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Comparative Assessment of Space Heating Systems in the Virtual Test Home – Phase 2

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GTI Project Managers:
Alejandro Baez Guada
aguada@gti.energy

1700 S. Mount Prospect Rd.
Des Plaines, Illinois 60018
www.gti.energy

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Executive Summary – Comparative Assessment of Space and Water Heating Systems in the Virtual Test Home, Phase 2

Advancements in gas and electric heat pump technologies make possible to achieve annual space and water heating efficiencies greater than 100% at the source-energy basis. Such systems are working with hydronic loops to provide space and water heating using a single heating source. This approach mitigates the need of typical refrigerant volume used in air-to-air heat pump systems while reducing the potential refrigerant leak that impacts the greenhouse gas (GHG) emissions and potential safety risks associated to adoption of new toxic and low-carbon refrigerant inside of homes. Additionally, the utilization of hydronics loop in combined space and water heating systems allow the integration of electric and gas equipment for a hybrid (dual-fuel) systems that can implement fuel-switching strategies center around decreasing operating cost or GHG emissions. This report investigates the detailed performance of a hybrid system for space and water heating applications in a cold climate similar to the rated cold climate zone 4 in ANSI method of tests (MOTs) used widely for gas-fired and electric-driven heat pumps testing.

GTI's Virtual Test Home (VTH) methods have demonstrated insightful assessments on space conditioning, water heating and power generation equipment. Unlike standard rating-point test methods such as Annual Fuel Utilization Efficiency (AFUE) and Heating Seasonal Performance Factor (HSPF) for space heating equipment, the VTH can be used to evaluate and characterize the performance of complex systems in a wide range of as-installed operating conditions to estimate annual GHG emissions and operating cost via building energy modeling. VTH assessments on a hybrid system provided an understanding of advantages and disadvantages of air-to-water heat pump (A2WHP) operation, and its hybrid implementation for space and water heating under as-installed conditions.

This detailed evaluation highlights the need of improving controls and hydronic strategies to successfully implement A2WHP technologies with gas-fired equipment for dual-fuel space and water heating operation. Additionally, a full comparison was developed to compare air-to-air and air-to-water technologies in the as installed conditions using the modeling tools calibrated with performance characterization developed under VTH evaluations from previous UTD funded projects. GTI suggests further evaluation of A2WHP technologies with integration features for gas-fired systems in a dual-fuel system environment including integration of micro-combined heat and power (mCHP) and renewables such as solar energy, for resilient low GHG emission and operating cost heating, ventilation and air conditioning and water heating (HVAC&WH) in the residential and commercial applications.

To help inform building and HVAC design professionals about the potential of hybrid heating systems, the results of this and related UTD research are planned to be presented at the ASHRAE 2024 Winter Conference in a technical paper focused on hybrid system operation.

Introduction & Background

As the energy industry continues to decarbonize residential end-uses such as space conditioning and water heating, emerging technologies such as hybrid (or dual fuel) systems and integrated energy system have been developed. Hybrid solutions have been shown to be a path to accelerate the reduction residential space and water heating GHG alternative to all-electric HVAC and water heating per the Technology Collaboration Programme on [Heat Pumping Technologies Final Report](). It also could allow the introduction of low- and zero carbon fuels to operate gas-fired equipment with near-zero GHG emissions.

Currently in North America, forced-air hybrid systems based on an air-source heat pump (ASHP) and furnace have been widely implemented to decarbonize residential space heating. Fuel-switch strategies are underway and could be grid-interactive with local utilities and regional transmission organizations (RTO) grid GHG emissions levels. Hybrid solutions are needed as advanced all-electric systems can provide high performing space only for low-load/new construction homes. Cold-climate air-source heat pumps (ccASHP) developed to address the lack of heating capacity of ASHP only can achieve 4-ton of heating down to 5°F outdoor air temperature (OAT) for residential applications. For the retrofit sector, hybrid solutions can provide high-performing space heating with ccASHP for the mild days while a furnace can be operated for the cold days.

In Europe and Asia, hybrid systems have been developed for radiant and water heating applications using electric A2WHPs integrated with gas-fired boilers. Examples of these are the commercially available European and Asian A2WHP systems that can support third-party boiler integration for supplemental heating or fuel switching as a function of OAT. Unlike the North America commercially available hybrid systems, these systems can provide hybrid solutions for both space and water heating applications. Nevertheless, none of these have been designed for or integrated with forced-air systems.

A2WHP systems are becoming more popular as decarbonization legislation continues to evolve for low-carbon refrigerants implementation in vapor compression systems. Refrigerant R410 is widely used in electric-driven heat pumps but will be discontinued at some point. R32 and other refrigerants have been selected to replace R410 in electric-driven heat pumps. Despite their lower-carbon impact, these new refrigerants are flammable, less efficient and toxic for indoor utilization. For A2WHPs, the refrigerant is contained within the outdoor unit while propylene-glycol/water mixtures extract the heat from the outdoor unit into the indoor(s) unit(s) for space and/or water heating.

Objective

The objective of this project was to evaluate globally available hybrid solutions for residential space and water heating applications in GTI's VTH. Weaknesses and strengths will be identified in the selected hybrid HVAC&WH systems to better craft advanced heating technologies for low-operating cost and GHG emissions based on U.S. climate zone and grid region. Tangible goals included:

- Identify two commercially available space and water heating unitary systems that integrate electric heat pump technology with gas-fired systems
- Characterize space and water heating part-load performance, operating range and comfort of hybrid systems considering all U.S. climate zones
- Demonstrate hybrid solution benefits per climate and grid location
- Predict hybrid systems GHG emissions and operating cost in multiple locations
- Identify system optimization strategies to further improve hybrid system design and operation.

- Results will be communicated to industry stakeholders, including building professional (through ASHRAE) and hybrid residential HVAC solution manufacturers

Market Landscape

Globally, there are many commercially available hybrids combination systems (combis) that are based on A2WHP operation. These systems have additional components that allow a la carte configurations for space and/or water heating application and for fuel-switching operation strategies using third-party boilers. Using a fixed OAT setpoint, these A2WHP systems can operate third-party boilers to provide space and water heating in cold days as an example. These hybrid combis are typically designed for floor heating/radiators and water heating applications in Europe and Asia. An example of this configuration is shown in Figure 1. Third-party boilers can be integrated in hydronic loops in many ways in A2WHP systems. Figure 2 shows an example of boiler integration for these A2WHP systems for space and water heating applications.

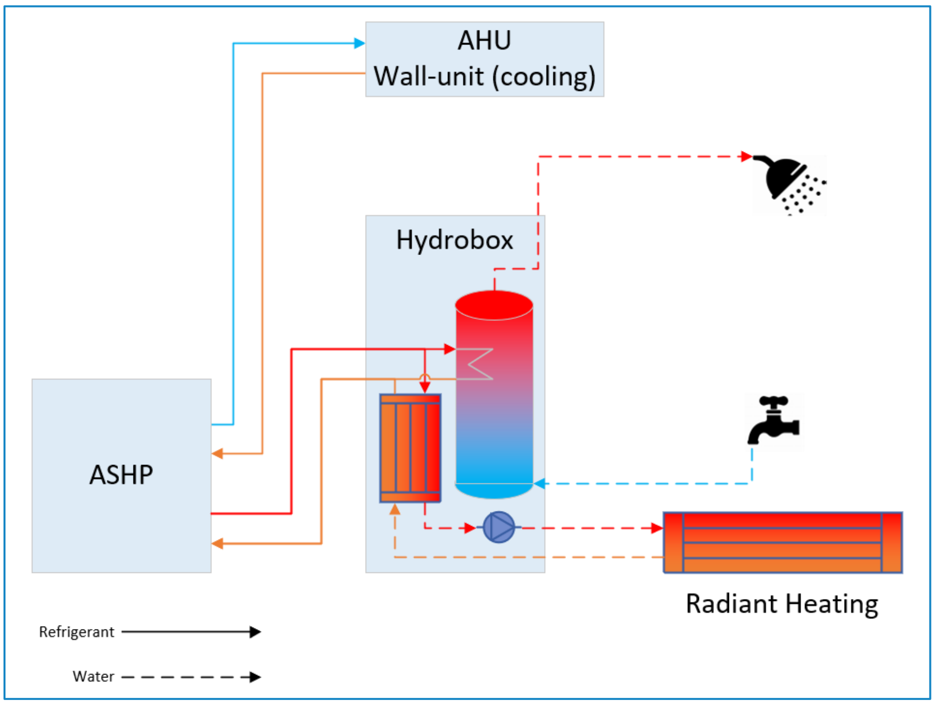

Figure 1 – Example European and Asian A2WHP System Configuration

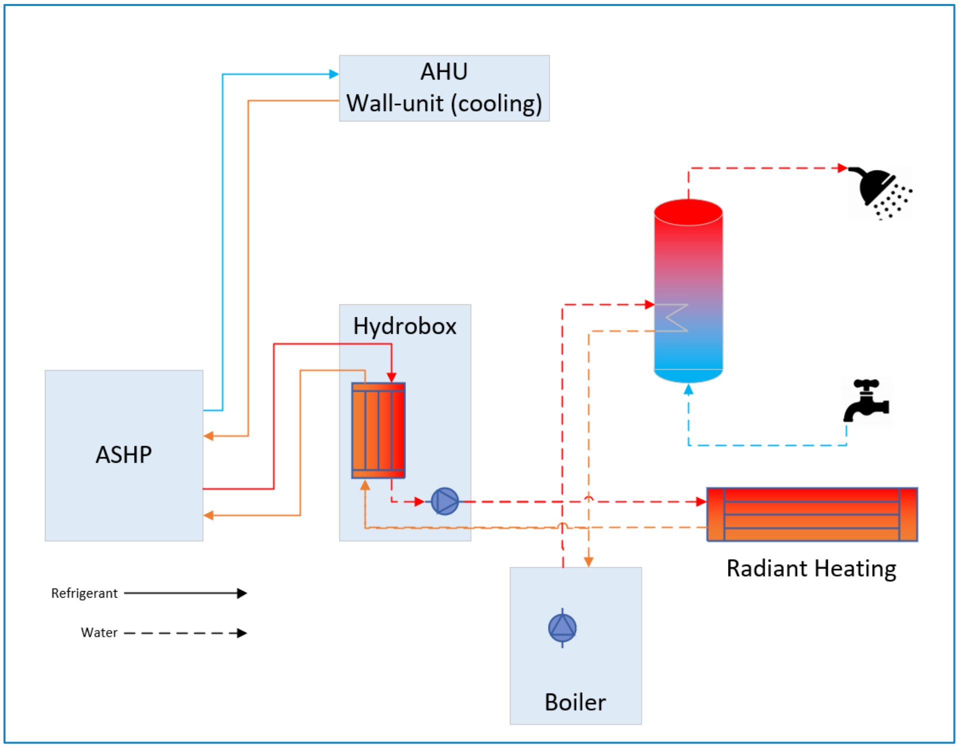

Figure 2 – Boiler Integration with A2WHP Systems

Currently, there is an A2WHP system commercially available in the U.S. capable of controlling third-party boilers for space and water heating application. Similar to these European and Asian systems, this system can be configured in many ways to optimize its efficiency for specific operations. An advantage that is has over some competing products is that it has forced-air solutions (both central and split systems) for U.S. residential space heating applications.

