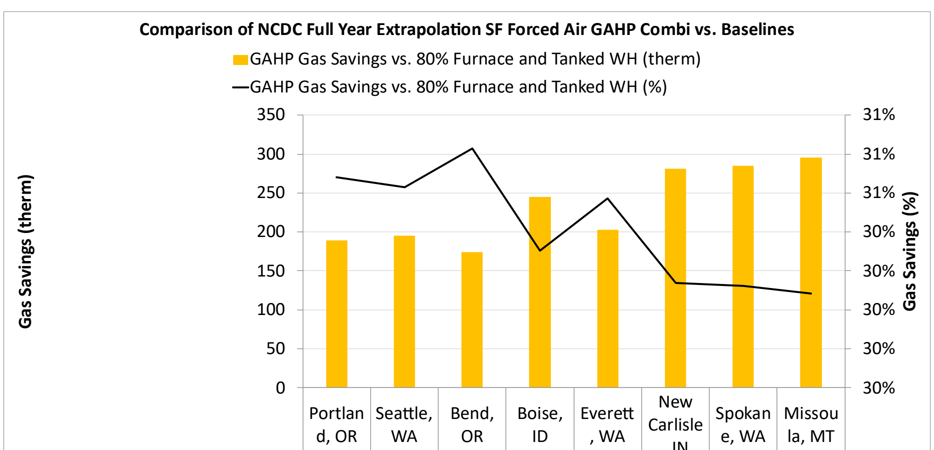


	Portland, OR	Seattle, WA	Bend, OR	Everett, WA	Boise, ID	Spokane, WA	Missoula, MT
Total Region GAHP Gas Savings vs. 80% Boiler and Tanked WH (Million therms)	5.4	6.9	0.8	3.1	2.9	4.4	2.7
Total Region GAHP Total Savings vs. 80% Boiler and Tanked WH (Million $)	2.6	3.4	0.3	1.6	0.6	2.8	1.7
Total Region GAHP Total GHG Emissions Savings vs. 80% Boiler and Tanked WH (thousand tonnes CO2e)	2.8	4.7	0.0	2.7	4.7	8.9	5.6

Figure 57: Pacific NW Full Scale Extrapolation of Energy, Cost, and GHG Savings –Single family Hydronic Site Annual Combi and DHW-Only

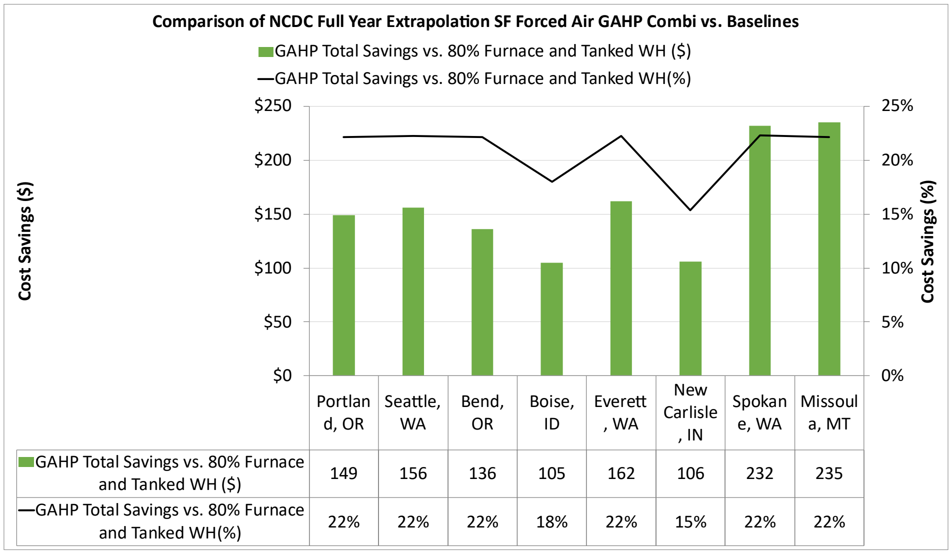
Site 3: New Carlisle Forced-Air System Combi

Finally, the same methodology was utilized to extrapolate energy consumption, cost, and GHG emissions savings for the forced air system field site. For each case, the GAHP heating system is compared to a conventional furnace and modeled low UEF tank-type water heater system using the data from the New Carlisle field site, if sites could retrofit such a system in place. Therm savings per region/climate zone ranges up to 31%, with the colder climates seeing larger savings due to longer runtime of the GAHP, despite the loss of GAHP capacity in colder peak conditions. As outlined in the appendix on DHW-only performance, this is due to this poor performance compared to combi performance taking up a larger proportion of operational runtime in milder climates.



	Portland, OR	Seattle, WA	Bend, OR	Boise, ID	Everett, WA	New Carlisle, IN	Spokane, WA	Missoula, MT
GAHP Gas Savings vs. 80% Furnace and Tanked WH (therm)	189	195	174	245	202	281	285	296
GAHP Gas Savings vs. 80% Furnace and Tanked WH (%)	31%	31%	31%	30%	31%	30%	30%	30%

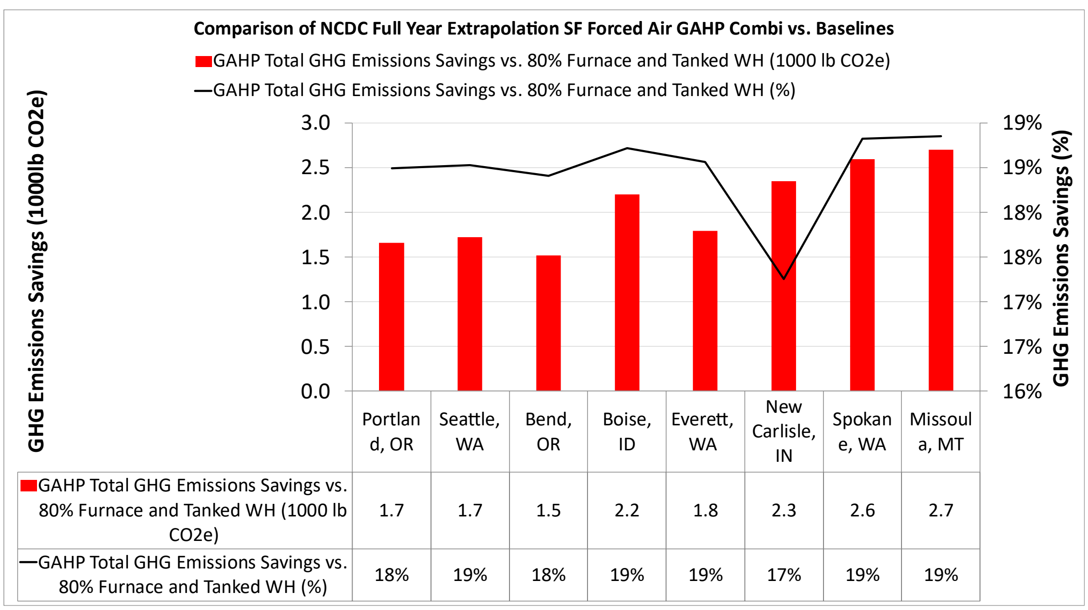
Figure 58: Gas Savings – Single Family Home Forced Air Site



	Portland, OR	Seattle, WA	Bend, OR	Boise, ID	Everett, WA	New Carlisle, IN	Spokane, WA	Missoula, MT
GAHP Total Savings vs. 80% Furnace and Tanked WH ($)	149	156	136	105	162	106	232	235
GAHP Total Savings vs. 80% Furnace and Tanked WH(%)	22%	22%	22%	18%	22%	15%	22%	22%

Figure 59: Cost Savings – Single Family Home Forced Air Site

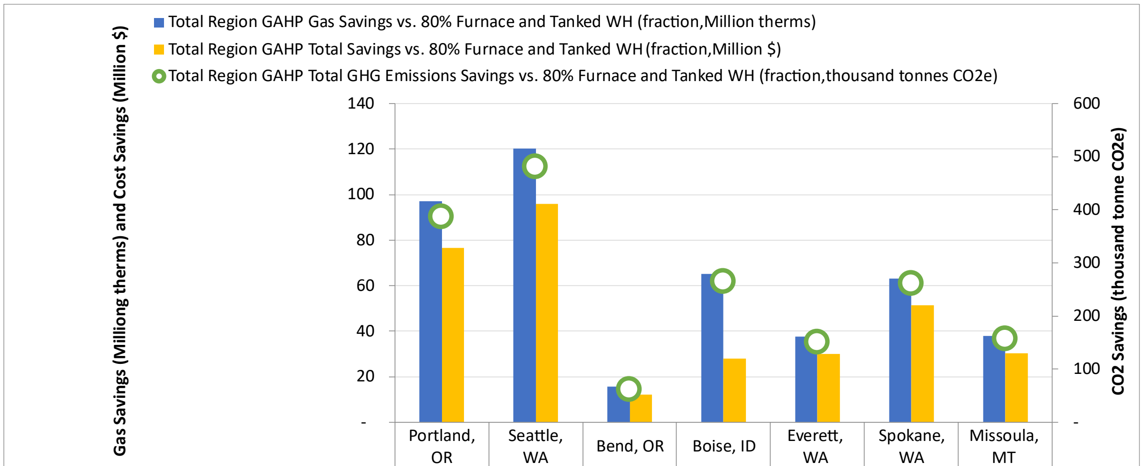
When electricity costs are utilized with regional rates all the modeled field sites see a reduction in overall energy savings percentages compared to the gas savings percentages due to an increase in electricity use for operating the GAHP and its pumps. However, all the locations see a total cost savings for utilization of the GHP Combi system compared to the modeled conventional HVAC equipment. As expected, the highest total cost savings are a result of the higher heating demand at the coldest modeled locations.



	Portland, OR	Seattle, WA	Bend, OR	Boise, ID	Everett, WA	New Carlisle, IN	Spokane, WA	Missoula, MT
GAHP Total GHG Emissions Savings vs. 80% Furnace and Tanked WH (1000 lb CO2e)	1.7	1.7	1.5	2.2	1.8	2.3	2.6	2.7
GAHP Total GHG Emissions Savings vs. 80% Furnace and Tanked WH (%)	18%	19%	18%	19%	19%	17%	19%	19%

Figure 60: GHG Savings – Single Family Home Forced Air Site

Like the total cost plot above, the GHG emissions savings plot tells a similar story. In all cases, despite an increase in electricity-based source emissions, large enough natural gas consumption savings resulted in moderate GHG reductions at all locations. The previous analysis for a like for like home in each region was then extrapolated using Table 9 to determine the savings for a full-scale implementation of a GHP Combi System across the Pacific NW region in replace of forced air furnace heating systems in single family homes.



	Portland, OR	Seattle, WA	Bend, OR	Boise, ID	Everett, WA	Spokane, WA	Missoula, MT
Total Region GAHP Gas Savings vs. 80% Furnace and Tanked WH (fraction,Million therms)	97	120	16	65	37	63	38
Total Region GAHP Total Savings vs. 80% Furnace and Tanked WH (fraction,Million $)	$76	$96	$12	$28	$30	$51	$30
Total Region GAHP Total GHG Emissions Savings vs. 80% Furnace and Tanked WH (fraction,thousand tonnes CO2e)	387	480	62	265	150	260	157

Figure 61: Pacific NW Full Scale Extrapolation of Energy, Cost, and GHG Savings –Single family Forced Air Site Annual Combi and DHW-Only

The above plot incorporates data from the previous three plots and scales the magnitude savings by the amount of population that could potentially retrofit their homes with a GHP combi system. As was expected, significant gas savings and total cost savings are possible in the larger population centers with the higher heating demand. Additionally, retrofitting a GHP Combi system across all locations would lead to significant reductions in GHG emissions.

Conclusions and Recommendations

In this project, the team extended the monitoring and performed extensive re-commissioning of a hybrid boiler/GAHP-based heating system at a multifamily building in the Chicago region, with support from a major boiler OEM and SMTI. Over the course of the project, all of the GAHP & boiler systems delivered 744 MMBtus of space heating and 244 thousand gallons of hot water to the three sites, with total operational runtime of 15,183 hours, per the table below.

Table 13: Totalized Figures for Full Demonstration Periods in 2021-2022 Heating Season Forward

Output	Evanston Multifamily		La Porte Single Family		New Carlisle Single Family		TOTAL
Runtime (h)	4,585	4,078	2,768	2,456	1,296	757	**15,183**
Space Heating Delivered (MMBtus)	378	161	103	61	41	34	**744**
DHW Output (1,000 Gal.)	171		36		37		**244**

Key accomplishments in this project were to as follows:

- *Demonstration Results at the Multifamily Site:* The first goal was to continue to **demonstrate the pre-commercial GAHP in 1st of its kind demonstration**, to extend this technology to the multifamily housing, a critical market segment, and to also advance commercialization efforts with a major boiler OEM. This demonstration, at a field test site in the Chicagoland area, required significant installation design and controls development in advance of the commissioning and building on several improvements in prior phases, this extended period included multiple improvements to the solution pump, system controls, and the GAHP itself.

This unique system, installed and operated at an apartment building from 2019 onwards, allows for a "hybrid" approach, wherein the GAHP component and boiler component can meet the building's space and water heating loads separately or jointly. While challenged by system operational issues and the ongoing COVID-19 pandemic, sufficient data were collected to extrapolate that the system could operate with a net efficiency upwards of 136% and save the building 54% gas consumption for hot water-only mode and up to 55% for combined space heating and water heating mode. When factoring in the added electricity usage of the GAHP and external glycol pump, the total cost savings of the GAHP and boiler system was 47% for hot water-only mode and up to 49% for combined space heating and water heating mode. Lastly, the implementation of On-Demand Recirculation Pump Controls on the DHW loop resulted in significant annual water savings of 30,845 Gallons or $11,340.

- *Demonstration Results at Single Family Hydronic & Forced Air Heating Sites:* The secondary goal was to expand this technology to the single family housing, a critical market segment, and to also advance commercialization efforts with the boiler OEM. The first of which included a hydronic field site located in the La Porte, Indiana area. Another single family field site was also retrofitted with a GHP Boiler system located in New Carlisle, Indiana with forced air heating distribution. Like the multifamily site, these sites had a "hybrid" approach, wherein the GAHP component and boiler component can meet the building's space and water heating loads separately or jointly, depending on the operational mode and heating loads. Where the New Carlisle site required minimal installation design and controls development since the GAHP was right-sized to meet the full space heat and DHW load, the La Porte site required modest installation design and controls development in advance of the commissioning to incorporate a backup boiler to be utilized during the coldest days of the heating system when the GAHP had insufficient capacity, and too low of a supply temperature for the home's radiators.

While challenged by system operational issues like the Chicagoland field site, and the ongoing COVID-19 pandemic, sufficient data were collected to extrapolate that the system could operate with a net efficiency upwards of 110%-130% and save the home up to 22%-30% (La Porte / New Carlisle) in operating costs for combined space heating and water heating mode, between the sites, depending on baseline. When factoring in the added electricity usage of the GAHP at an incremental 2,193 kWh / 882 kWh (La Porte / New Carlisle) per year, the total cost savings of the GAHP and boiler system was reduced for combined space heating and water heating mode but also driven by observed given controls related issues, and sub-optimized plumbing/sizing for the GAHP – specifically to 15% savings (New Carlisle) and no savings (La Porte).

- *Technical Assessment Multifamily Site:* Leveraging the hybrid system platform at the multifamily site, the team additionally made efforts to 1) further optimizing the controls when operating as a hybrid system, for both the specific and general case, 2) extrapolating the findings and optimized controls strategies to other multifamily buildings and commercial applications, and 3) publicizing the results, design guidelines, and other project results in an industry peer-reviewed paper to advance discussions and actions by developers, architect/engineers, and with the boiler OEM partner[20]. While the frequent system and site servicing had an impact on model development, progress was in modeling to recreate multifamily buildings in the Pacific Northwest. The technical potential for these GAHP-based systems as compared to traditional hydronic boilers was estimated for low-rise and mid-rise buildings in seven regions including OR, WA, ID, and MT. For a single site, the therm savings were estimated as 37%-57% and GHG emissions reduced by 45%-51% over baseline for the seven metropolitan regions considered. Extrapolating to all existing low-rise and mid-rise multifamily buildings in this Pacific Northwest region, the technical potential of the hybrid GAHP/hybrid system was estimated as saving up to 361.1 million therms/year, 2.2 $MMTCO_2$/year, and $212 million/year in operating costs.
- *Technical Assessment Single Family Sites:* Leveraging the hybrid system platform at the two single family sites, the team performed the same modeling as above. With this modeling approach to recreate single family buildings in the Pacific Northwest, the technical potential for these GAHP-based systems as compared to traditional single-family detached homes with either furnace forced air systems or hydronic boilers was estimated in seven regions including OR, WA, ID, and MT. Extrapolating to all existing single family forced air systems, the technical potential of the hybrid GAHP/hybrid system was estimated as saving up to 436.6 million therms/year, 1.8 $MMTCO_2$/year, and $324 million/year in operating costs. Meanwhile, the same extrapolation for

20 The paper *Hybrid Heating and Hot Water in Multifamily Buildings: Demonstration and Analysis of Integrated Boilers and Thermally-Driven Heat Pumps* was published in the proceedings of the 2022 ASHRAE Winter Conference.

all single family hydronic boiler system homes would result in an estimated saving up to 26.3 million therms/year, 29 $MTCO_2$/year, and $13.0 million/year in operating costs.

Looking to the future, this study identified several improvements to system design and operation, which could be implemented in future, new field sites. For the multifamily application, several improvements were implemented on the system controls to increase GAHP runtime relative to the boilers. While in these application scenarios of GAHP and boiler systems, there will always be a tradeoff between maximizing GAHP runtime and occupant comfort and having a dynamic and intelligent "switchover" point for the system to operate only with boiler(s) is critical. On system configurations, challenges with placement of buffer tanks and indirect tanks were identified that limit the efficiency of DHW-only operation and the need for means of preventing unwanted thermosiphons with the hydronic loops were also identified as critical. One solution to improve both comfort, energy savings, and water savings that was well documented in this report was the utilized of On-Demand Recirculation Pump Controls. This ensured that the occupants of the building readily had hot water for DHW applications, while also limiting wasteful operation of the GAHP & boiler hybrid system. For single family applications of the GHP, traditional methods on boiler or furnace sizing are not appropriate for GAHP units or heat pumps more broadly, as capacity is a function of operating conditions (ambient and loop temperatures), once controls for systems like these are optimized, subsequent analysis is needed to determine the optimal sizing relationship between the GAHP, the auxiliary boiler (if any), and the home's estimated SH / DHW loads. For GAHP hydronic systems, right-sizing is more difficult since a greater importance relies on the hydronic system fixtures (radiators, unit heaters, etc.) to determine how well the GAHP heating system can shed a heating load to the space, and the amount of supplementary heating required to continue to meet the load at colder outside air temperatures. Therefore, determining energy savings potential of a GAHP hydronic system is more difficult and will require more data and research to optimize system configuration and controls.

List of Acronyms

Acronym	Description
Btu	British thermal unit
CEC	California Energy Commission
cf	cubic feet
CMIC	Carbon Management Information Center
CO2	Carbon dioxide
COP	Coefficient of performance
CT	current transformers
DACS	data acquisition system
DHW	Domestic hot water
DOE	Department of Energy
EFLH	equivalent full load hour
GAHP	gas absorption heat pump
GAHPWH	gas heat pump water heater
GTI	GTI Energy
HDD	heating degree day
HDD65	heating degree day with base temperature of 65 ºF
HVAC	heating, ventilating, and air conditioning
kW	kilowatt
kWh	kilowatt hour
MBH	1000 British thermal units/hour
NEEA	Northwest Energy Efficiency Alliance
OA	outside air
OAT	outside air temperature
ODRPC	On-Demand Recirculation Pump Controls
OEM	original equipment manufacturer
PRV	pressure relief valve
SMTI	Stone Mountain Technologies Inc.
UTD	Utilization Technology Development
WH	Water heater

Appendix A: Multifamily Monitoring Plan (from 51799)

The array of sensors, integrated with the DACS, is intended to quantify a) the energy consumption and heating output of the overall system and individual components, b) the nature of heating and DHW loads of the demonstration site, and c) the operational "health" of the GAHP itself, including internal temperatures and other sensors. On energy consumption, efficiency, and heating capacity, the GAHP performance will be a function of operating conditions (outdoor, indoor temperature, heat demand, activity of boilers) which are expected to vary over the monitoring period. On the load side, space heating and DHW consumption are both impacted by occupancy and behavioral effects. Key metrics to evaluate the GAHP "health" include:

- Heat Pump Coefficient of Performance;
- System Coefficient of Performance;
- Heat Pump Capacity;
- Evaporator Superheat as a function of cycle conditions;
- Desorber Shell Temperature as a function of cycle conditions; and
- Other cycle properties.

For continuously monitored data points, GTI will continue to use the Logic Beach *Intellilogger* datalogger platform, with all clocks will be synchronized to the NIST clock available on the web and with dataset upload via FTP to a GTI secure location. With this datalogging platform, to quantify performance metrics, the data in the table below will be collected on a continuous basis with a frequency of recording of no less than one minute and more frequently with activity.

During site visits and soliciting from project partners, GTI will make batch measurements of the following, to be used in model development and analysis:

- True RMS power measurements will be made on operating existing components (e.g. pumps)
- Natural gas heating value and inlet natural gas pressure (at meters).
- Excess air level in flue gases for GAHP, as measured using a portable combustion analyzer.

Table 14: Multifamily Site Measurement Points

Measurement	Method	Accuracy	Measurement Point – Indoors	Measurement Point – Outdoors
Natural Gas Input	Positive displacement diaphragm meter with integrated pulser	±1%, Temperature Compensated	- Boiler #1 - Boiler #2	- GAHP
Electricity Input	True RMS power transducer with split core current transformers (CT)	±0.5% (Meter), ±0.75% (CT)	N/A	- GAHP
Water Flow	In-line turbine flow meter with pulse output	±2% over range or better	- SHW Output	N/A
Recirculating Loop Flow	Magnetic-inductive flow meter	±2% of range or better, effectively ±0.5 GPM or better	N/A*	- GAHP Loop
Water Temperature (Hot/Cold & Supply/Return) & GAHP Internal Temperatures	Thermocouple Type T	±1.8 °F	- Boiler #1 Supply/Return - Boiler #2 Supply/Return - Main Loop Supply/Return - Buffer Tank Supply/Return - SHW Tank Supply/Return - SHW Supply / Cold Inlet	- PHX Loop Supply/Return - SHW Tank Preheat Temp. - GAHP Evaporator In/Out - GAHP Desorber Shell
Water Temperature (Hot/Cold & Supply/Return)	RTD sensor	± 0.81 °F	N/A	- GAHP Loop Supply/Return**
Air / Flue Gas Temperature	Thermocouple Type T	±1.5°F	- Mechanical Room - Boiler #1 Flue Gas - Boiler #2 Flue Gas	- GAHP Flue Gas - Ambient at GAHP
Ambient Weather Condition	Publicly Accessible Weather Station	N/A	N/A	- Outdoors
Equipment Runtime	Dry contact	N/A	- Individual Unit Zone Valves - Circulation Pumps* (P2-P6)	- GAHP

* Hydronic flow rates are measured using portable ultrasonic flow meters (external mount, Model: FSVEYY12-SYYB-N) during on-time measurements
** These measurements are calibrated in-situ, using a dry-well calibrator

Data Quality Control and Analysis

Using automated data quality control during weekly data file transfers, GTI will identify and resolve issues with data collection and the project team will seek to resolve GAHP system and DACS operational issues to minimize data loss. Data from each site will be downloaded, analyzed, and reviewed on a weekly basis to spot issues, trends, and identify needs for field servicing of DACS or the GAHP systems.

The GAHP is uncertified and, given its prototype nature, requires additional attention for servicing and maintenance. GTI employees the following automated warning emails, sent by the DACS, to key staff from the project team – as employed in prior GAHP demonstration projects:

- *Low refrigerant temperatures* – If the evaporator inlet temperatures drop below 10°F, this represents an off-design operating condition resulting in frosting of the evaporator. The pre-commercial GAHP is equipped with a defrosting system; however, it is not expected to be used in the Los Angeles-area climate. Staff will remotely power down the GAHP system and contact the host site to arrange for a servicing visit.
- *Excessive heating* – If the hydronic supply temperature exceeds 150°F or if the desorber shell temperature exceeds 350°F, this represents an off-design operating condition which could result in a GAHP system automatic shutdown due to excessive high-side pressures. The GAHP controls can recover from this event; however, following email notification, staff may arrange for a site visit to investigate this overheating event.

In the event of a loss of GAHP system functionality, the building will have full redundancy via the boilers, for both space and water heating. The local contractors and on-site personnel have received training from the project team members to detect, and if possible, rectify GAHP system issues over the course of the demonstration, in addition to compliance with project and local public health requirements.

Concerning host site safety, beyond the email alert system to identify and diagnose system operational issues, an ambient ammonia sensor and alarm—able to detect ambient ammonia and alert the host site in the event of an ammonia leak—will be deployed in the vicinity of the GAHP. The ammonia alarm is well below the 8-hour federal workplace exposure limits (50 ppm for OSHA / 25 ppm for NIOSH). Host sites will be trained to recognize this alarm and what to do in the event it is heard.

Data Analysis

With datasets downloaded on a weekly basis and analyzed with custom programming, the following data will be summarized in reporting:

- Operating conditions: Outdoor temperature/humidity, indoor temperature in mechanical room, inlet water mains temperature.
- Heating load: Main supply/return temperatures, boiler loop/GAHP loop temperatures, estimated space heating load, activity of hydronic zone valves, activity of circulation pumps.
- Hot water consumption statistics: Daily draw volumes, draw rates, draw durations, draws per day, delivered hot water temperature, delivered energy of hot water.
- Boilers: Daily/weekly natural gas consumption, cycling behavior of boilers, energy flows from boiler loop to main loop, from boiler loop to indirect storage tank, impact of GAHP preheating on space heating/DHW performance.
- System efficiency: Daily/weekly "System Efficiency", including and excluding electricity demand.

GAHP System Focus

- GAHP component operating conditions:
    - GAHP loop hydronic return/supply temperatures, condenser/absorber outlet temperatures, desorber shell and flue gas temperatures.
    - Hydronic return/supply temperatures, evaporator inlet/outlet temperatures, desorber shell and flue gas outlet temperatures.
    - GAHP cycle startup health, observed operational issues, and service calls.

- GAHP system output and cycling:
    - GAHP system cycling, utilization, COP_{Gas}, GAHP system COP, utilization of GAHP (fraction of total loads served).
    - GAHP system energy inputs (gas/electricity) and energy balance at PHX, estimated heat losses.