This A2WHP system can be configured in many ways to generate hot water for space and water heating in a hybrid approach. Examples of these system configurations are shown in Figure 3. These two configurations have the pros and cons.

Dual-zone Configuration

The dual-zone configuration (left side of Figure 3) is designed to operate the A2WHP with two zones: the hot-water tank Aquastat and heat-calls by the air handler unit (AHU). For this application, the hot water setpoint at the tank must maintain temperatures to mitigate legionella formation around 140°F. This configuration will force the A2WHP to operate at lower coefficient of performance (COP) as shown in Figure 3 for both space and water heating operations. The fuel switch-over strategy will force to generate hot water and air with either fuel independently. A tankless or boiler could be used as the gas-fired equipment in this configuration.

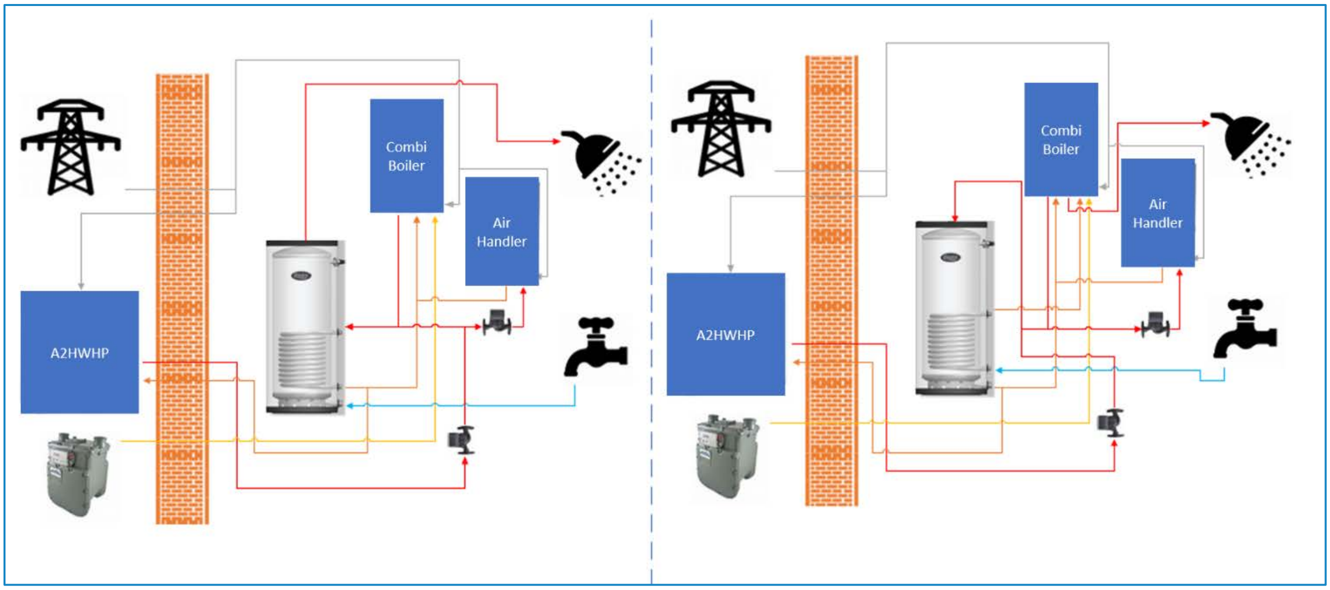

Figure 3 – A2WHP in a two Hybrid Configurations: Dual-zone (left) and Single-zone (right)

Single-zone Configuration

This configuration (right side of Figure 4) allows the A2WHP to run more efficiently using low hot water setpoint with a single zone. The hot water set point could be set to follow an outdoor reset curve based on the building load. Unlike the dual-zone, hot water is preheated by the indirect tank and achieve 140°F leaving the hot water side of a combi-boiler. Therefore, hot water is generated with both equipment. When the fuel-switching strategy reaches the OAT setpoint, the space heating side of the boiler runs space heating without compromising the potable water for water heating. From a research perspective, the single-zone configuration provides more robust and efficient operation by providing the conditions to run the A2WHP more efficient while maintaining reliable 140°F domestic hot water.

General Methodologies

The single-zone hybrid combi system will be evaluated in the VTH to address:

- A2WHP space heating performance
- Hybrid A2WHP/combi-boiler water heating performance
- Combi-boiler space and water heating performance

VTH Evaluation

The single-zone hybrid system configuration was evaluated using a load based approach considering actual weather loads and corresponding space and water heating loads of simulated single-family low-load building. For additional information of testing methodology and system components, review Appendix A – Hybrid System Test Plan.

Hybrid System Performance Characterization

The hybrid system performance was characterized in the daily perspective for space and water heating simulated loads. The hybrid system operated for six-weeks in A2WHP heating only to capture most of the effects due to ambient temperatures. For combi boiler operation, two-weeks were sufficient to capture the system representative performance.

A2WHP Space Heating Performance

Figure 4 shows the breakdown of the daily performance of the A2WHP system for space heating relative the daily total building load. The A2WHP COP (blue dots) represents the system performance within the A2WHP boundary referenced in Figure 29 in (purple rectangle). This A2WHP COP performance demonstrated to be aligned with the manufacturer specifications (blue dash line). The impact of the auxiliary components (Aux) power consumption such as pumps and AHU is captured by the difference between the A2WHP COP and A2WHP + Aux COP (light blue dots). The difference between the A2WHP + Aux COP and system COP (grey dots) represents the thermal losses of the hydronic loop and buffer tank. This substantial heat loss can be associated to:

- Poor design guidelines for hydronic heating systems for space heating
- Poor controls associated to thermal storage management including buffer tank setpoint and A2WHP outdoor reset curve configuration

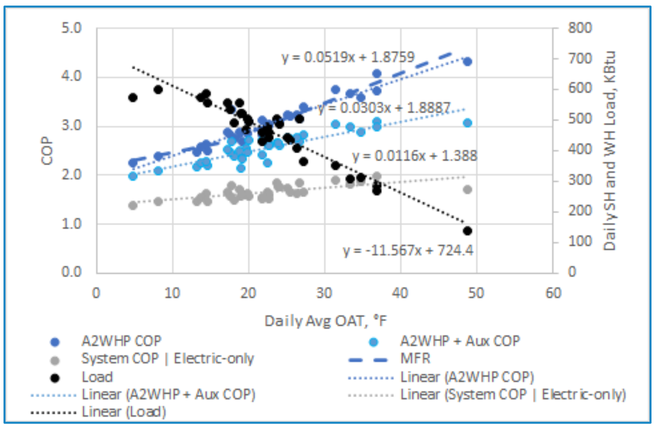

Figure 4 – Daily A2WHP and System Electrical Efficiencies Breakdown and Building Space and Water Heating Loads

Hybrid A2WHP/Combi-boiler Water Heating Performance

Figure 5 shows the daily gas COP for water heating while the A2WHP was operating for space heating loads. Gas COP exceed combustion efficiency of the combi-boiler as it takes credit for the pre-heating process of the city water running through the indirect storage tank. The following observations were made for the combi-boiler operating with pre-heated water:

- For loads lower than minimum combi boiler firing rate, the leaving water temperature exceeded the setpoint temperature
- The daily water heating COP was a function of water heating load and A2WHP return water temperature outdoor reset curve. The higher hot water load and the lower OAT, the higher gas COP water heating during the A2WHP space heating operation

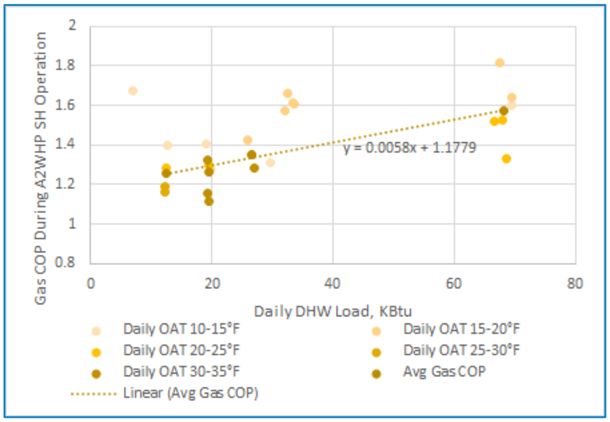

Figure 5 – Hybrid Water Heating COP During A2WHP Space Heating Operation

Combi Boiler Space and Water Heating Performance

Figure 6 shows the daily combined space and water heating of the combi boiler breakdown. The combi boiler gas efficiency (dark yellow dot) at the combi boiler boundary (referenced in Figure 29 as a green rectangle) demonstrated system similar efficiencies to its rating combustion efficiency as AFUE. The difference between combi boiler at the combi boiler boundary and system (yellow dots) boundaries in the gas basis is associated to the thermal losses between piping to the AHU. The offset between the combi boiler system gas-only and gas and electric is associated to the electric consumption of the combi boiler with integrated pump and AHU.

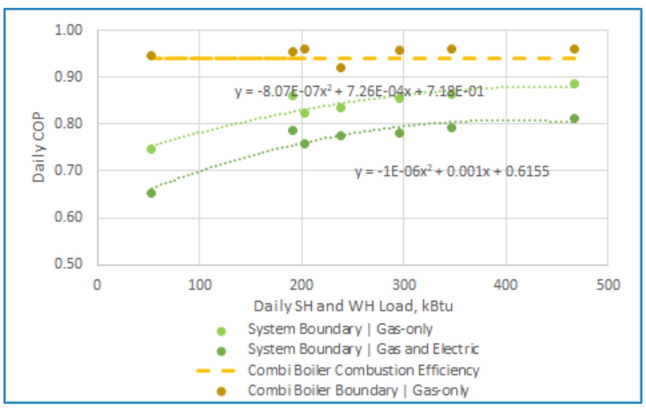

Figure 6 – Combi Boiler Daily Space and Water Heating Gas Only and Total System COPs

System Market Impact Considerations

The integration of ASHPs and furnaces is the most popular hybrid solution implemented in North America for residential space heating applications. This approach can potentially reduce the GHG emissions associated with the residential space heating sector by using well-understood off-the-shelf technologies that fit the new construction and retrofit applications. Unlike these technologies, this commercially available A2WHP system is a complex a la carte solution for space and water heating applications with a substantial premium in first cost and real-estate relative to ASHPs and furnaces.

How Does It Compare with ASHPs?

Figure 7 shows the comparison between daily COP as a function of daily averaged OAT for a ccASHP and A2WHP systems including the data from A2WHP manufacturer (MFR). This comparison in the daily perspective indicates that this A2WHP (blue dots) has similar COP than a ccASHP (orange dots) including parasitic loses due to auxiliary pumps. However, due to its system hydronic design and controls, daily efficiencies are significantly lower than a ccASHP (grey dots).