On calculated outputs, key formulae are:

Outputs:

- Hydronic Heating: Boiler output, GAHP output, main loop input, and buffer/storage tank input are all based on simple energy balances: $\dot{Q}_{Hydronic} = \dot{V}_{Flow} C_P \rho \left(T_{Supply} - T_{Return}\right)$ [=] Btu/hr; $C_P \rho$ evaluated at T_{Return}.
- Hot Water Output: $Q_{DHW} = V_{DHW} C_P \rho (T_{DHW} - T_{CW})$ [=] Btus; for $C_P \rho$ evaluated at T_{CW}.
- GAHP output capacity will be determined at the GAHP unit, as: $\dot{Q}_{THP} = 60 \cdot \dot{V}_{THP} C_P \rho \left(T_{THPSup} - T_{THPRtn}\right)$ [=] Btu/hr; for $C_P \rho$ evaluated at T_{THPSup}.

Inputs:

- Natural gas input: $Q_{NG,Boilers} = \left(V_{NG_{Boiler1}} + V_{NG_{Boiler2}}\right) \cdot HHV$ [=] Btus, $Q_{NG,THP} = \left(V_{NG_{THP}}\right) \cdot HHV$ [=] Btus; evaluated for each cycle with the fuel value (HHV) adjusted to local barometric/line pressures and as supplied by local utility, and converted to a firing rate as a rolling average over each cycle, $\dot{Q}_{NG}$.
- Power consumption: Power consumption is directly measured in $Q_{\text{Elec\_GAHP}}$, noting that in the case of pumps, these may be estimated based on runtime, state loggers, and a combination of nameplate and field measurements of power consumption.

Efficiency Metrics:

- GAHP Load Fraction: Defined as the ratio of GAHP output to total daily output, defined as $THP\ Load\ Fraction = \sum Q_{Hydronic,THP} \Big/ \sum Q_{Hydronic,Main}$
- GAHP COPs, focusing on just the inputs/outputs to the GAHP on a gas-input basis. The Heating COP is defined as: $COP_{Gas} = \frac{\dot{Q}_{Hydronic,THP}}{\dot{Q}_{NG,THP}}$; estimated and reported as, both time and cycle-averaged. Time-averaged permits comparison to instantaneous operating conditions (COP vs. ambient temperature), while cycle-averaged is a better assessment of energy efficiency.
    - Time-averaged: For each heating on-cycle, the instantaneous COP_{Gas} using 5-minute averaged firing rates (GAHP is modulating), the time-averaged COP_{Gas} will be reported.
    - Cycle-averaged: For each complete heating on-cycle, the total useful heating output measured at each time step, through the 'wind-down' stage, is compared to the total gas input over the complete cycle, $Q_{Hydronic,THP}$ [=] Btus.

- System Efficiency: Defined as the ratio of total system energy outputs (hydronic) to total system energy inputs, defined as:

$$System\ Efficiency = \frac{\sum(Q_{Hydronic,THP} + Q_{Hydronic,Boiler1} + Q_{Hydronic,Boiler2})}{\sum(Q_{NG,Boilers} + Q_{NG,THP} + Q_{Elec,Pumps} + Q_{Elec,Boilers} + Q_{Elec,THP})}$$

- To compare to prior GAHP testing, the "Input/Output" method will be utilized, which posits that the daily energy input vs. output of a heating system can yield a delivered efficiency (DE) from their linear relationship of the transient energy input to the energy output (Bohac, 2010 and Butcher, 2011). When plotted on an "I/O" chart the slope and y-intercept can be used to estimate the DE_{IO}, as follows:

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

With a known Output (heating and DHW) and the linear fit parameters, the DE_{IO} is readily estimated, which can be compared to those from laboratory tests and for baseline equipment, the rated efficiency.

Table 15: Multifamily Measurement Points and Variables

Measurement Type	Measurement Category	Measured Quantity	Measurement Point(s) and Variable(s)	Units
Continuous Measurement	Natural Gas Flow	Natural Gas Flow	Boiler 1 [$V_{NG\ Boiler1}$], Boiler 2 [$V_{NG\ Boiler2}$], GAHP [$V_{NG,GAHP}$]	ft^3
	Power Consumption	Power Consumption	Boilers Total [$Q_{Elec\ Boilers}$],GAHP [$Q_{Elec\ GAHP}$], Circulation pumps (individually and in aggregate) [$Q_{Elec\ pumps}$]	Wh
	Service Hot Water (SHW)	Water Flow	SHW [V_{SHW}]	gal.
		Temperature	Hot Water Outlet [T_{SHW}], Cold Water Inlet [T_{CW}]	°F
	Ambient/Indoor Air	Temperature	Indoor Mechanical Room [$T_{Air\ Mech}$], Outdoor GAHP [$T_{Air\ GAHP}$]	°F
	Hydronic Loops	Temperature	Boiler #1 Supply [$T_{Supply\ Boiler1}$], Boiler #1 Return [$T_{Return\ Boiler1}$], Boiler #2 Supply [$T_{Supply\ Boiler2}$], Boiler #2 Return [$T_{Return\ Boiler2}$], Main Loop Supply [$T_{Supply\ Main}$], Main Loop Return [$T_{Return\ Main}$], Buffer Tank Supply [$T_{Supply\ Buffer}$], Buffer Tank Return [$T_{Return\ Buffer}$], SHW Tank Supply [$T_{Supply\ SHW}$], SHW Tank Return [$T_{Return\ SHW}$], PHX Supply [$T_{Supply\ PHX}$], PHX Return [$T_{Return\ PHX}$], SHW Tank Reheat Supply [$T_{Supply\ SHWReheat}$], GAHP Supply [$T_{Supply\ GAHP}$], GAHP Return [$T_{Return\ GAHP}$],	°F
		Flow Rate	Circulator Pump Loops (Pump X) [$\dot{V}_{pump,x}$], GAHP Hydronic Loop [$\dot{V}_{GAHP}$]	GPM
	GAHP Internal / Boiler Internal	Temperature	Evaporator NH_3 Inlet [$T_{NH3\ In}$], Evaporator NH_3 Outlet [$T_{NH3\ Out}$], Desorber Shell [T_{Des}], GAHP Flue Gas Outlet [$T_{FG\ GAHP}$], Boiler 1 Flue Gas Outlet [$T_{FG\ Boiler1}$], Boiler 2 Flue Gas Outlet [$T_{FG\ Boiler2}$]	°F
Batch Measurement		Inlet Fuel Pressure	At GAHP and Boiler gas inlet [P_{NG}]	in. WC
		GAHP Operating Noise	Measured 1.0 m from GAHP	dB
		Excess air level, as dry stack O_2	GAHP Stack [n_{O2}]	%, dry
		Excess air level, as dry stack CO_2	GAHP Stack [n_{CO2}]	%, dry
3rd Party Data		Tank volumes	Indirect Storage Tank [$V_{Tank\ IST}$], Buffer Tank [$V_{Tank\ Buffer}$]	gal.
		Outdoor Temperature	Ambient Weather [$T_{Outdoor}$]	°F
		Outdoor Humidity	Ambient Weather [$RH_{Outdoor}$]	%
		Barometric Pressure	Ambient Weather [P_{Baro}]	in. Hg
		Natural Gas HHV	From Utility [HHV]	Btu/scf

* Note that gas and power consumption may be approximated using state loggers here, as noted previously

Appendix B: Additional Photos, Data, and Information from Site Selection

Site Recruitment, Screening, and Selection Phase

The following materials were developed during the initial site survey/inspection of the Evanston site and two Indiana field sites, post-selection:

Multifamily Site Selection

Boiler/GAHP Hybrid Demonstration – Site No. 7

2321-2323 Central, Evanston, IL

> Building approximately 60+ years
> 6 apartments (approx. 1000 ft² each unit)
> Double pane windows installed approx. 7 years ago
> Roof insulated at same time
> One gas meter for boiler and water heater

GTI Overview 2

Boiler/GAHP Hybrid Demonstration – Site No. 7

2321-2323 Central, Evanston, IL

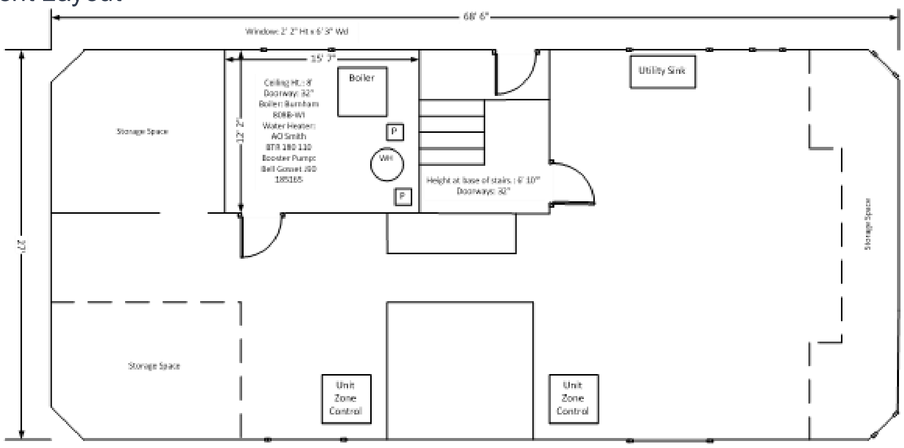
> North elevation ideal site for GAHP install. Space not an issue.
> Boiler room located on north wall
> Sewer located outside for condensate disposal
> Outdoor temp sensor located against chimney

GTI Overview 3

Boiler/GAHP Hybrid Demonstration – Site No. 7

2321-2323 Central, Evanston, IL

> Basement Layout



Boiler/GAHP Hybrid Demonstration – Site No. 7

2321-2323 Central, Evanston, IL

> Boiler Room Photos

Boiler/GAHP Hybrid Demonstration – Site No. 7

2321-2323 Central, Evanston, IL

> Boiler Room Equipment
- Burnham Boiler
  - Model 808B-WI
  - Input 462K; Output 369K
  - 140F Set Point
  - Near end of life
- A.O. Smith Water Heater
  - 81 gallon capacity
  - Input 180K Btu
  - 138F Set Point
  - Installed 2010

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gti

Boiler/GAHP Hybrid Demonstration – Site No. 7

2321-2323 Central, Evanston, IL

> Boiler Room Equipment
- Booster Pump
  - Bell & Gossett
  - Model J90 189165
- Hydronic Heating Control
  - Varistat III
  - Currently disabled; expected operation parameters of 130F – 160F once repaired

GTI Overview 7

gti

Boiler/GAHP Hybrid Demonstration – Site No. 7

2321-2323 Central, Evanston, IL

> Boiler Room Equipment
- Electric Service Panel
  - Updated electric
  - Outlets available for DAQ

GTI Overview 8

Boiler/GAHP Hybrid Demonstration – Site No. 7

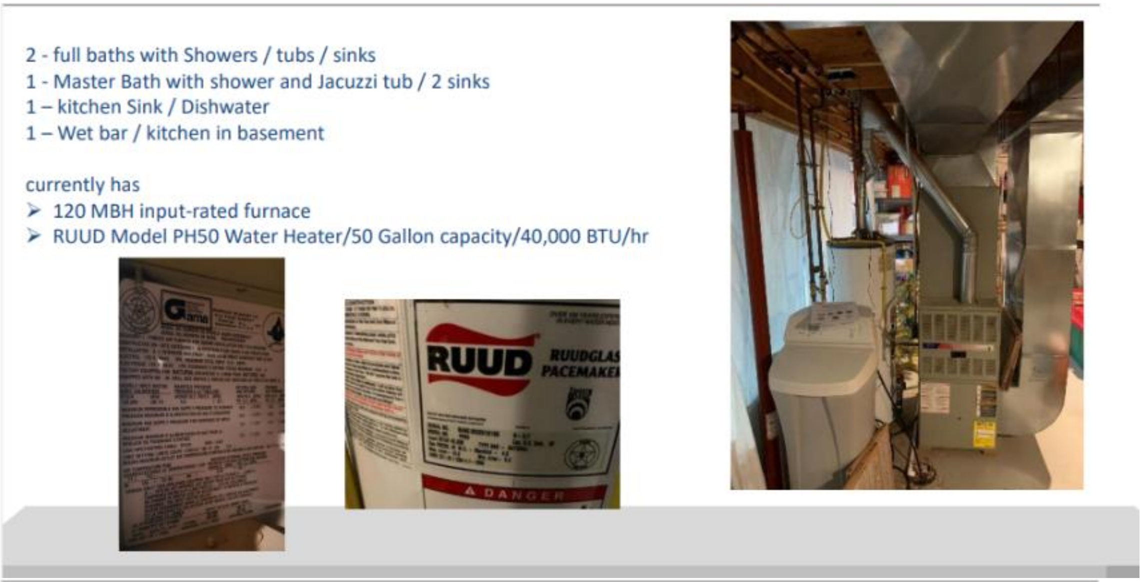
2321-2323 Central, Evanston, IL

> Additional equipment info
- Zone heating control
  - 3rd floor units supplied by 1” pipe; all other units supplied by ¾” pipe
- Portions of pipe may be insulated with asbestos

GTI Overview 9

Single family Site Selection

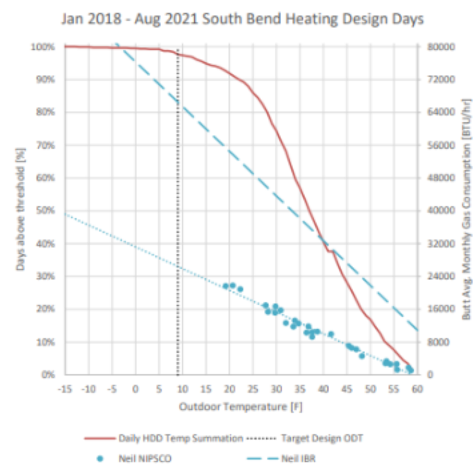
First the forced-air site:



GTI ENERGY

The Outside/Inside of the same wall

- Proposed Heat Emitter: Hydronic Air Handler
- Est. IBR Heat Loss @ 70F inside, 9F outside
  - 66,500 BTU/hr
- Est. Heating Consumption @ 70F inside, 9F outside
  - 26,400 BTU/hr
  - Based on provided wintertime utility consumption



Next the hydronic site:

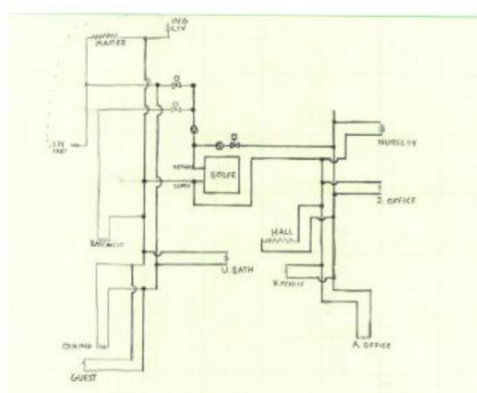
164,000 BTU/hr Burnham unit

80 ft of baseboard installed, and one small iron radiator.

RATINGS

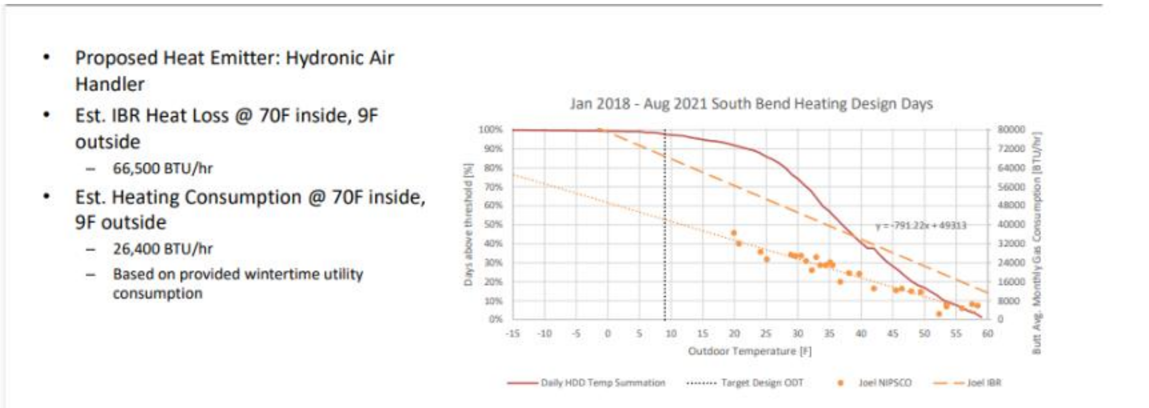
BB Model Number	Element Type	Tube Size and Material	Fin Size and Material (Width x Height x Thickness)	Fins per Foot	Water Flow	Pressure Drop†	Steam 1 PSI ‡ Btu/Hr. Per Foot	HOT WATER RATINGS ‡ BTU/HR./FT. 110°F	120°F	130°F	140°F	150°F	160°F	170°F	180°F	190°F	200°F	210°F	220°F
80-D	H-1	1" copper	3 x 3¼" x .024" aluminum	48	1 GPM	47	—	210*	290*	360*	440*	520	610	700	790	880	970	1060	1140
					4 GPM	525		220*	310*	380*	470*	550	640	740	840	930	1030	1120	1200
80-A	H-3	¾" copper	2¼" x 2¼" x .011" aluminum	55	1 GPM	47	—	200*	270*	340*	410*	490	570	650	730	810	890	970	1050
					4 GPM	525		210*	290*	360*	430*	520	600	690	770	860	940	1030	1110
80-D	H-4	1" copper	3" x 2½" x .011" aluminum	48	1 GPM	13	—	200*	260*	330*	400*	480	560	640	720	800	880	960	1040
					4 GPM	146		210*	270*	350*	420*	510	610	680	760	850	930	1010	1100
80-D	H-5X	1¼" copper	3" x 3¼" x .020" aluminum	48	1 GPM	6	1130	190*	260*	320*	390*	470	550	650	740	830	920	1010	1100
					4 GPM	68		200*	270*	340*	410*	500	580	690	780	890	970	1070	1150
80-D	H-6X	1¼" IPS steel	3" x 3¼" x .028" aluminized steel	48	1 GPM	3	990	—	—	—	—	410	490	560	640	710	790	860	940
					4 GPM	41		—	—	—	—	430	520	590	680	750	840	910	990

† Milinches per foot. *Ratings at 140°F and lower temperatures determined by multiplying 150°F rating by the applicable factor specified in Table E in the I=B=R Testing and Rating Standard for Baseboard radiation.
‡ With 65°F entering air.
NOTE: Ratings are for element installed as per drawing shown in "Dimensional Data" window (open "Dimensional Data" window to view) with damper open, with expansion cradles. Ratings are based on active finned length (3" to 6" less than overall length) and include 15% heating effect factor.
Ratings are also based on:
81-A: 3/4" nominal copper tubing with 3" x 3-1/4" x .024" aluminum fins spaced 48 per linear foot (unpainted).
83-A2: 3/4" nominal copper tubing with 2-3/4" x 2-1/2" x .011" aluminum fins spaced 55 per linear foot (unpainted).
84-A3: 1" nominal copper tubing with 3" x 3-1/2" x .011" aluminum fins spaced 48 per linear foot (unpainted).
85-AX: 1-1/4" nominal copper tubing with 3" x 3-1/4" x .020" aluminum fins spaced 48 per linear foot (unpainted).
86-AX: 1-1/4" IPS steel with 3" x 3-1/4" x .028" aluminized steel fins spaced 48 per linear foot (unpainted).

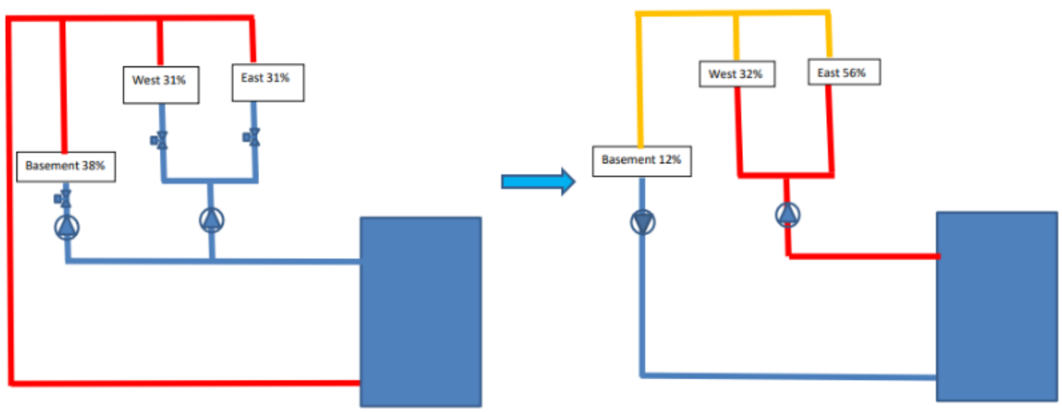


There is actually two circulators. One is a honeywell PC3F1558IUF00 and the other is a taco 007-F5

Two Circulators
Three Zone Valves
One Thermostats



Proposed Heat Emitter: Hydronic Air Handler
Est. IBR Heat Loss @ 70F inside, 9F outside
66,500 BTU/hr
Est. Heating Consumption @ 70F inside, 9F outside
26,400 BTU/hr
Based on provided wintertime utility consumption
Jan 2018 - Aug 2021 South Bend Heating Design Days
Days above threshold [%]
Butt Avg. Monthly Gas Consumption [BTU/hr]
Outdoor Temperature [F]
y = -791.22x + 49313
Daily HDD Temp Summation
Target Design ODT
Joel NIPSCO
Joel IBR



West 31%
East 31%
Basement 38%
West 32%
East 56%
Basement 12%

Appendix C: On-Demand Recirculation Pump Controls (ODRPC)

ODRPC Installation and Commissioning

The following timeline and supporting text outline the full sequence of events to properly install and commission the ODRPC.

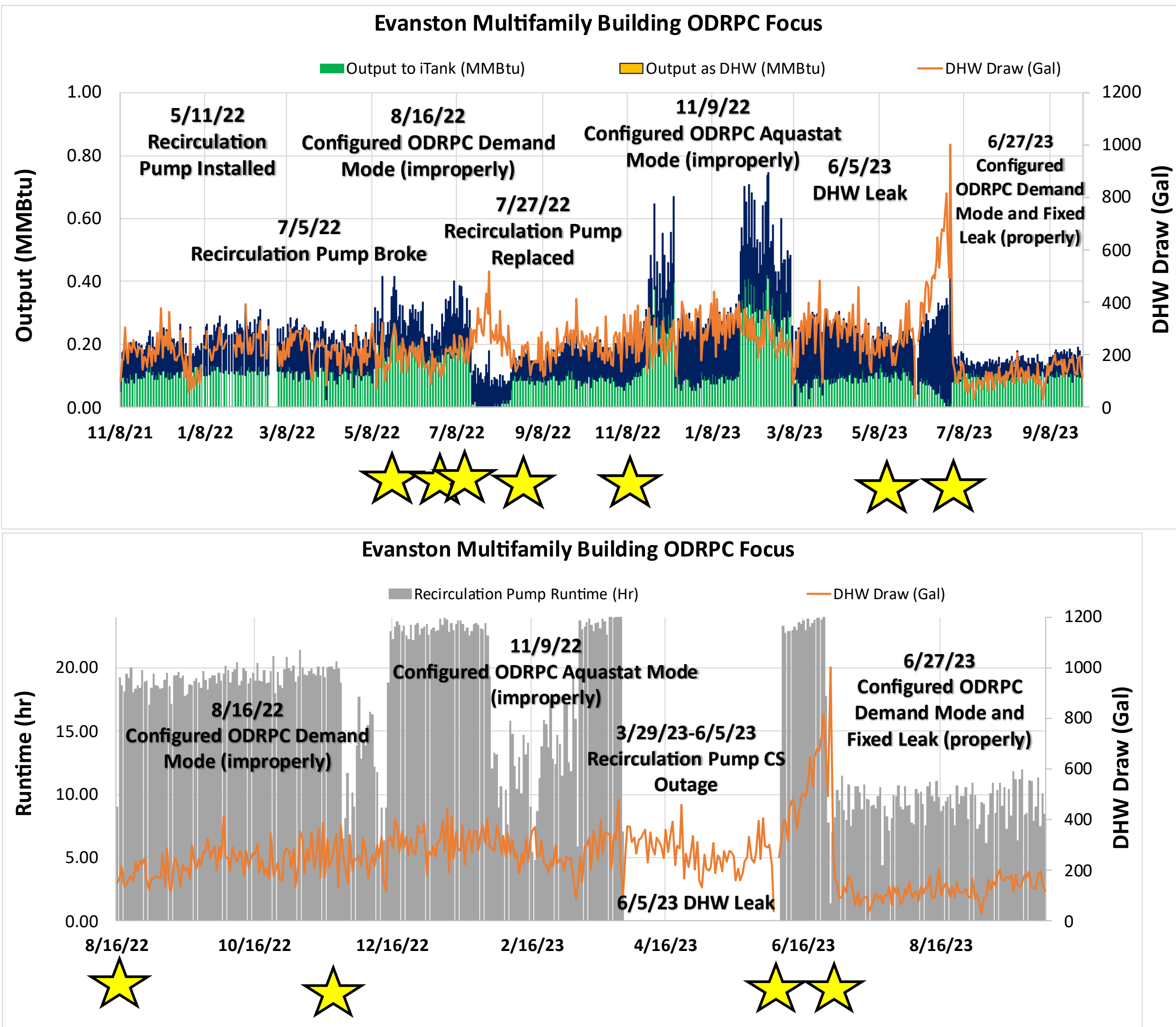


Figure 62: Summary of ODRPC DHW-Focused Load Profile at Multifamily Site

- In early May, 2022 a recirculation pump with ODRPC was installed on the DHW loop. This was not properly commissioned at first, so the recirculation pump was allowed to run 24/7 through early July, 2022.

- On July 5, 2022, the recirculation pump broke, so the recirculation was not utilized for a couple weeks.
- On July 27, 2022, the recirculation pump was fixed; however it still was not properly commissioned, so it ran 24/7.
- On August 16, 2022, the ODRPC the controls were configured, but they were set-up with improperly placed thermistors which were not accurately depicting DHW water draws. This led to random, and ineffective controls of the recirculation pump.

  The controller included installed thermistors on the recirculation return temperature and inlet to the WH/tank, which were used to determine if there is DHW draw. Typically, during a DHW draw, the inlet to the WH/tank will decrease. The controller requires four inputs, a recirculation return setpoint, a flow setpoint, and differential setpoints for each. A DHW draw is determined by looking for a differential between the inlet and recirculation compared to the differential setpoint. A differential between the inlet and recirculation less than the differential setpoint tells the controller that there is DHW draw. This comparison paired with a recirculation return temperature greater than the difference between the recirculation return setpoint and recirculation return differential will thus turn off the recirculation pump.