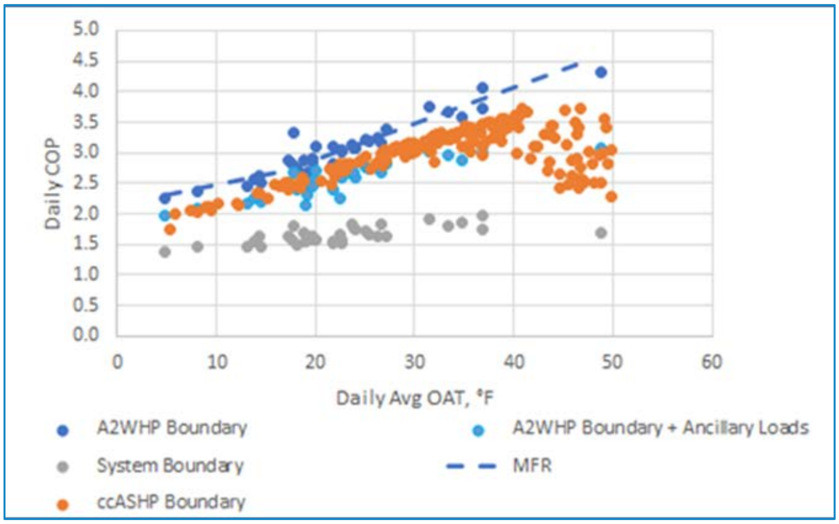

Figure 7 – A2WHP system and ccASHP COP Performance Comparison

Figure 8 shows the initial cost comparison between ASHP, ccASHP and this A2WHP with the same heating capacity estimated at the time of this project. The cost of this A2WHP system is about twice the cost of an ASHP, which are typically used in forced-air hybrid systems. Beside the equipment cost, the installation cost between these systems should be substantially different as the A2WHP system requires hydronic loops to interconnect the outdoor, indoor unit and auxiliary equipment such pumps, relative to prefabricated line sets for vapor compression systems.

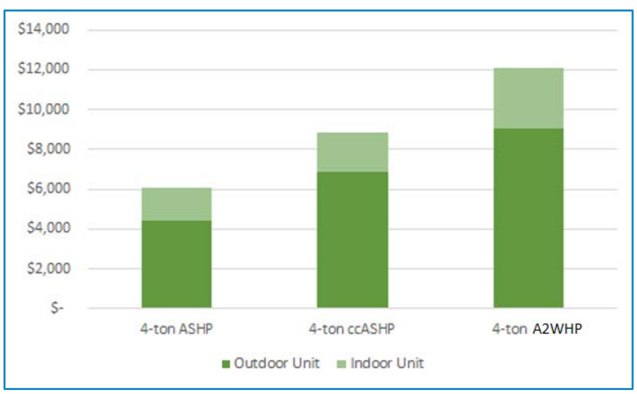

Figure 8 – Initial Cost Comparison Between ASHP, ccASHP, and A2WHP System

Space and Water Heating Modeling Performance in Cold Climates

Given the low performance in this hybrid system, the modeling task of this project will be limited to representing its performance relative to advanced all-electric and gas-fired space and water heating systems. Figure 9 shows the modeled heating source-energy based COP (SCOP) of the hybrid system relative to advanced all-electric and gas-fired systems as characterized using the VTH methodology from previous work under Phase 1 of UTD 1.19.I – *Comparative Assessment of Space and Water Heating Systems in the Virtual Test Home.* Both Chicago, IL and Albany, NY have similar weather load with very distinct source energy factors. For Albany, NY with an electric source energy factor of 2.14 annual for all plants per Emissions & Generation Resource Integrated Database (eGRID), the advanced all-electric system that includes an ccASHP and electric heat pump water heater (EHPWH) outperforms the other two systems due to its high annual COP. The advanced gas-fired system, a combination system based on a smart air handler system integrated with a 0.97 UEF tankless water heater, performs the same as this hybrid system. For Chicago, IL with an electric source energy factor of 3.0 annually for all plants per eGRID, both advanced all-electric and gas-fired systems outperform this hybrid system due to its low performance managing thermal losses.

Figure 9 – Hybrid System Daily Performance Across the Heating Season Considering Source Energy Factors for Albany, NY (left) and Chicago (right)

Conclusion & Next Steps

GTI evaluated a commercially available hybrid appliance for space and water heating in the VTH in order to determine the detailed performance of the technology and to better understand how hybrid gas-electric systems can be implemented to achieve the most efficient, cost-effective and comfortable space heating. Extensive evaluations were performed to create performance characterizations using simulated-use testing in the VTH for 6 weeks. Additionally, advanced building energy modeling was performed to formulate conclusions based on extensive laboratory, in-field and modeling research using these performance characterizations and previous VTH best-in-class gas-fired system performance curves. Results of this holistic research suggest:

- This hybrid system needs further engineering to address thermal losses in order to improve thermal performance in the system for both space and water heating applications
- The A2WHP system demonstrated to have similar performance to a ccASHP at the outdoor unit level suggesting that hydronic and control solutions are required to best utilize the system output. A modeled example is shown in Figure 10 which showcases the benefit of the hybrid combi in cold climate scenarios from different power generation mix. These results suggests that hybrid combi can provide a solution for dual fuel space and water heating application that can potentially interact with the grid to further reduce GHG emissions and potentially cost.
- To better understand the potential of electric-driven A2WHPs, a product similar to the European or Asian A2WHP systems needs to be evaluated in the VTH. These systems may have better sub-component features such as the heat management unit with buffer tank and pump.
- High-performance circulators are needed to decrease the parasitic loads associated to displacing water from the tank to the A2WHP and from the tank to the AHU.

Figure 10 – Hybrid System Without Heat Losses Daily Performance Across the Heating Season Considering Source Energy Factors for Albany, NY (left) and Chicago (right)

Next Steps

GTI recognizes the advantages of hybrid systems to reduce operating costs and GHG emissions. GTI recommends further research on other electric A2WHP system such as the European and Asian commercially available systems to properly integrate force-air systems and potentially mCHP for heat recovery and resilient HVAC&WH operation as part of the integrated energy system research with renewables and storage. Example of these integrated energy systems, where an A2WHP is used for both space and water heating applications powered by mCHP and solar power.

To help inform building and HVAC design professionals about the potential of hybrid heating systems, the results of this and related UTD research are planned to be presented at the ASHRAE 2024 Winter Conference in a technical paper focused on hybrid system operation.

Appendix A – Hybrid System Test Plan

The goal of this test plan was to evaluate an electric-driven A2WHP hydronic heating system as a hybrid combi system for single-family home space and water heating loads. This A2WHP with low-ambient capability, has auxiliary components and controls to provide flexibility given the application. Such controls have features to enable gas-fired boiler operation as part of this hydronic heating system. This hybrid combi system used both the A2WHP and gas-fired combi boiler for simulated single-family space and water heating loads.

This hybrid combi system could be optimized to operate with a combined gas and electric source-energy efficiencies greater than 1 using manufacturer specifications for annual space and water heating loads of a single-family home located in the International Energy Conservation Code (IECC) zone 5, shown in Figure 11. The outcomes of this test plan originally were to address heat pump sizing guidance and switch-over control strategies to maximize this hybrid combi system as a solution for low GHG emissions and operating cost in single-family homes located in cold climate zones.

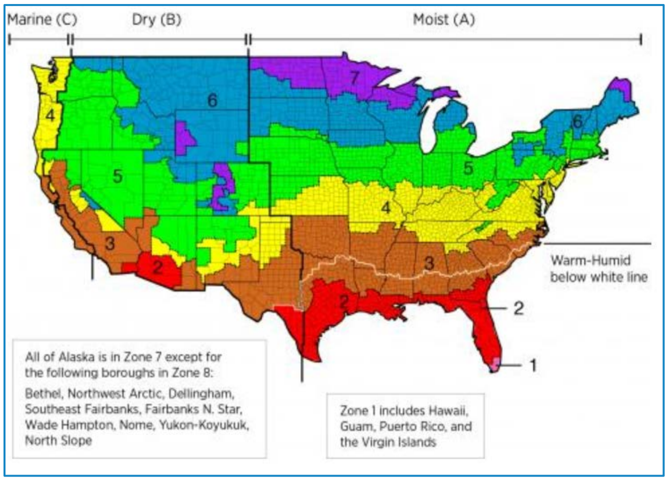

Figure 11 – IECC Climate Map

Equipment

The equipment listed in the section was used for this hybrid combi system.

Low-ambient A2WHP

This low-ambient A2WHP rated to 48 kBtu/h of heating was the electric-driven engine of the hybrid combi system. This unit comes with a control that allows users to customize the system operation depending on the application. This device interconnects to an outdoor air temperature sensor to modulate the water setpoint (and therefore capacity) of the A2WHP system. A main zone is required to provide heat calls to the A2HWP. With a series of 24VAC input to 120VAC output relays, this device can control pump to circulate the propylene-glycol/water mix for heat transfer during A2HWP operation. This control system can manage multiple heating zones. A third-party gas-fired boiler could be actuated by this device if needed. A fuel switch-over strategy is built into this device that can actuate either heating engine by an outdoor air temperature set point.

Central Hydronic Air Handler Unit

A central hydronic AHU was used for space heating simulation with 4 tons of capacity.

Indirect Water Heater

A 120-gal indirect tank was used in this hybrid combi system evaluation. This tank was used as a buffer tank for the A2WHP heating output. The A2WHP supply and return lines were teed out the storage line connection of this tank, as shown in Figure 12.

Combi Boiler

A rated150 kBtu/h / 95 AFUE combi boiler was used in this hybrid combi system evaluation. The combi boiler unit was used to provide space heating at low ambient temperatures and heating portable water for water heating loads.

Operation and Installation

The hybrid combi system was installed in the GTI laboratories to operate under-simulated use testing procedures used in the VTH. A2WHP was installed outside the lab to be exposed to a large variety of ambient conditions during the heating season in Des Plaines, IL. To acquire data of the A2WHP operating in multiple conditions, the hybrid system prioritize heat operation for most of the heating season. The combi boiler operation for space heating was scheduled for two weeks at the end of the heating season to evaluate its performance with simulated load profile that were not function of ambient conditions established outside of GTI laboratories.

System Configuration

Figure 12 shows the hydronic integration of the A2HWP, combi boiler and indirect tank. The space and water heating operation are described in the following subsections.

A2HWP Operation

A2HWP operated with an outdoor reset curve that selects the A2WHP supply temperature set point as a function of OAT. An outdoor reset curve was implemented in the system to switch from 95 °F return temperature to 115 °F linearly from 40 °F to 5 °F OATs. The A2WHP heating output was stored in the indirect tank storage compartment. A variable-speed pump controlled by GTI's DAQ provided hot water to the AHU. The AHU operation was operated per Table 1 depending on the A2WHP set point and heating engine type.