  The recirculation return temperature was initially installed on the recirculation return and inlet to the IST; however, the inlet to the IST is preheated from the GAHP heated buffer tank. This means that this temperature is heated by the buffer tank when the IST dips below a target setpoint. This means that this temperature will not correlate with DHW water draws due to the water consistently being heated up by the buffer tank. Due to this operation, the project team utilized consulting from the PT-electronics technician to move the thermistor to a location that would accurately capture DHW draw induced temperature changes.
- On November 9, 2022, knowing that the thermistor location for the "demand" control was incorrect, the project team reconfigured the ODRPC to "Aquastat Mode", meaning that the Recirculating Pump is activated when recirculating loop temperature drops below a User Defined Setpoint. This was set to 118F with a 3F differential originally, then raised to 120F on November 30, 2022.
- On June 27, 2023, the project team met with an ODRPC technician on-site to relocate the ODRPC thermistors, and to officially commission the ODRPC. When operated under "OnDemand" Mode, the recirculating pump is activated unless both:
    - Recirculating loop temperature (return Line) has dropped below a user defined setpoint
    - Flow is sensed (fixtures opening)

  The pump is deactivated when recirculating loop temperature rises to user defined setpoint, with a recirculation return temperature of 110°F, return differential of 2°F, and target inlet to the water heating tank of 115°F with a tank differential of 3°F.

  After these changes, the on-demand recirculation pump would operate until the Recirculation Return Temp dipped below 107°F and the inlet to WH/tank temperature was less than 110°F.

Figure 63: DHW On-Demand Recirculation Pump and Controls

The final, correct locations of the ODRPC thermistors are shown below. The process in determining the correct thermistor locations given this is an unconventional DHW heating system was a learning opportunity and may open the door for further implementation in similar systems.

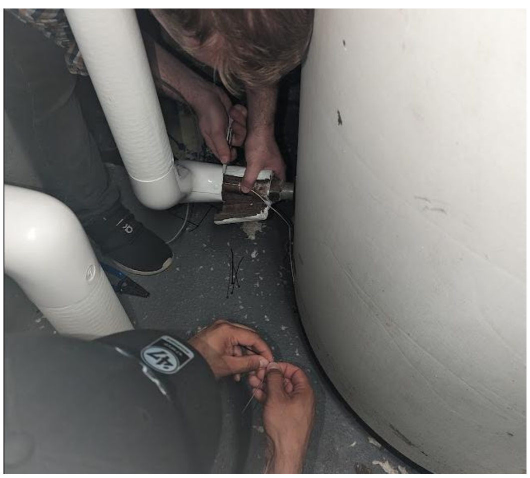


Figure 64: Final On-Demand Recirculation Pump Controls Thermistor Locations on Buffer Tank Inlet (left) and Recirculation Return to IST (right)

ODRPC Energy and Water Savings

Due to the long duration between installing the ODRPC, and properly setting it up, the project team was able to examine its effect on DHW operation and performance across several monitoring periods. While substantial changes to the GAHP, and other heating controls also affected operation and performance, the project team sought to highlight the effects of the ODRPC.

Compared to the non ODRPC periods, when utilizing the ODRPC, the field site saw an increase in DHW Supply temperatures and decrease in DHW Water Use (Figure 70), with a small effect on DHW heating system performance (Figure 71). Without the use of the ODRPC, the DHW heating system likely drew in Cold City water more often to be heated by the DHW heating system, which contributed to a high amount of thermal and standby losses. When the ODRPC was utilized correctly, the Recirculated Return water could be reused when there was a demand, in place of needing to reheat the Cold City water. This resulted in significant water savings. However, since this behavior meant that the DHW heating system was utilized less often, and likely with more short cycling behavior, this explains why the performance of the DHW heating system likely decreased in efficiency.

As illustrated in the prior sections, substantial annual water savings of 30,845 Gallons or $11,340 using the local utility water rate. Note that when the recirculation was utilized, the pump consumes an additional electrical penalty, this was not included in this analysis. For 24/7 operation, the recirculation pump would consume 2,842 kWh and for ODRPC, the pump would consume 1,098 kWh. Utilizing the local utility rates for electricity, this penalty would result in an electrical penalty of $274 for 24/7 operation and $106 for ODRPC pump operation.

Appendix D: Information Regarding Sensor Calibration

Multifamily Home System Sensor Calibration and Methodology

During the initial and re-commissioning period, several key datapoints were taken either to support the GAHP commissioning itself or to collect batch data to characterize the host site. Captured in the subsequent tables, the following data were collected:

- A Bacharach portable combustion analyzer, model PCA 400, was used to sample stack gases from the GAHP units, primarily to assure the combustion system is adjusted to the site specifics per SMTI requirements (e.g. local gas quality, pressure, elevation). The table below summarizes the readings from one of these sampling periods, in this case for the commissioning of the replacement 80 kBtu/h GAHP unit. These readings are not representative of all operation but are shown as an example, as the GAHP typically operates with higher levels of excess air.
- Due to the importance of the temperature measurements at the GAHP hydronic supply and return, both in calculating the GAHP's output capacity and its operating efficiency as a COP_{Gas}, these RTDs were calibrated in-situ using a Fluke 9100s dry well calibrator. The results of this calibration over three points, for each RTD, are shown in the table below. This linear adjustment is applied in all reported datasets.
- Noted in the measurement plan, the flow rate within the hydronic loops at multiple points were measured using an ultrasonic flow meter, the Fuji model FSVEYY12-SYYB-N. The results from these measurements, which are used in subsequent calculations, are summarized in the subsequent tables.

Table 16: Combustion Gas Analysis – GAHP Commissioning (Original)

Stack Constituent	Measurement, High-fire	Measurement, Low-fire
O_2	3.5%	3.3%
CO_2	9.8%	10.0%
CO	87 ppm	40 ppm
NO_x	34 ppm	32 ppm
T_{stack}	126°F	121°F

Table 17: RTD Calibration – Results and Linear Shift Coefficients

	Supply	Return
60°F Point	59.959	59.879
100°F Point	99.864	99.859
140°F Point	139.880	139.879
Y-Intercept	0.000305	0.126908
Slope	1.000988	1.000006

Table 18: Ultrasonic Flow Meter Measurements - Pumps

			Velocity	Flow	Flow
Fluid	**Pump No.**	**Description**	**ft/s**	**CFH**	**GPM**
Water	P1	DHW Recirculator	n/a	n/a	n/a
	P2	Boiler #2*	1.30	107.90	12.95
	P3	Boiler #1*	1.29	109.90	13.19
	P4	Building Loop Circulator	n/a	n/a	n/a
	P5	Indirect Tank Circulator*	4.60	77.80	9.34
	P6	Buffer Tank Circulator*	2.88	90.23	10.83

Table 19: Ultrasonic Flow Meter Measurements - Zones

		Velocity	Flow	Flow
Fluid	**Zone Valve**	**ft/s**	**CFH**	**GPM**
Water	1W	0.72	32.05	3.85
	2W	0.66	29.11	3.49
	3W	0.70	31.23	3.75
	1+2W	1.34	59.59	7.15
	1+2+3W	1.92	86.56	10.39
	1E	0.70	31.30	3.76
	2E	0.63	28.28	3.39
	3E	0.67	30.72	3.69
	1+2E	1.28	56.67	6.80
	1+2+3E	1.74	77.98	9.36
	1+2+3W+1E	2.57	115.56	13.87
	1+2+3W+1+2E	2.94	130.89	15.71

To refine the space heating delivered energy calculations, on 3/6/2023 the project team relocated the portable ultrasonic flow meter that was measuring total boilers return flow and moved it to measure the main system return flow. This would then be used in the space heat delivered energy calculations to more accurately estimate the space heating delivered to the six zones, and to recalculate previous space heating energy delivered values utilizing the zone valve temperature measurement proxies for zone specific heating calls.

Figure 65: Relocation of Ultrasonic Flow Meter to Main System Space Heat Return to Zones on 3/6/2023

Utilizing the surface thermocouples mounted on each of the six zone valve supply pipes, and ultrasonic flow measurements of the main system flow, the following plot illustrates the system flow dynamics as the number of zones calling for heat increases and decreases.

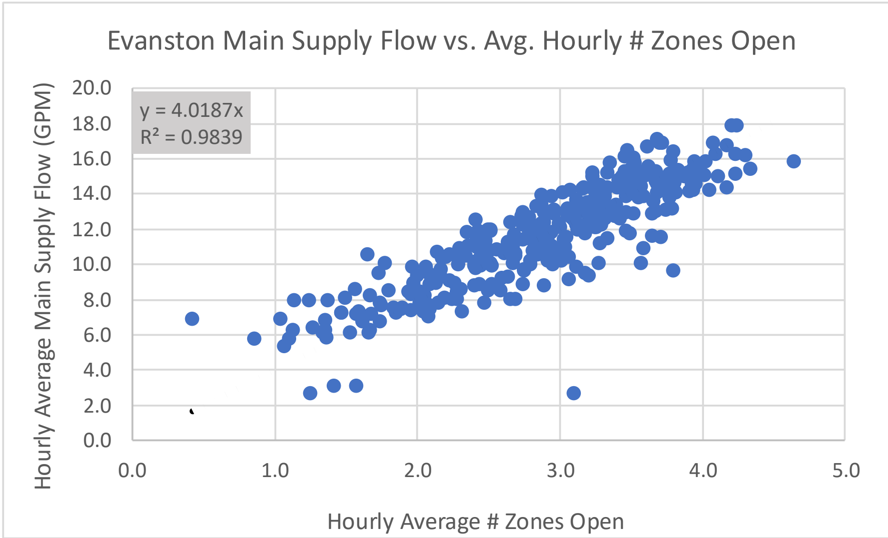


Figure 66: Hourly Average Main System Flow vs. Average # Zones Calling for Space Heat

Even though the space heating system was no longer balanced, there was a distinct linear relationship between the main system flow and # of zones calling for heat.

Appendix E: Detailed Overview of DHW-Only Performance

This section summarizes the DHW-only performance for the three sites, largely logged between heating seasons during the summer and milder portions of the shoulder seasons.

Site 1: Evanston Multifamily Home DHW-Only

Noted previously, the multifamily site featured a few major changes to the site's heating system. The first of which was the GAHP replacement in July, 2022 and shortly after a recirculation pump was installed on the DHW recirculation loop, though the recirculation pump was not optimized until the subsequent summer. Each of these milestones are demarcated on the subsequent plots and will be highlighted in the DHW-only analysis to determine the effect on the heating system. The observed weather conditions are shown in the figure below for the full DHW-only period. The subsequent charts catalogue the site activity over these four distinct periods, "boiler-only no recirculation", "GAHP and boiler no recirculation", "GAHP and boiler Aquastat Based Recirculation", and "GAHP and Boiler On-Demand Recirculation". The subsequent plot of these regimes highlights the output contributions of the GAHP, the boilers, and the DHW demand.

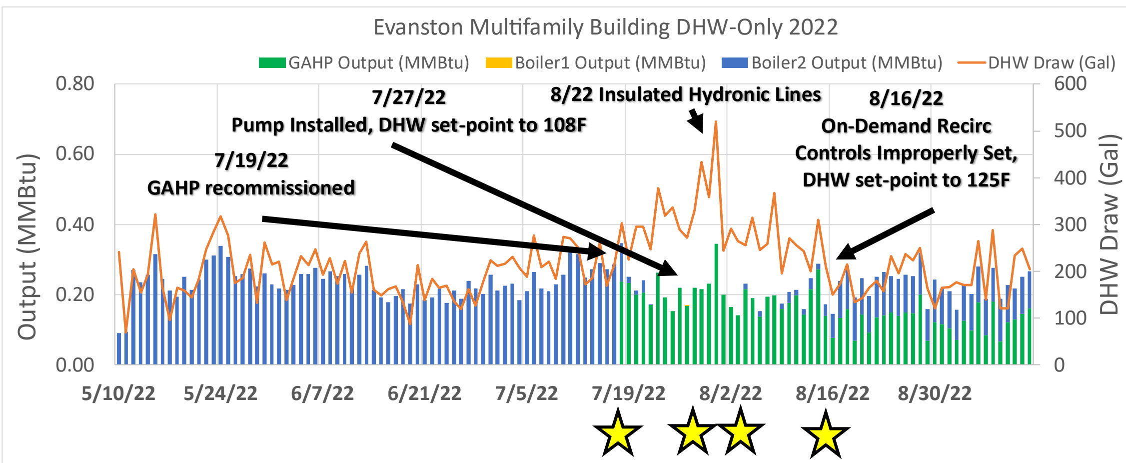


Figure 67: Summary of 2022 GAHP + Boilers DHW-only Load Profile at Multifamily Site

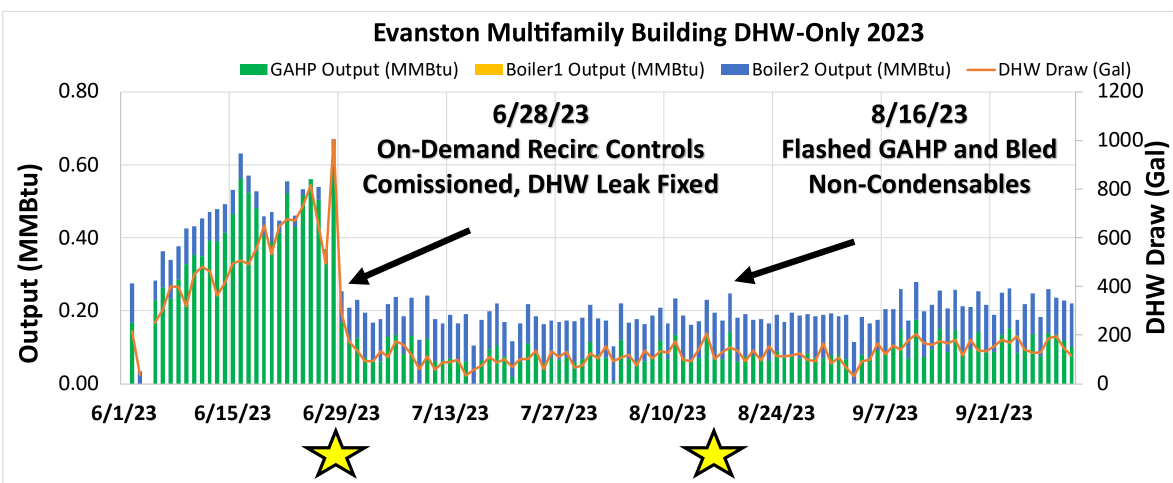


Figure 68: Summary of 2023 GAHP + Boilers DHW-only Load Profile at Multifamily Site

Operating Efficiency

The operating efficiency of the system in DHW-only operation can be broken down into two parts. First is the efficiency of the GAHP itself, which is a function of ambient operating conditions, and secondarily, the delivered efficiency which measures the ability for the heating system to effectively use the delivered energy for DHW. When it comes to the GAHP's efficiency in this mode, the COP_gas was analyzed against its cycling conditions.