Table 1 – AHU Expected Operation

Engine	**gpm**	**cfm**	**EWT**	**LWT**	**MBH**
A2WHP	6	1,150	90	83.3	19.8
	6	1,150	100	89.7	30.1
	6	1,150	110	96.2	40.5
Combi Boiler	2	1,150	140	92.8	46.2

Water Heating Operation

The hybrid combi system used the process loop of the indirect tank coil to pre-heat water from the A2HWP operation. The pre-heated water entered the portable water side of the combi boiler to provide hot water at a set point of 140°F. The control actuated a three-way solenoid valve to stop city water accessing the indirect storage tank for pre-heating if fuel-switch strategy was set for boiler only. Therefore, the city water was heated by the portable side of the combi boiler. This operation took advantage of the high-efficiency operation of the A2HWP while maintaining the hot water temperature at 140°F and mitigating legionella risks. Table 2 shows the expected water heating performance as a function of city water temperature and OAT.

Table 2 – Water Heating Performance

OAT, °F	**CWT, °F**	**Water flow, gpm**	**Estimated WH Source-energy COP**
60	60	0.5	1.28
	40	0.5	1.39
40	60	0.5	1.15
	40	0.5	1.22
20	60	0.5	0.86
	40	0.5	0.87

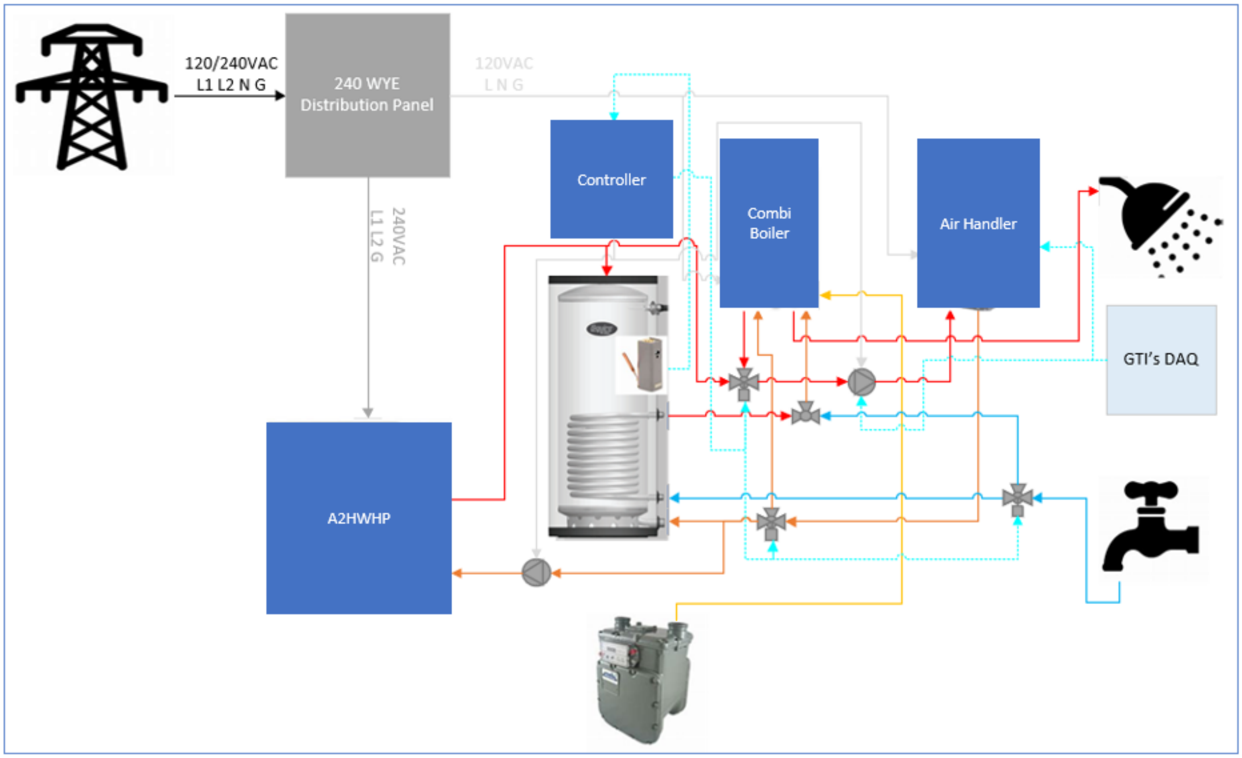

Figure 12 – Hybrid Combi Concept

Simulated Use Evaluation

The hybrid combi was evaluated using simulated use approach. Space and water heating loads associated to a simulated single-family home of 2,050 sq-ft. implemented in this laboratory evaluation. The home has 3 bedrooms, 2.5 bathrooms, 3 occupants, and 70°F winter thermostat set point. The building construction was referenced to 2010 Building America Reference Home standards, which incorporated 2009 IECC building code measures. This single-family home space and water heating loads was associated to humid region of IECC zone 5, which is similar to the HSPF rating climate zone. Figure 13 shows the hourly and annually space and water heating loads for this evaluation. Figure 14 shows the space and water heating load distribution as a function of OAT implemented in the VTH.

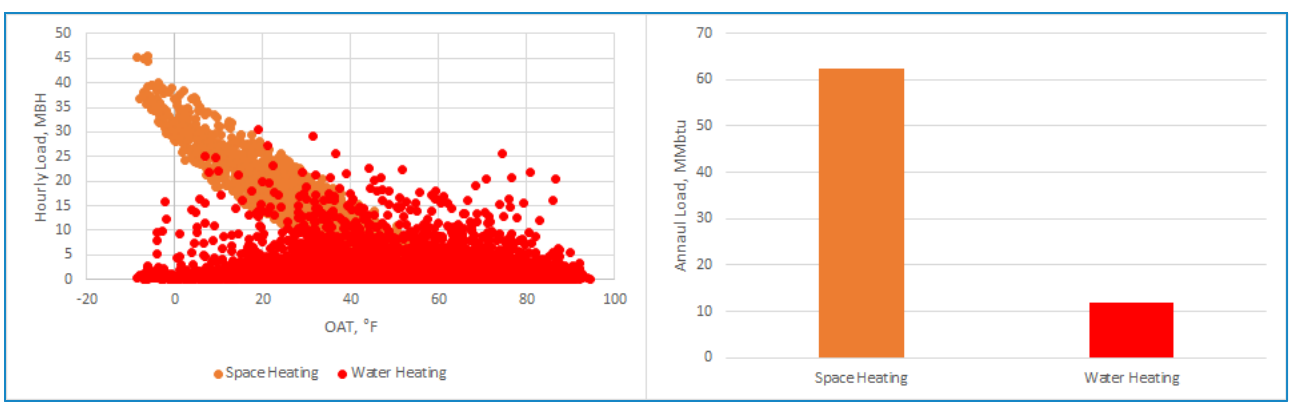

Figure 13 – Hourly (left) and Annually (right) Space Heating/Cooling and Water Heating Loads

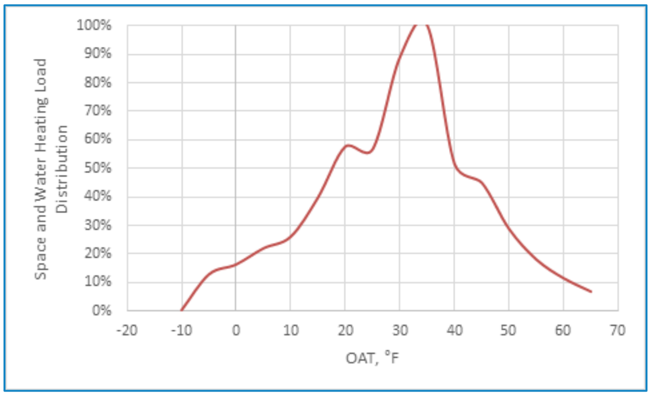

Figure 14 – Space and Water Heating Load Distribution as a Function of Outdoor Air Temperature (OAT)

Evaluation Infrastructure

The A2WHP was installed outside of the VTH laboratory. The hydronic components and controller were installed inside this laboratory.

Space Heating Loads

The space heating loads were simulated with the building energy model load and OAT regression curve, shown in Figure 15. Using the outdoor air temperature conditions outside of the lab, the building energy space heating load was determined in the hourly basis. The energy delivered by the AHU was used in the building energy modeling software. The building energy model software was computing the simulated room temperature in the second basis. This simulated room temperatures dictated when a space heating call was needed. Both simulated building load and energy delivered to the air are variables that affect the simulated room temperature cycling.

Space Heating Simulator

Figure 16 shows the infrastructure that was used to simulate and measure the energy delivered to the air in the building energy software. GTI has used these simulators for to evaluate system in the VTH laboratory, as shown in Figure 17. Room air was pulled by the AHU system, and the air flow and mass flow were measured with a thermocouple and low-pressure device PT attached to a pitot-tube array following ISO-3966 *Measurement of Fluid Flow in Closed Conduits- Velocity Area Method Using Pitot Static Tubes* and ISO-5801 *Industrial Fans – Performance Testing Using Standardized Airways* guidance. Two thermocouple-arrays were used in the return and supply duct work to measure air temperature rise following temperature distribution measurements guidance from ANSI/ASHRAE 41.1 – *Standard Methods for Temperature Measurement.* The return and supply air relative humidity were measured by a relative humidity transmitter RHT per ANSI/ASHRAE 41.4 – *Standard Methods for Temperature Measurement.*

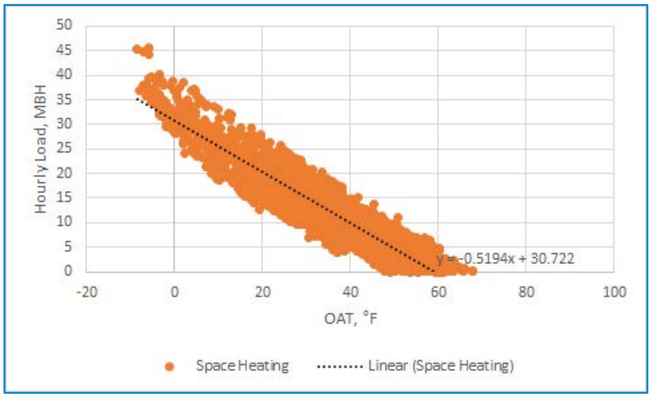

Figure 15 – Building Space Heating Load Regression Curve as a Function of OAT

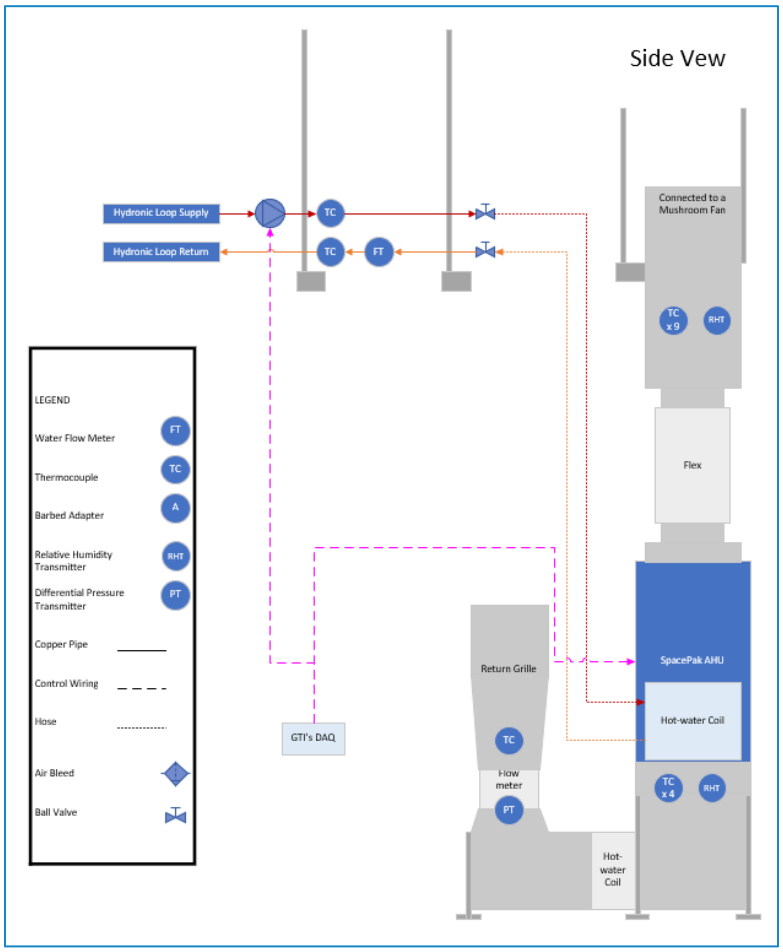

Figure 16 – Space Heating and Cooling Simulator Infrastructure

The hydronic coil leaving water flow was measured with a water flow meter FT. Two thermocouples TCs were used to measure the hydronic coil leaving and entering water temperatures. A variable-speed pump was used to provide space heating from A2HWP heat stored in the indirect tank during A2WHP operation. The onboard pump of the combi boiler was activated when gas heating was required for space heating while maintaining the variable speed pump off.

Figure 17 – Space Heating and Cooling Simulator Infrastructure in the VTH Laboratory

Water Heating Loads

The water heating loads was based on National Renewable Energy Laboratory (NREL) Domestic Hot Water Event Schedule Generator. The daily water heating load pattern per unit was based on medium-usage draw pattern from Appendix E to Subpart B of Part 43, Title 10, CFR - Uniform Test Method for Measuring the Energy Consumption of Water Heaters developed by the Department of Energy (DOE). The weekly water heating load pattern was based on the annual water heating load frequency distribution for Chicago, IL for a 3-bedroom occupancy shown in Figure 18. Figure 19 shows the weekly water heating loads per building unit.

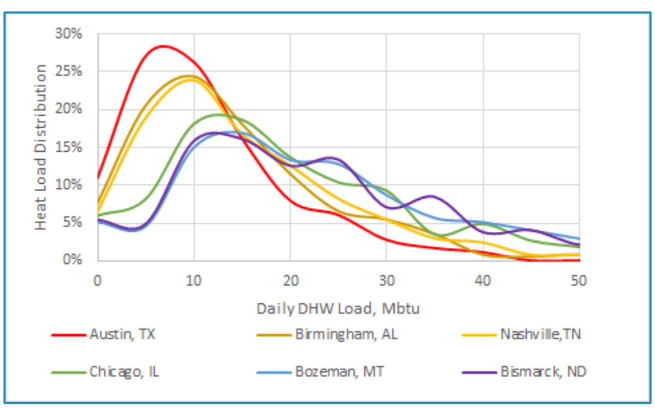

Figure 18 – Annual Water Heating Load Frequency Distribution

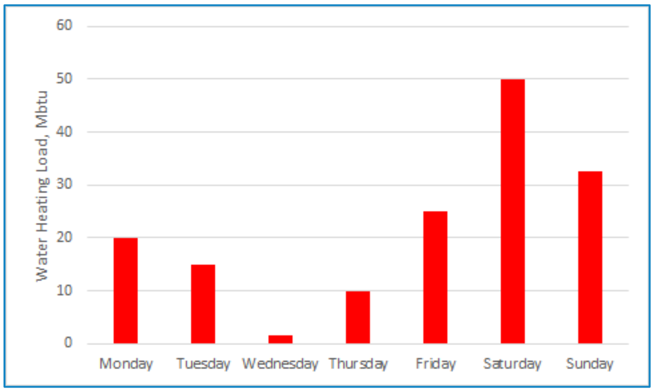

Figure 19 – Daily Water Heating Load

Hydronic and Water Heating System

Figure 22 shows the indoor indirect water heating system, hydronic loop and combi boiler system. The operation of the A2HWP, combi boiler and AHU loops are described below.

A2WHP Operation

Hot water provided by the A2HWP was delivered to the storage compartment of the indirect storage tank. A thermocouple was used to measure the internal tank temperature. This signal was used to make the GTI's DAQ actuate controller Zone 1 for heating. This actuation started A2WHP operation.

AHU Operation

The hot water energy provided to the AHU was measured using a flowmeter FT and two thermocouples TCs. A variable-speed pump was controlled by the GTI's DAQ per Table 1 and simulated use described on Simulated Use Evaluation section.

Combi Boiler Operation

The combi boiler was actuated by the controller. The three-solenoid valves switched the flow path to avoid indirect tank loop that connect to the A2WHP.

Hot Water Loads

A flowmeter FT and two thermocouples TCs were used to measure the hot water load called by the Water Heating Simulator. One TC and the FT were installed upstream the solenoid valve in the city water line. The other TC was installed downstream the combi boiler hot water line.

Water Heating Simulator

Figure 20 shows the water heating simulator P&ID. This simulator has three solenoid valves to allow three different flow rates at the test stand. This simulator allows to test water heating system at different flow rates. This testing infrastructure has been implemented in many simulated use evaluations in the GTI laboratories, as shown in Figure 21.

Table 3 – Water Heating Scheduler for the Hybrid Combi Evaluation

Hour	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday

	Water Flow Rate, gpm	Daily Water Heating Load, Mbtu						
		20	15	1.5	10	25	50	32.5
		Hourly Water Usage, Gal						
1	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0
3	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	2	5.8	4.3	0.4	2.9	7.2	14.4	9.4
6	1	3.1	2.3	0.2	1.5	3.8	7.6	5.0
7	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
11	1	3.1	2.3	0.2	1.5	3.8	7.6	5.0
12	1	3.1	2.3	0.2	1.5	3.8	7.6	5.0
13	0.5	1.0	0.8	0.1	0.5	1.3	2.5	1.7
14	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
15	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
16	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
17	0.5	1.7	1.3	0.1	0.8	2.1	4.2	2.8
18	1	2.4	1.8	0.2	1.2	3.0	5.9	3.9
19	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
20	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
21	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
22	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
23	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
24	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

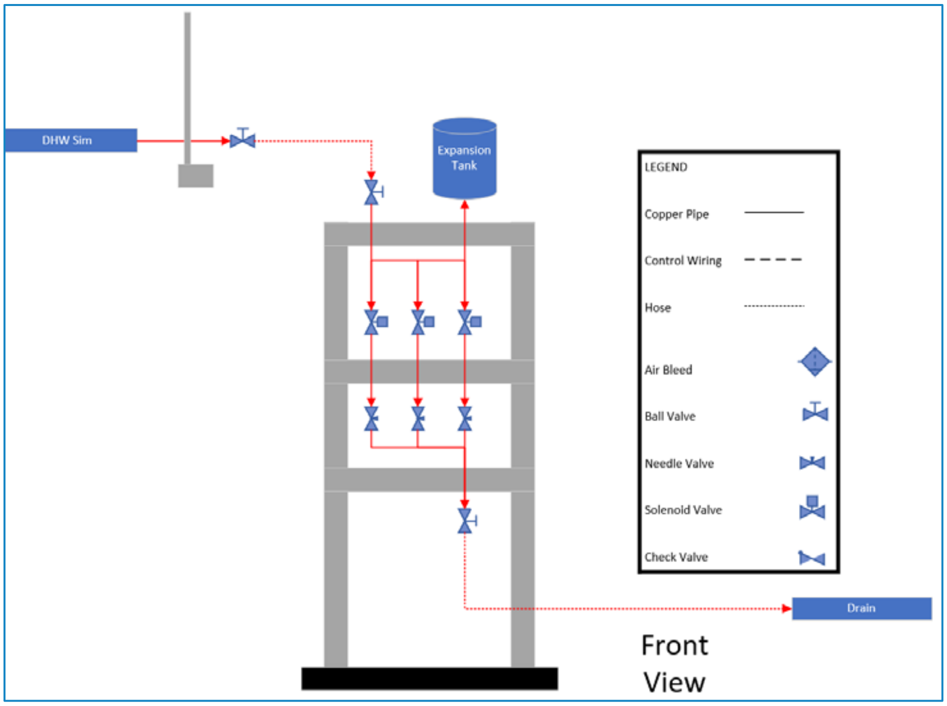

Figure 20 – Domestic Hot Water Simulator P&ID

For the hybrid combi evaluation, three flow rates were selected to represent typical flow rates based on NREL Domestic Hot Water Event Schedule Generator. These flow rates and hourly usage per weekly day are shown in Table 3.