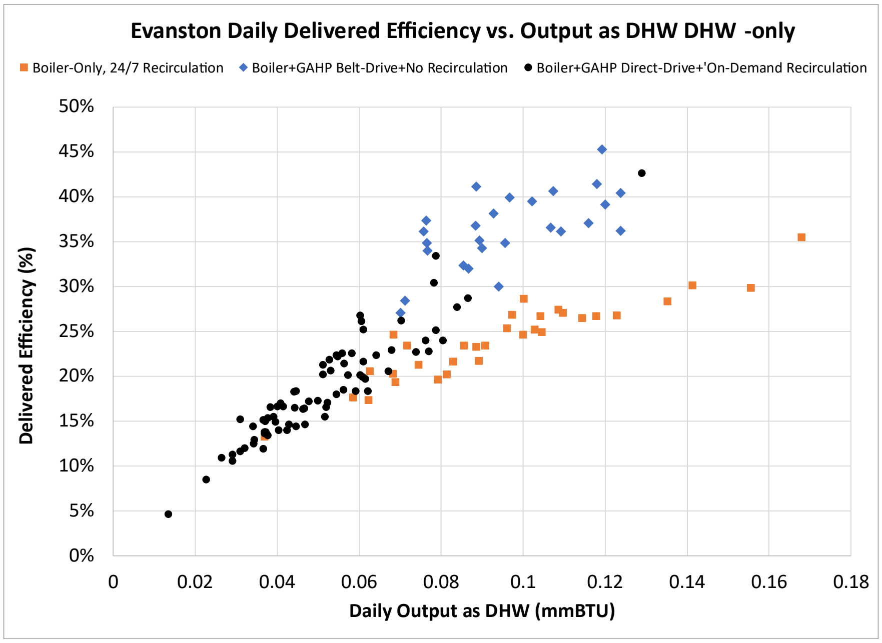


Figure 69: DHW-Only Delivered Efficiency vs. Output as DHW

It is apparent that the best performing DHW operating period was the boiler and GAHP with the belt-drive solution pump with no recirculation. This is interesting because despite the improved efficiency of the GAHP with a direct-drive solution pump when using the ODRPC, efficiency decreased. However, when utilizing the on-demand recirculation pump controls, a significant drop in DHW output was observed due to a significant reduction in standby and system losses. It is likely that when using the recirculation pump, the smaller DHW load would cause the GAHP and boiler to short-cycle more often for decreased runtimes, an issue that is already known for GAHP systems serving smaller DHW-only loads.

Controls Considerations

Once commissioned and adjusted, the GAHP and ODRPC in the prior monitoring periods had two distinct operating phases before and after installation and configuration. Initially, the recirculation was 24/7, and then once properly commissioned, the recirculation pump was controlled based on demand. The impact of these changes and past monitoring of the DHW system were analyzed in this section of the report. Operation was dictated by the indirect storage tank setpoint, while the recirculation pump was controlled by a recirculation return temperature setpoint and differential, and a cold inlet temperature and differential that determined DHW flow. For changes in these setpoints, it was expected to result in a variation in:

- DHW Supply temperature

- Total GAHP and Boiler gas consumption
- Boiler part load percentage and overall lower delivered efficiency

The figure below illustrates how the DHW supply temperature varied.

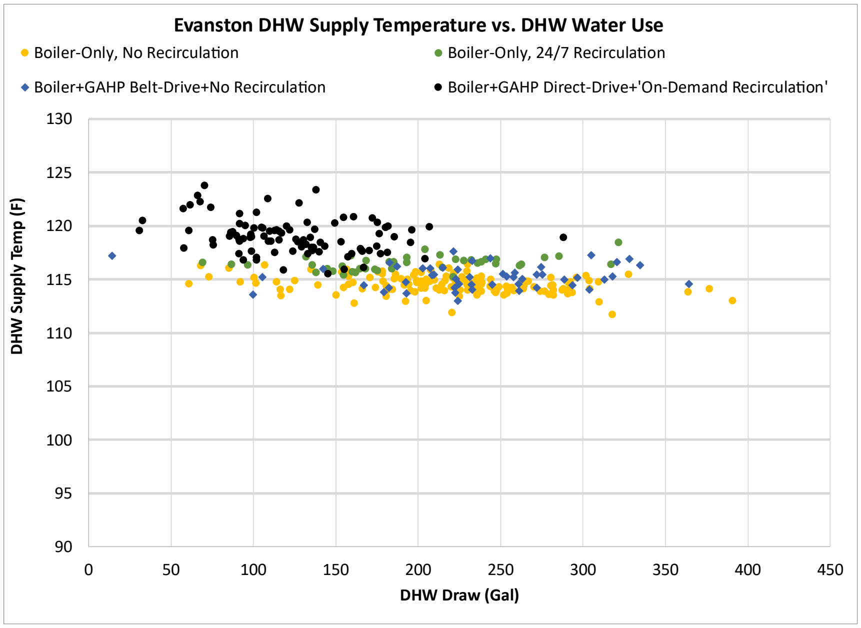


Figure 70: Daily DHW Output Temperature vs. Daily DHW Water Use

It was observed that for no changes to the IST setpoint of 115°F, that higher temperatures were observed during the ODRPC period compared to all other periods. It was also seen that there was a significant reduction in output to DHW, as noted previously.

Energy Extrapolations

Despite the tradeoff of utilizing the ODRPC (short-cycling, etc.), the various periods of operation in DHW-only mode were compared on an energy basis to determine the energy savings of the GAHP and boiler system compared to the baselines. The three periods analyzed in for energy savings are the 2021 GAHP and boiler period without recirculation, the 2022 Boiler-only period, and the 2022 GAHP and boiler period with ODRPC.

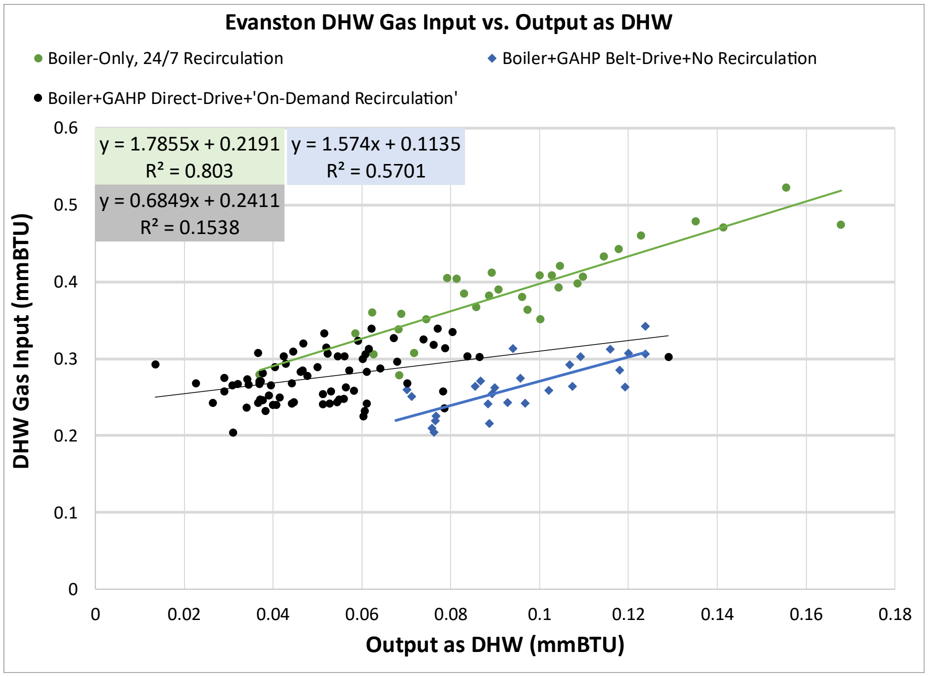


Figure 71: Comparison of DHW Gas Input vs. DHW output During DHW-only Operation from 2021 to 2023

To extrapolate the previous chart into full year energy consumption on a DHW output basis, which normalizes DHW supply temperatures, a daily average of the DHW draw was calculated from the entire 2021 to 2023 dataset. This equates to a daily average DHW draw of 221 Gal. Then, to determine the daily average output as DHW for each input vs. output regression seen above in Figure 71, the following chart of daily DHW output vs. daily DHW draw was utilized

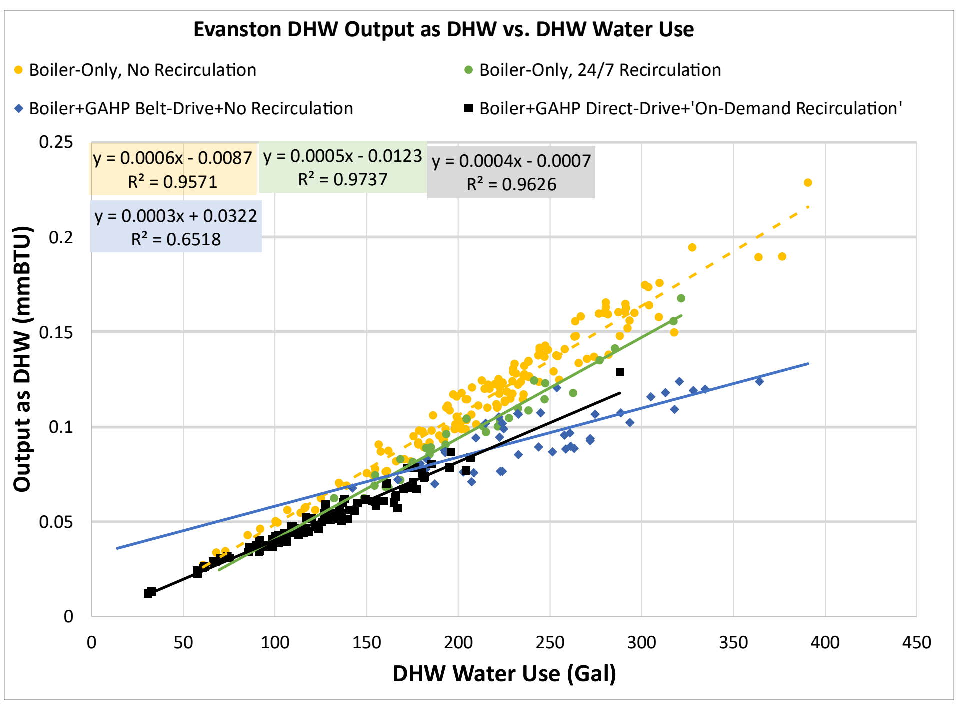


Figure 72: Comparison of Output as DHW vs. DHW Draw During DHW-only Operation from 2021 to 2023

For comparative purposes, the baseline condition of boiler-only and dataset of retrofit GAHP + Boiler ODRPC were used to determine what the daily average DHW output would be for the energy savings analysis. Therefore, for the baseline boiler-only daily average DHW draw of 259 Gal, the daily average output to DHW was kept at .14 mmBTU, while the retrofit GAHP+Boiler ODRPC daily average DHW draw of 110 Gal meant the daily average output to DHW was .05 mmBTU. It is these values and the linear regressions of Figure 71 that were used to calculate the daily average DHW gas input each day, and then extrapolated for a year.

The table illustrates that the highest energy savings occurred for the Direct-Drive GAHP and boiler operation with ODRPC. Note that when the recirculation was considered, which was always active, the pump consumes an additional electrical penalty, this was not included in this analysis. For 24/7 operation, the recirculation pump would consume 2,842 kWh and for ODRPC, the pump would consume 1,098 kWh. More importantly, the utilization of the ODRPC led to an increase in the DHW supply temperatures without an increase to the DHW set-point, as seen in Figure 70, which paired with a more consistent hot water temperature, led to a substantial reduction in DHW water consumption of 30,845 Gallons. Therefore, not only did the recirculation allow for more consistent DHW water, but it also resulted in water and energy savings, however the shift in reduced DHW demand may have been influenced by the ongoing COVID-19 pandemic.