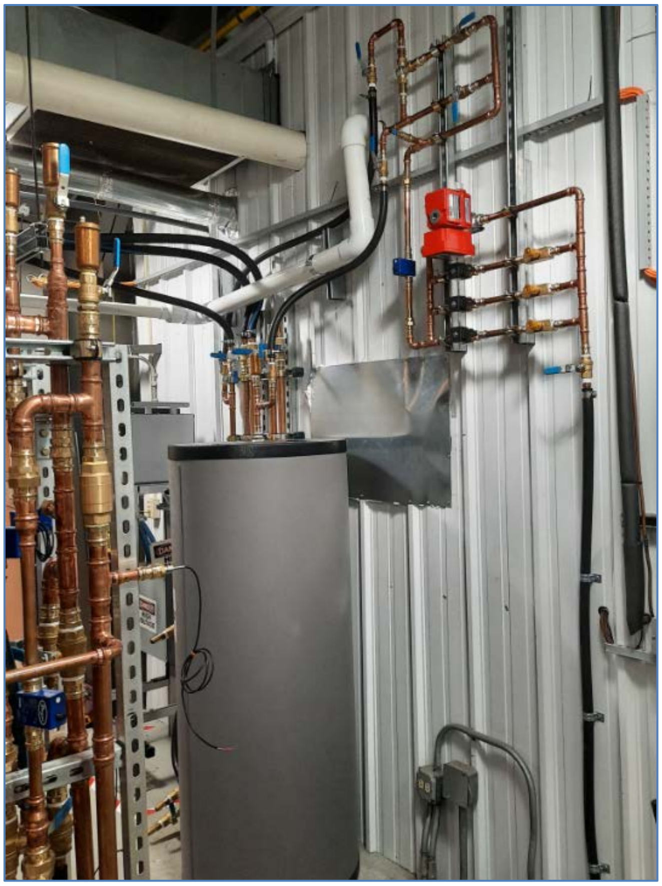

Figure 21 – Water Heating Simulator Infrastructure in the VTH Laboratory

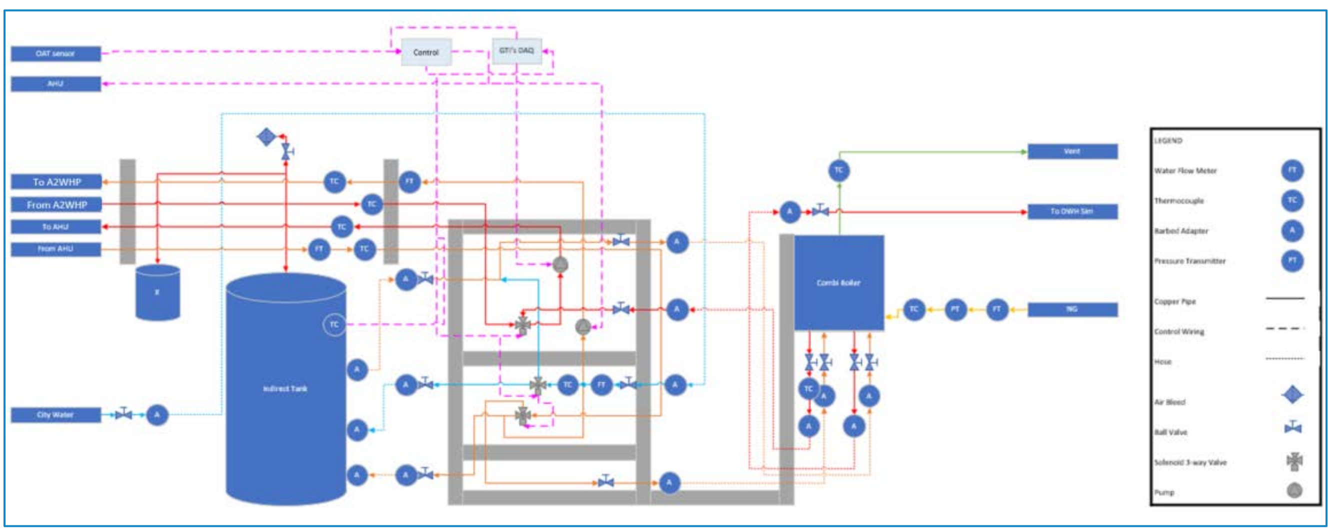

Figure 22 – Hybrid Combi Hydronic and Water Heating Systems

A2WHP Installation

Figure 23 shows the off-the-floor A2HWP installation infrastructure. This infrastructure was installed to mitigate icing built-up and snow overflow. A four-thermocouple array and one relative humidity transmitter RHT was installed on each A2HWP intake grille. Piping will be used to connect to the indoor hydronic and water heating systems. Similar infrastructure which has been built in the VTH lab is shown in Figure 24 for ccASHP evaluation.

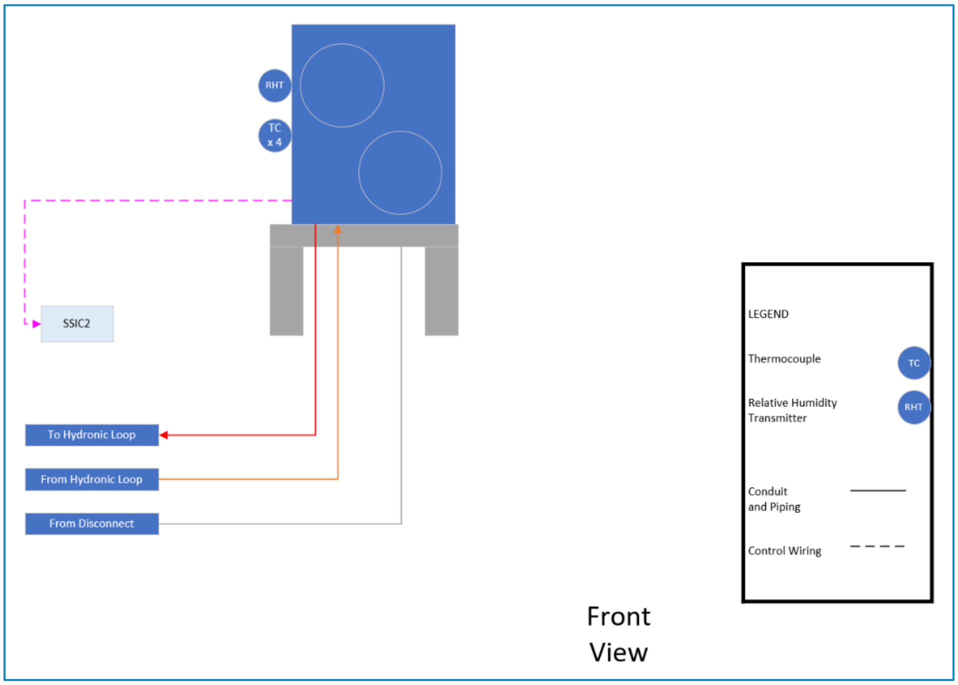

Figure 23 – A2WHP Installation

Figure 24 – ccASHP Outdoor Installation in GTI Laboratories

Power Distribution Infrastructure

Figure 25 shows the electrical diagram for the hybrid combi. 208 WYE distribution panels were available in the lab. Three power metering panels Power Panels 1 through 3 measured and distribute power to the hybrid combi system components. Power transmitters were used in these panels to measure power consumption in the A2HWP, AHU, combi boiler, pumps and controls. Figure 26, Figure 27 and Figure 28 show the electrical diagrams for Power Panels 1, 2 and 3, respectively.

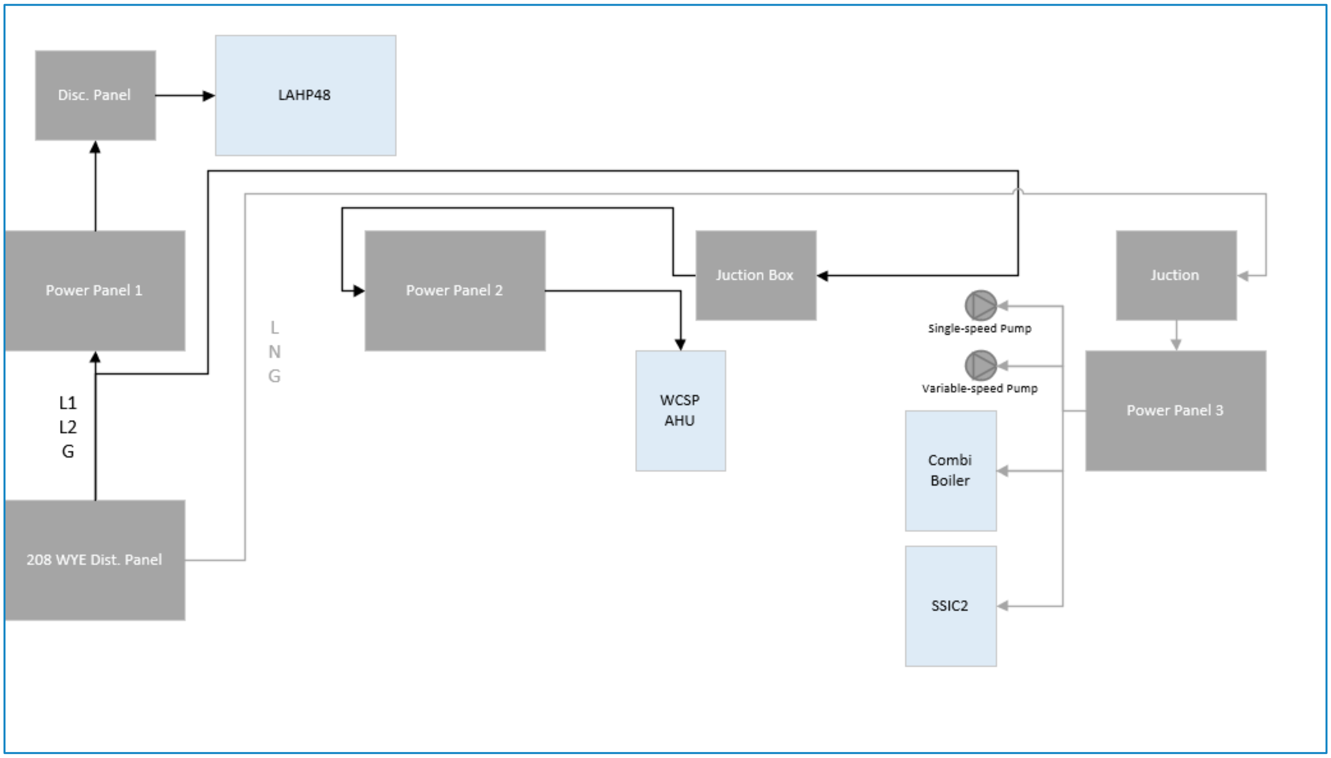

Figure 25 – Hybrid Combi Electrical Diagram

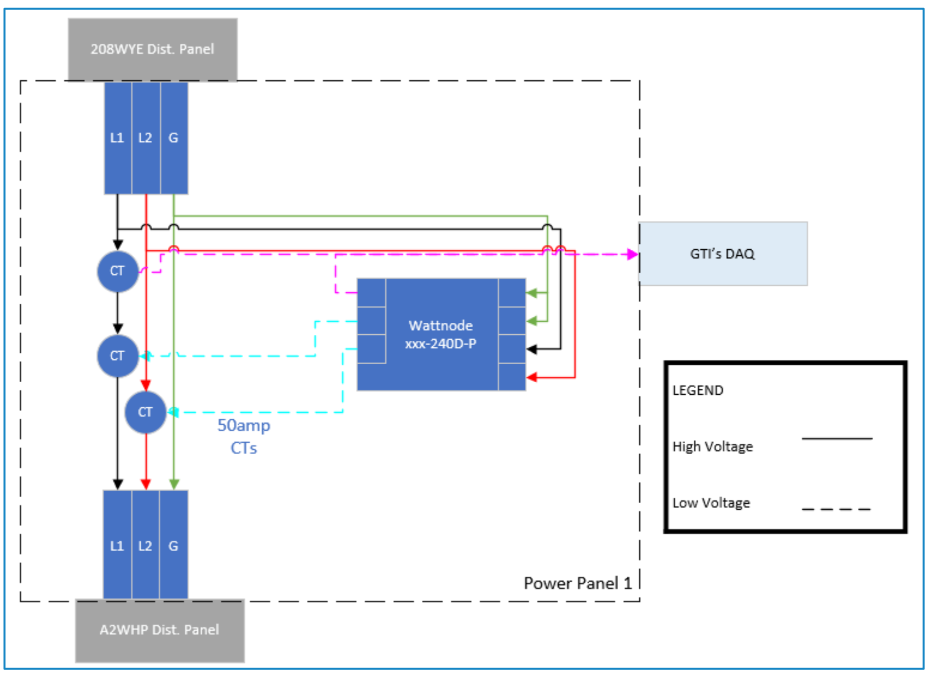

Figure 26 – Power Panel 1 Schematic

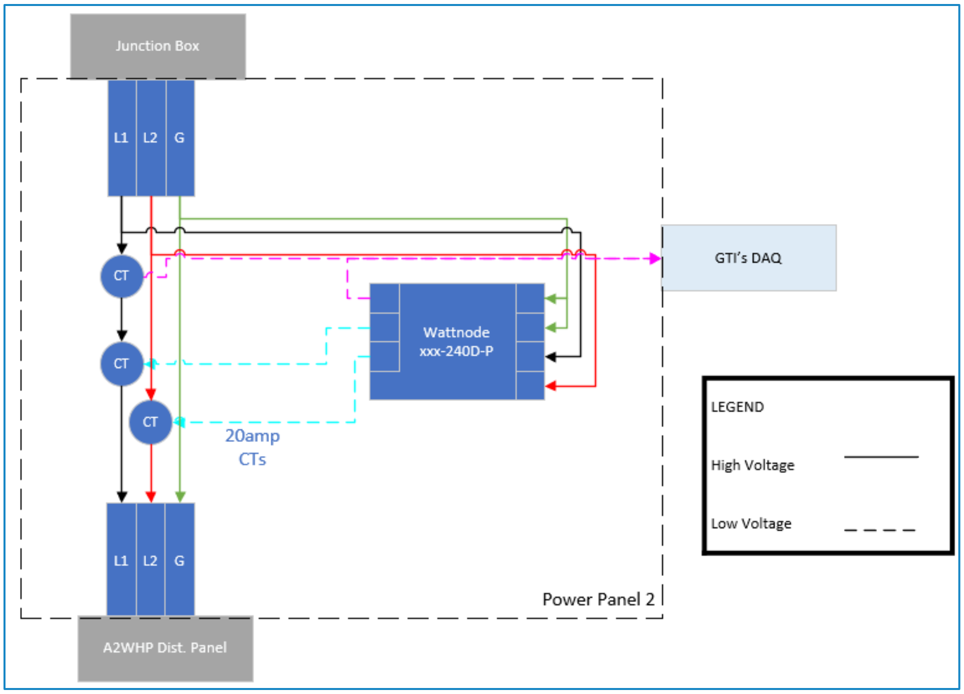

Figure 27 – Power Panel 2 Schematic

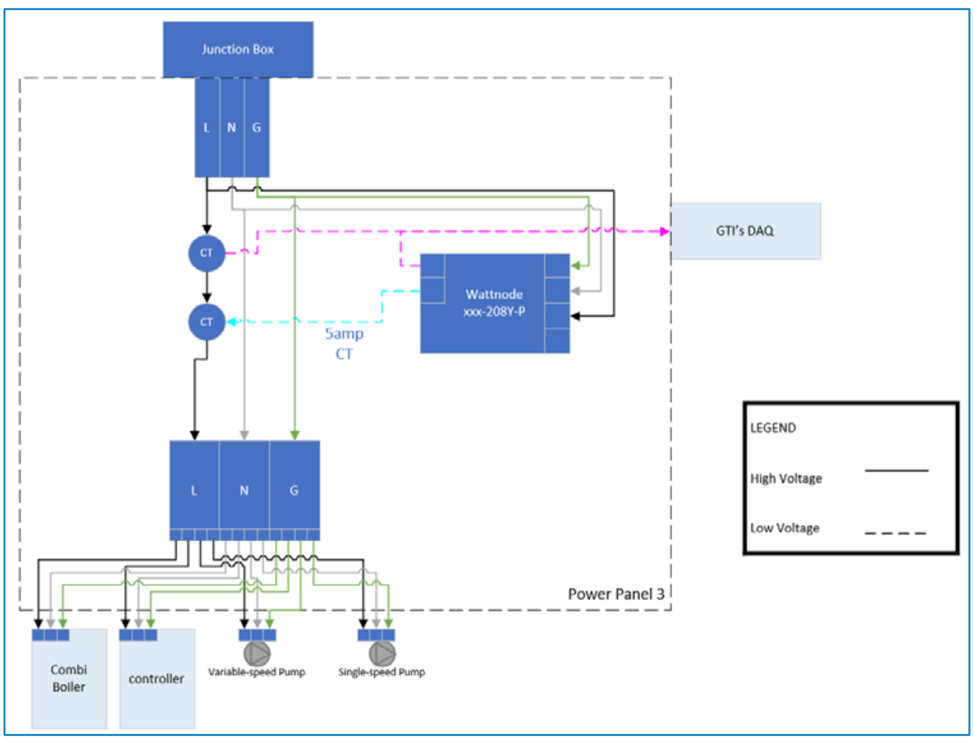

Figure 28 – Power Panel 3 Schematic

Control System

The control managed the hydronic components and engines for space and water heating loads. GTI's DAQ controlled the heating call to the indirect tank and the space and water heating simulators based on the strategies described in Simulated Use Evaluation section.

System and Component Boundaries

The hybrid combi system boundary is shown in Figure 29 in the black rectangle. This boundary is defined by the amount of energy delivered to air and water over the combi boiler natural gas and system power consumption. The component boundaries associated to the A2WHP and combi boiler operation in purple and green rectangles respectively and define by the amount of heat delivered to the water over the energy consumption of each component.

Natural Gas Energy Input

The following equation was used to calculate the energy input utilizing the appropriate calculation methods depending on the fuel type and measurement equipment:

$$Q_{fuel} = \sum HHV \cdot \dot{V}_f \cdot \Delta t / \rho_f$$

where,

Q_{fuel} = accumulated HHV fuel energy input, (Btu)

HHV = fuel higher heating value obtained in the daily basis based on sample bomb, (Btu/ft^3)

$\dot{V}_f$ = flow rate of fuel, (lbm/h)

Δt = testing period, (h)

ρ_f = fuel density, (lbm/ft^3)

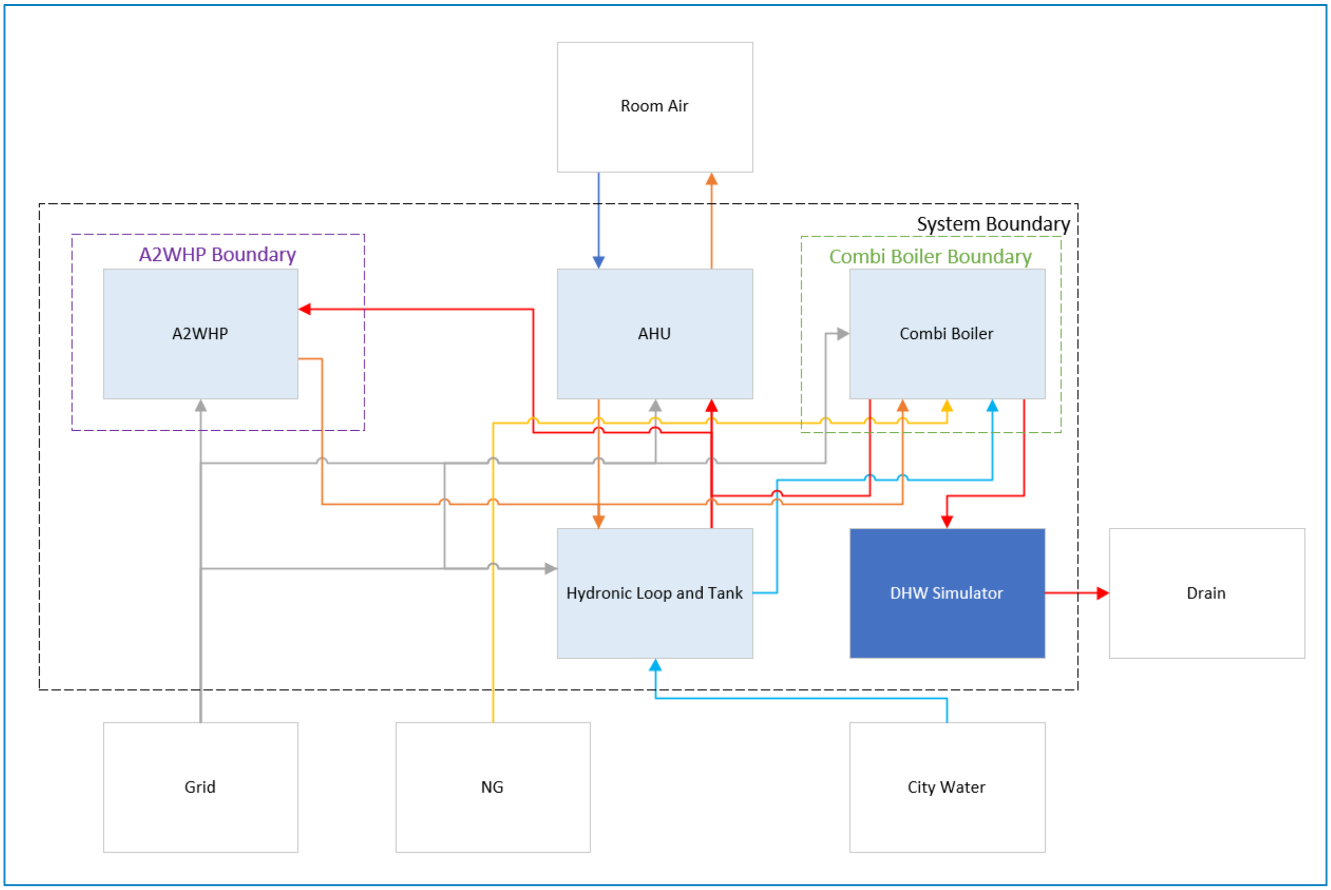

Figure 29 – System and Component Boundary

Net Power Utilization

Electrical output was measured and reported based on the real power indication (electrical output) as measured at the user's interconnection location and included parasitic losses, as appropriate. The units electrical output was based on direct measurement taken during testing at Power Panel 1, 2 and 3. The net power utilization was calculated with the following equation:

$$E_{NET} = E_{p1} + E_{p2} + E_{p3}$$

where,

E_{NET} = net electrical output, (kW-h)

E_{p1} = electricity consumption at the Power Panel 1 associated to the A2WHP operation, (kW-h)

E_{p2} = electricity consumption at the Power Panel 2 associated to the AHU operation, (kW-h)

E_{p3} = electricity consumption at the Power Panel 3 associated to the 120VAC equipment operation, (kW-h)

Water Heating Load Output

The water heating output calculation was based on direct measurement taken during testing at water heating systems calculated with the following equation:

$$Q_{WH} = \sum V_{WH} \cdot \rho_{WH} \cdot c_{p_{WH}} \cdot \Delta T_{WH}$$

where,

Q_{WH}	= energy delivered for water heating loads, (Btu)
V_{WH}	= hot water consumption, (gal)
ΔT_{WH}	= positive temperature difference between domestic hot and city water temperatures, (^{o}F)
$c_{p_{WH}}$	= water specific heat at the average operating temperature, (Btu/lbm-^{o}F)
ρ_{WH}	= water density based on fluid temperature at the flow meter, (lbm/gal)

Hydronic Heating Output

The hydronic heating from either A2WHP or combi boiler was based on direct measurement taken during testing at the hydronic loop calculated with the following equation:

$$Q_{hyd} = \sum V_{hyd} \cdot \rho_{hyd} \cdot c_{p_{hyd}} \cdot \Delta T_{hyd}$$

where,

Q_{hyd}	= energy delivered from A2WHP or combi boiler, (Btu)
V_{hyd}	= water volume circulated, (gal)
ΔT_{hyd}	= positive temperature difference between entering and leaving temperatures of the appliances, (^{o}F)
$c_{p_{hyd}}$	= water specific heat at the average operating temperature, (Btu/lbm-^{o}F)
ρ_{hyd}	= water density based on fluid temperature at the flow meter, (lbm/gal)

Space Heating Load Output

AHU heating output was based on the direct measurement taken during testing at heat transferred at the space heating simulator infrastructure calculated with the following equation:

$$Q_{heat} = \dot{V}_a \cdot \rho_a \cdot c_{p_a} \cdot \Delta T_a \cdot t$$

where,

Q_{heat}	= accumulated total thermal output at the AHU, (Btu)
$\dot{V}_a$	= AHU airflow, (cfm)
ΔT_a	= positive temperature difference between leaving and entering air temperatures at the AHU, (^{o}F)

c_{p_a} = air specific heat at the average operating temperature, (Btu/lbm-°F)

ρ_a = air density based on fluid temperature at the airflow meter, (lbm/cF)

t = data collection time step, (min)

System Efficiency

The system efficiency was calculated with the following equation:

$$\eta = \left(\frac{Q_{WH} + Q_{heat}}{Q_{fuel} + E_{NET}}\right) \cdot 100\%$$

where,

η = hybrid combi efficiency, (%)

Instrumentation Plan

The following section lists the instrumentation that was used for the measurements at the hybrid hydronic and water heating systems, space heating simulator infrastructure, power metering panels and natural gas line.