Table 20: Energy Savings Analysis of DHW-Only Operation at Multifamily Building (Annualized)

	Gas Use (therm)	GAHP Electricity Use (kWh)	DHW Total (gal)	Gas Savings vs. Boiler-Only (therm)	Gas Savings vs. Pre-2019 Tanked WH (therm)
Direct-Drive GAHP + Boilers + ODRPC	1007	1287	47067	570.6 (36%)	1166 (54%)
Belt-Drive GAHP + Boilers + No Recirculation	1100	1386	77912	477.7 (30%)	1073 (49%)
Backup Boilers Only + 24/7 Recirculation	1578	0.0	77912	-	595 (27%)
Baseline Old Tanked WH Pre-2019 (Utility Bill)	2174	0.0	77912	-	-

Site 2: La Porte Hydronic System

During the boiler-only and DHW-only operational period in 2021, the outdoor temperatures had minimal effect on system performance, so the following plot of weather conditions for the DHW-only operation are for the DHW-only GAHP operation starting in May 2023. The next two plots illustrate the energy flow and DHW water consumption of the heating system during the 2022 boiler-only DHW-only, and the 2023 GAHP DHW-only periods.

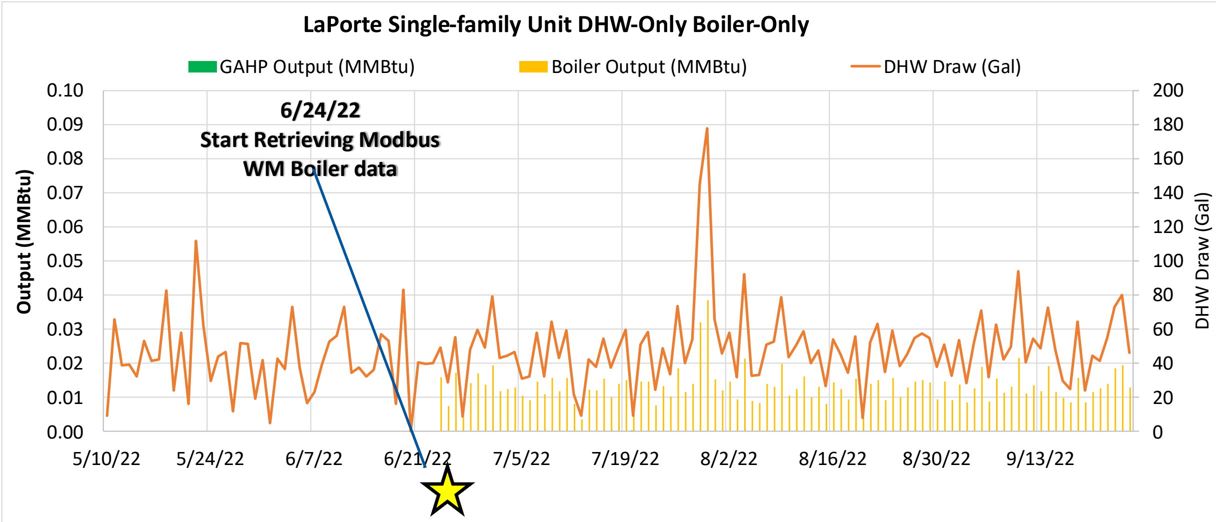


Figure 73: Summary of 2022-2023 Boiler-Only DHW-only Load Profile at Single family Hydronic Site

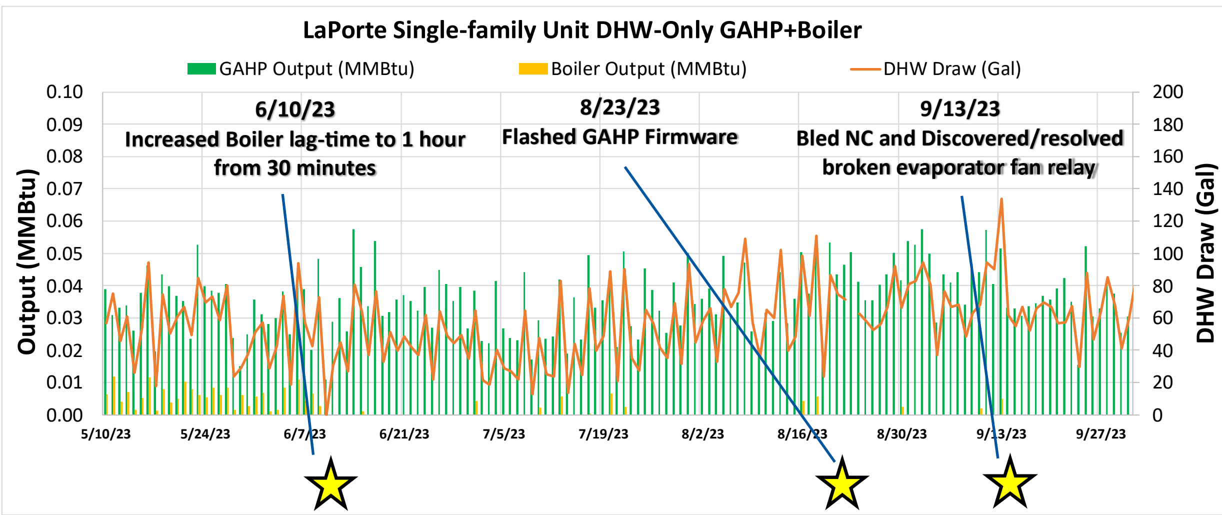


Figure 74: Summary of 2022-2023 GAHP DHW-only Load Profile at Single family Hydronic Site

Comparing the two monitoring periods, the two periods were very similar with respect to the output energy required for DHW, as well as the daily DHW use. Given that the DHW setpoint likely didn't change, this is not much of a surprise. However, the significant difference between the two monitoring periods is seen when analyzing the system performance during each monitoring period. Since the boiler was rated at 95% efficiency, and the GAHP could operate with an AFUE upwards of 140%, modest gas savings should have been achieved when comparing gas consumption of the DHW-only heating system. The following section dives into the system performance.

Operating Efficiency

First, the performance of the GAHP was analyzed. This first figure illustrates the GAHP COP, given as the output energy to the hydronic loop divided by the gas consumption. Given that the GAHP operates most efficiently during steady-state (fewer, longer on-cycles), the highest COP should be achieved for higher values of output energy, given that the total output consists of as few cycles as possible.

Overall, GAHP COPs ranging from 0.8 to 1.1 were observed, lower than the steady state performance at these conditions, but expected given the nature of DHW-only operation, this degradation in performance is typically due to shorter and more frequent cycles and performance with rapidly rising GAHP loop temperatures. The backup boiler delivered efficiencies ranged from 30% to 35%, which illustrates the same challenges when comparing to the 95% AFUE.

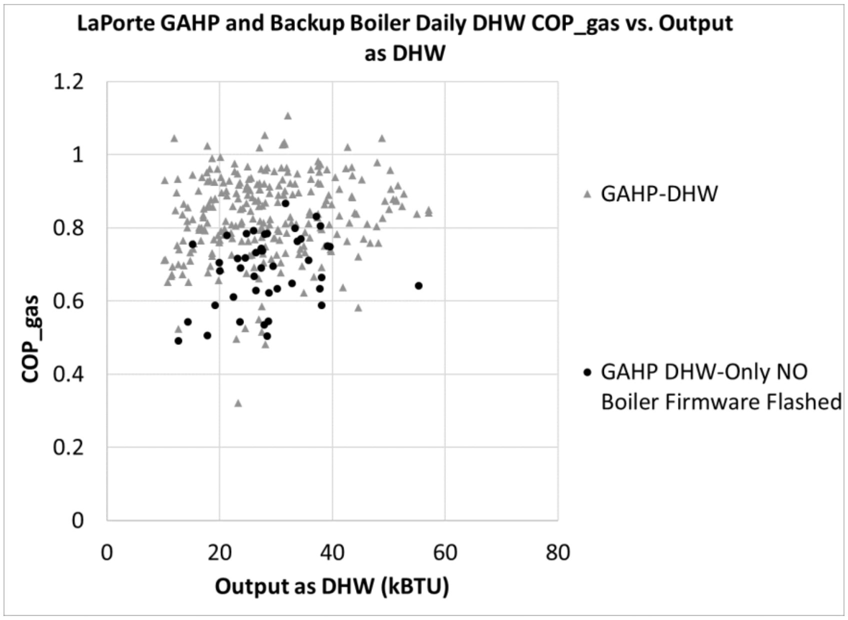


Figure 75: DHW-Only GAHP or Boiler COP_gas vs. Output as DHW and Operational Mode at La Porte Site

Energy Extrapolations

As with Site #1, to extrapolate savings it is important to develop a relationship between the output energy and input energy. The figure below compares this relationship of the boiler-only operational period from 2022, and the GAHP operation from 2023.

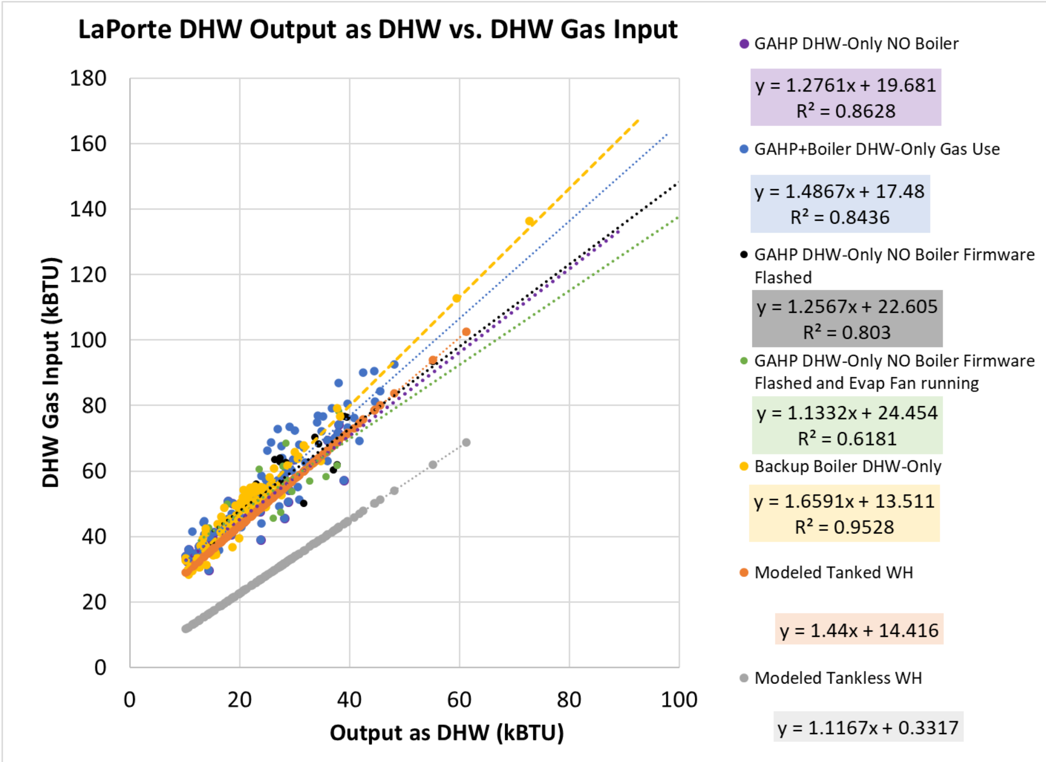


Figure 76: Comparison of DHW Gas Input vs. DHW output During DHW-only Operation from 2021 to 2023 at La Porte Site

We see from the above figure that the boiler had a similar behavior to the modeled tanked WH. Given that this heating system incorporates an indirect tank, and a high efficiency boiler, this comparison makes sense given expected thermal and standby losses. In this type of analysis, the slope of the input and output is equivalent to the heating efficiency, while the prominence of a y-intercept illustrates energy losses (energy input with no load). It is also clear that the GAHP was able to operate much closer to that of a tankless WH, in terms of slope. However, due to the usage of the indirect storage tank, and due to imperfect controls, a tankless WH is still better performing for DHW-only operation due to eliminating standby losses of a tank, mainly in terms of the linear offset. Additionally, the lower than expected performance of the GAHP at this field site was hypothesized to be due to a build-up of non-condensable gases in the system, which led to higher than expected return water temperatures, thus lowering operating efficiency.

To extrapolate this into full year energy consumption on a DHW output basis, (which normalizes DHW supply temperatures), a daily average of the DHW draw was calculated from the entire 2021 to 2023 dataset. This equates to a daily average DHW draw of 49 Gal. Then, to determine the daily average output as DHW for each input vs. output regression seen above in Figure 71, the following chart of daily DHW output vs. daily DHW draw was utilized.

For comparative purposes, the baseline condition of boiler-only was used to determine what the daily average DHW output would be for the energy savings analysis. The DHW, economic, and greenhouse gas emission extrapolations were utilized in the following SH and DHW section where the combi operation linearizations were utilized in replace of the above linearizations for

DHW-only operation. For the DHW-only period, the daily average DHW draw of 49 Gal, the daily average output to DHW was kept at 22 kBTU. The annual water consumption would equate to 17,423 Gal. It is these values that were utilized with the linear regressions of Figure 71 that were used to calculate the daily average DHW gas input each day, and then extrapolated for the DHW-only period.