Hydronic and Water Heating Infrastructure

Table 4 shows the instrumentation for hydronic and water heating systems infrastructure.

Table 4 – Hydronic and Water Heating Systems Infrastructure Instrumentation List

Parameter	Make	Model	Range	Accuracy	Output
NG flow	IMAC	AC-250	0 – 250 cfh	± 1% of reading	Count / 2w
NG temperature	Omega	TMQSS-125G-6	–454 to 700°F	± 1.8°F or 0.75%	Resistance
NG line pressure	Setra	2091001PG2M1102	0-1 psi	± 0.25% full-scale	4-20mA
Exhaust temperature	Omega	TMQSS-125G-6	–454 to 700°F	± 1.8°F or 0.75%	Resistance
Combustion air temperature	Omega	TMQSS-125G-6	–454 to 700°F	± 1.8°F or 0.75%	Resistance
AHU water glycol flow	Dwyer	MFS2-4	0 – 26gpm	± 1% of reading	Count / 4w
A2WHP water glycol flow	Belimo	FM-100	0 – 21 gpm	± 1% of reading	0-10VDC

City water flow	Dwyer	MFS2-2	0 – 6gpm	± 1% of reading	Count / 4w
A2WHP leaving temperature	Omega	TMQSS-125G-6	–454 to 700°F	± 1.8°F or 0.75%	Resistance
A2WHP entering temperature	Omega	TMQSS-125G-6	–454 to 700°F	± 1.8°F or 0.75%	Resistance
AHU water glycol leaving temperature	Omega	TMQSS-125G-6	–454 to 700°F	± 1.8°F or 0.75%	Resistance
AHU water glycol entering temperature	Omega	TMQSS-125G-6	–454 to 700°F	± 1.8°F or 0.75%	Resistance
City water temperature	Omega	TMQSS-125G-6	–454 to 700°F	± 1.8°F or 0.75%	Resistance
Domestic Hot Water temperature	Omega	TMQSS-125G-6	–454 to 700°F	± 1.8°F or 0.75%	Resistance
Storage tank temperature	Omega	TMQSS-125G-6	–454 to 700°F	± 1.8°F or 0.75%	Resistance

Space Heating and Cooling Simulator Infrastructure

Table 5 shows the instrumentation for the space heating and cooling simulator infrastructure.

Table 5 – Space Heating Simulator Instrumentation List

Parameter	**Make**	**Model**	**Range**	**Accuracy**	**Output**
Airflow velocity pressure	Setra	2641-R25WD-11-T1-F	0 to 0.25inWC	± 0.25% full-scale	4-20mA
Airflow	Paragon	FE-1500-1-A-0-16x08-R-0-FX-1	300 – 1800 cfm	± 2% reading ± 0.12% full-scale	Tied with Airflow velocity pressure
Airflow temperature at the flow meter	Omega	5TC-TT-T-24-72	–454 to 700°F	± 1.8°F or 0.75%	Resistance

Return air temperature	Omega	5TC-TT-T-24-72	–454 to 700°F	± 1.8°F or 0.75%	Resistance / 4 signals
Supply air temperature	Omega	5TC-TT-T-24-72	–454 to 700°F	± 1.8°F or 0.75%	Resistance / 9 signals

A2WHP System Infrastructure

Table 6 shows the instrumentation list for the A2WHP system infrastructure.

Table 6 – A2WHP System Infrastructure Instrumentation List

Parameter	Make	Model	Range	Accuracy	Output
Entering air temperature	Omega	TMQSS-125G-6	–454 to 700°F	± 1.8°F or 0.75%	Resistance / 4 signals
Domestic hot water temperature	Dwyer	RHP-2O10	0 to 100% @ -40 to 140°F	± 2.0% of reading	4-20mA

Power Metering and Distribution Infrastructure

Table 7, Table 8 and Table 9 show the instrumentation list for the Power Panel 1, 2 and 3, respectively.

Table 7 – Power Panel 1 Instrumentation

Parameter	Make	Model	Range	Accuracy
A2WHP Power	Continental Control System	WNB-3D-240-P	0 – 50amps/leg	±0.5% nominal
A2WHP Current	AcuAMP	ACT050-10-S	0 – 50amps/leg	±1% full-scale

Table 8 – Power Panel 2 Instrumentation

Parameter	Make	Model	Range	Accuracy
AHU Power	Continental Control System	WNB-3D-240-P	0 – 20amps/leg	±0.5% nominal
AHU Current	AcuAMP	ACT050-10-S	0 – 20amps/leg	±1% full-scale

Table 9 – Power Panel 3 Instrumentation

Parameter	**Make**	**Model**	**Range**	**Accuracy**
120VAC Equipment Power	Continental Control System	WNB-3Y-208-P	0 – 5amps/leg	±0.5% nominal
120VAC Equipment Current	AcuAMP	ACT050-10-S	0 – 5amps/leg	±1% full-scale

Appendix B – VTH Evaluation Methods

Space Heating Thermostat Simulator

The laboratory test setup was designed such that energy in warm air delivered by the furnaces could be determined using accurate airflow measurements along with supply- and return-air temperature measurements. However, that energy was not delivered to a conditioned space, like it would be in a home. Rather, the test setup was designed to expel the warm air from the lab space. As such, the furnaces did not operate on actual calls from their thermostats. Instead, for each incremental part-load test, algorithms in a computer-generated, or virtual home were used to calculate room air temperatures and simulate thermostat cycle times (on/off or modulation calls). During the on cycles, the amount of energy delivered in warm air by the furnace was calculated every five seconds using measurements from the test setup. Knowing the energy delivered at 5-second intervals, and the required heating demand for the particular part-load test, room air temperatures in the virtual home were calculated every five seconds as well. It is important to note, conditioned space volume is also needed to determine how the room air temperatures change. Since part-loads were based on the Building America B10 Benchmark reference house, building volume and construction were arbitrarily defined by that reference model. The model used to define the volume can be arbitrary as only the resulting cycle times are important in order to map the part-load force-air system performance with single-stage or modulation operation.

Thermostats operate based on room air temperature set points and dead-bands, which are adjustable. The thermostat dead-band is important because it could negatively affect efficiency as a result of short cycling. For instance, the smaller the dead-band, the shorter the furnace cycle time, and the lower the efficiency. The dead-band allows a force-air system to cycle on or modulate between allowable minimum and maximum room air temperatures. The force-air cycling algorithms developed for this project used a 2°F dead-band, allowing the room air temperature in the virtual home to be between 69°F and 71°F. Therefore, the force air system came on at 69°F and shut off at 71°F. Examples of force-air system operation with single- and modulating capacity is shown on the left and right of Figure 30, respectively.

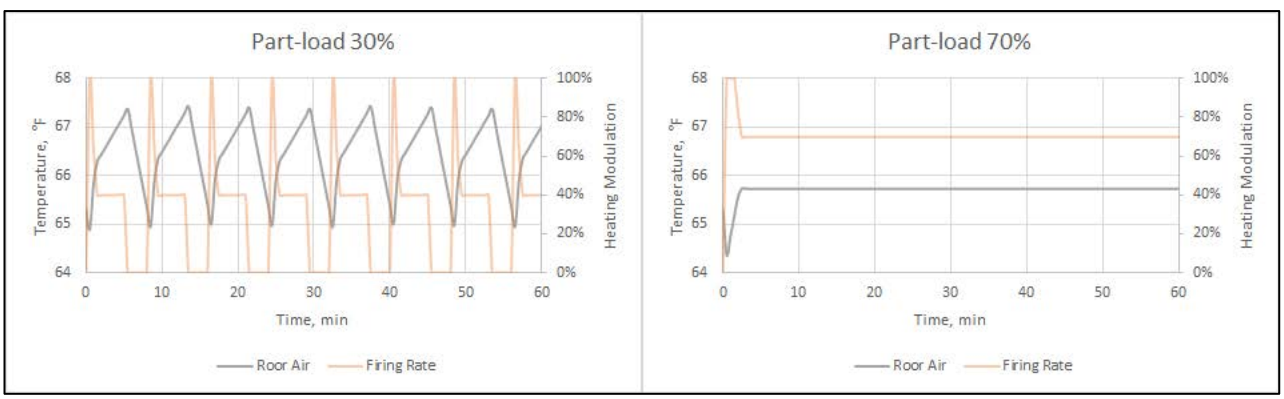

Figure 30 – Thermostat Simulation Strategies

Appendix C – Acronyms

Table 10 shows the acronyms used in throughout this document.

Table 10 – Acronyms List

Acronym	Description
A2WHP	Air-to-Water Heat Pump
AFUE	Annual Fuel Utilization Efficiency
AHU	Air Handling Unit
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
Aux	Auxiliary
ccASHP	Cold Climate Air Source Heat Pump
CFR	Code of Federal Regulations (U.S.)
COP	Coefficient of Performance
DOE	U.S. Department of Energy
eGRID	Emissions & Generation Resource Integrated Database
EHPWH	Electric Heat Pump Water Heater
GHG	Greenhouse Gas
HSPF	Heating Seasonal Performance Factor
HVAC	Heating, Ventilating and Air Conditioning
IECC®	International Energy Conservation Code®
mCHP	Micro Combined Heating and Power (i.e. < 50kW)
MFR	Manufacturer
MOT	Method of Test
NREL	Natural Renewable Energy Laboratory (U.S. DOE)
OAT	Outside Air Temperature
RTO	Regional Transmission Organizations
SCOP	Source Energy COP
TC	Thermocouple
VAC	Volts Alternating Current
VTH	Virtual Test Home (at GTI Energy's Laboratory)
WH	Water Heating