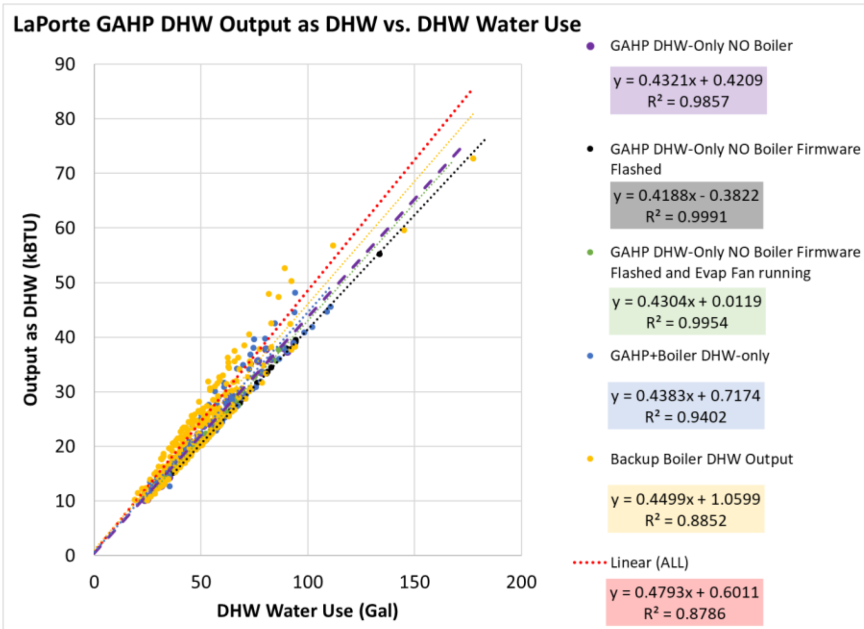


Figure 77: Comparison of Output as DHW vs. DHW Draw During DHW-only Operation from 2021 to 2023 La Porte Site

Site 3: New Carlisle Forced-Air System

Like the La Porte site, GAHP issues during the 2021-2022 period also expanded the boiler-only operational period during both the 2021-2022 heating season and the 2022 DHW-only period. The following plot of weather conditions for the DHW-only operation are for the DHW-only GAHP operation starting in May 2023. The next plots illustrate the energy flow and DHW water consumption of the heating system during the 2022 boiler-only DHW-only, and the 2023 GAHP DHW-only periods.

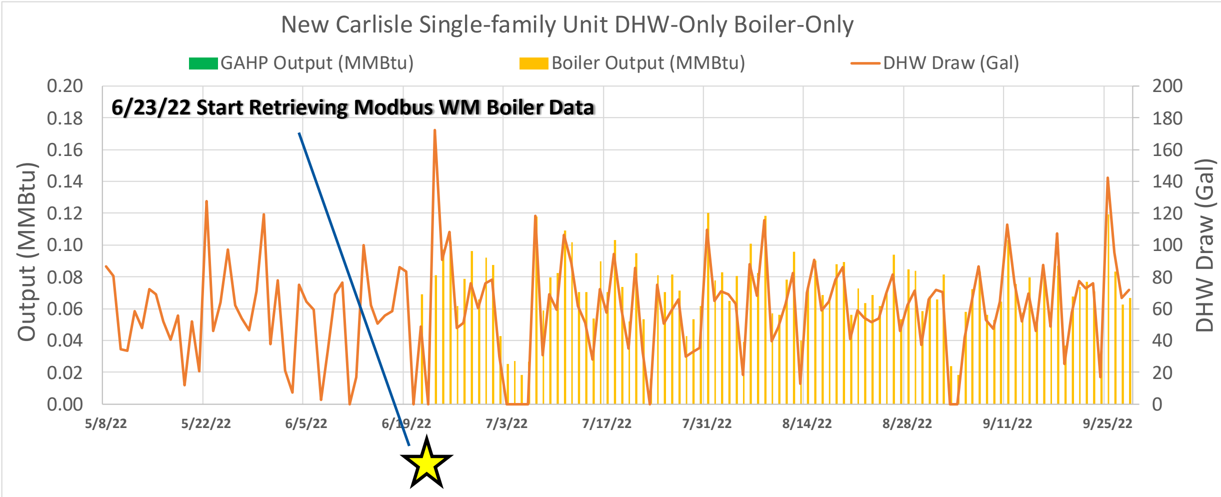


Figure 78: Summary of 2022-2023 Boiler-Only DHW-only Load Profile at Single family Forced Air Site

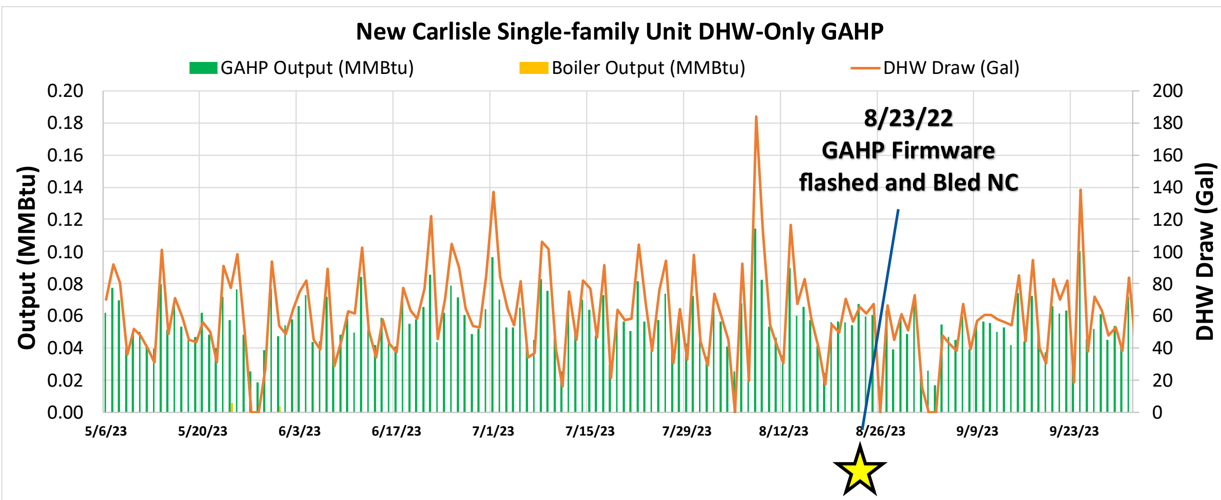


Figure 79: Summary of 2022-2023 GAHP-Only DHW-only Load Profile at Single family Forced Air Site

Comparing the two monitoring periods, the two periods were very similar with respect to the output energy required for DHW, as well as the daily DHW water use. Given that the DHW setpoint likely didn't change, this is not much of a surprise. However, the significant difference between the two monitoring periods is seen when analyzing the system performance during each monitoring period. Since the boiler was rated at 95% AFUE, and the GAHP could operate with an AFUE upwards of 140%, modest gas savings should have been achieved when comparing gas consumption of the DHW-only heating system. The following section dives into the system performance.

Operating Efficiency

First, the performance of the GAHP was analyzed, Overall, GAHP COPs ranging from 0.8 to 1.3 were observed, slightly lower than the steady state operating efficiencies at the same conditions as expected, and also quite similar to the La Porte site – but higher at this site overall. This was expected since each GAHPs were the same specification, and given field site occupancy, similar DHW consumption was observed.

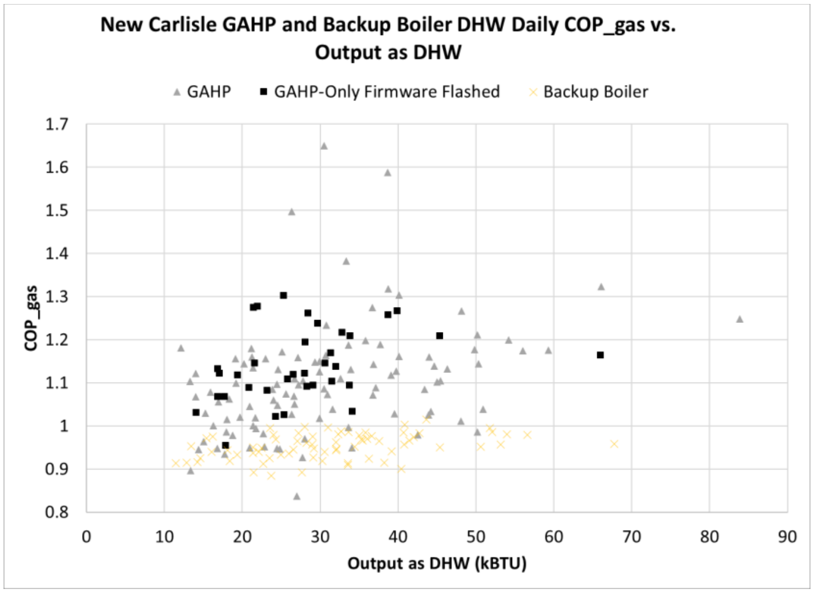


Figure 80: DHW-Only GAHP or Boiler COP_gas vs. Output as DHW at New Carlisle Site

Energy Modeling

Another way to illustrate and compare the performance of the two systems and to extrapolate energy consumption is to develop a relationship between the output energy and input energy, as noted in prior sections.

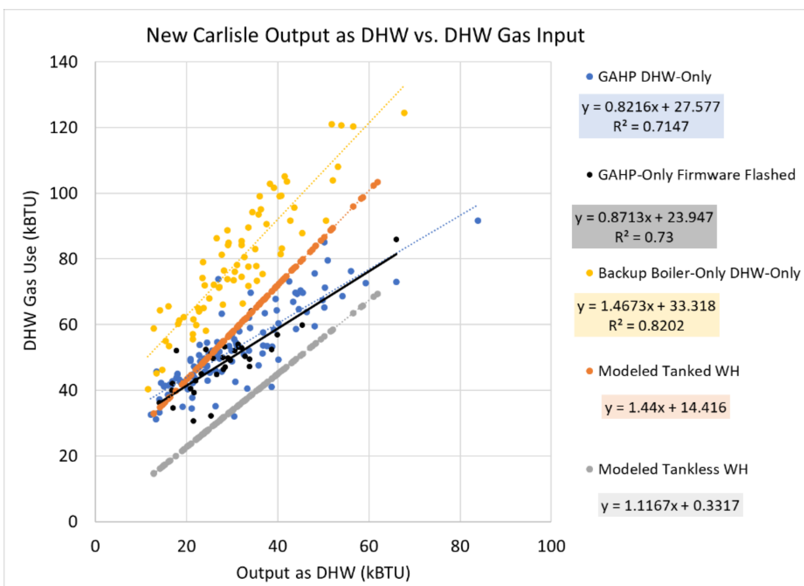


Figure 81: Comparison of DHW Gas Input vs. DHW output During DHW-only Operation from 2021 to 2023 at New Carlisle Site

We see from the above figure that the boiler operated similarly, but less efficient than a modeled tanked WH. Given that this heating system incorporates an indirect tank, and a high efficiency boiler, this comparison makes sense given expected thermal and standby losses. The amount of thermal losses at this site were triple what was observed at La Porte. At the beginning of the heating season in November, 2022, the project team discovered that the way the system was plumbed, and the controls implemented during Boiler-only operation that the system would continuously send the boiler heated hydronic water outside to the GAHP, and then back inside before entering the indirect storage tank. This process substantially increased the thermal losses to transport the hot water outside. It is also clear that once again, the GAHP was able to operate much closer to that of a tankless WH in terms of slope, a marker for efficiency. However, due to the usage of the indirect storage tank, and due to imperfect controls, a tankless WH is still better performing for DHW-only operation due to eliminating standby losses of a tank, in terms of linear offset, a marker for standby losses (energy consumption at zero load).

To extrapolate the previous chart into full year energy consumption on a DHW output basis, which normalizes DHW supply temperatures, a daily average of the DHW draw was calculated from the entire 2021 to 2023 dataset. This equates to a daily average DHW draw of 59 Gal. Then, to determine the daily average output as DHW for each input vs. output regression seen above in Figure 71, the following chart of daily DHW output vs. daily DHW draw was utilized.

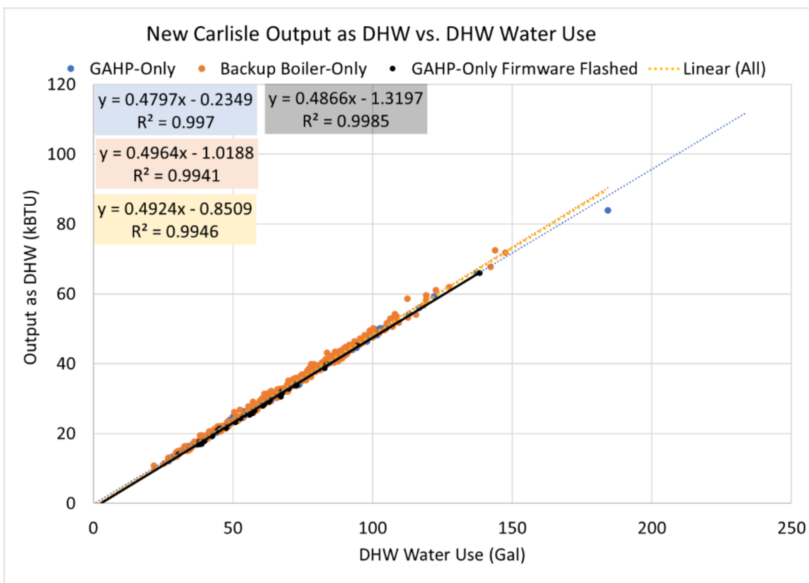


Figure 82: Comparison of Output as DHW vs. DHW Draw During DHW-only Operation from 2021 to 2023 New Carlisle Site

For comparative purposes, the baseline condition of boiler-only was used to determine what the daily average DHW output would be for the energy savings analysis. The DHW, economic, and greenhouse gas emission extrapolations were utilized in the following SH and DHW section where the combi operation linearizations were utilized in replace of the above linearizations for DHW-only operation. For the DHW-only period, the daily average DHW draw of 59 Gal, the daily average output to DHW was kept at 28 kBTU. The annual water consumption would equate to 21,805 Gal. It is these values that were utilized with the linear regressions of Figure 71 that were used to calculate the daily average DHW gas input each day, and then extrapolated for the DHW-only period.