Gas Absorption Heat Pump (GAHP) #1 Performance Mapping With Hydrogen

Project Number ET24SWG0004

GAS EMERGING TECHOLOGIES (GET) PROGRAM
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Prepared by ICF for submission to Southern California Gas Company

ICF

CONTENTS

LIST OF TABLES

LIST OF FIGURES

List of Equations

Acknowledgements

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Executive Summary

The GET Program conducted a laboratory study to evaluate the performance of a commercially available gas absorption heat pump (GAHP) unit. In collaboration with GTI Energy, who provided laboratory services and technical assistance, a thorough test plan was developed for hydrogen-natural gas fuel blend testing to include equipment commissioning; a 0-30% hydrogen plus natural gas blend steady state evaluation; and a 0-30% hydrogen plus natural gas blend load-based evaluation of the Robur GAHP-A unit.

The steady-state testing resulted in a negligible difference to the overall system coefficient of performance (COP) as the hydrogen blend percentage increased. This proved to be a positive finding as efficiency is not negatively impacted by increasing the hydrogen blend percentage. A direct correlation between the firing rate and the Wobbe Index (WI) was modeled, which highlighted the impact on the gas mixture density and high heating value. Additionally, this testing resulted in an overall reduction in pollutant emissions such as CO and NOx.

The load-based testing was conducted using the steady state testing operating conditions where various cycle ON and OFF times were tested. Based on the steady state capacity experimental data, the load-based curves were developed where the COP as a function of part load percentage was modeled.

EnergyPlus modeling performance curves were developed, which resulted in a ±5% accuracy above a 25%-part load ratio. These performance curves will be integrated with EnergyPlus to develop the GAHP modeling portfolio.

Introduction

This study aims to characterize the performance of a Robur GAHP-A unit with a 10%, 20%, and 30% hydrogen-natural gas (NG) (i.e., methane) fuel blend to sufficiently populate model inputs in EnergyPlus. This study is an extension of a completed GET Program – ET23SWG0015 GAHP Performance Mapping [1, 11]. Gas heat pump water technology is a new technology where evidence-based lab testing has confirmed that the technology functions well with energy savings of approximately 50% over the incumbent technology. Some key advantages of a GAHP unit over the incumbent equipment include the following [2, 3]:

- Reduction in energy usage – Heat pumps have the capability to operate over 100% efficiency (COP basis).
- Maintain optimal efficiency levels – The thermal compressor integrated in GAHP units is more efficient and has lower operation costs relative to traditional gas-fired appliances.
- Lower emissions – The reduction in full reliability on fossil fuels ultimately lowers emissions relative to traditional heating/cooling systems.
- Hydrogen blend benefits – The ability to operate using the existing technology along with reduction in pollutant emissions primarily related to NOx formation.
- Decentralized heating/cooling – GAHPs are suitable for decentralized heating and cooling applications as the unit is sufficient to operate independently. Therefore, without the need for a complex network of pipes or ducts to transport hot or cold air, water, or steam across long distances, this simplifies infrastructure and can reduce energy losses and installation/maintenance costs.

Additionally, there are some disadvantages associated with this technology, which include the following:

- Short cycling effects due to suboptimal temperature and flowrate set points, which ultimately result in a decrease in efficiency.
- Minimal training guidance and/or support tools are available to contractors when it comes to installation and unit commissioning for GAHP units, therefore, increasing the risk of running the unit at a lower efficiency than what it is rated for.

With water heating being the largest non-industrial end-use of natural gas in California, a significant impact can be made where reductions in natural gas consumption are implemented. The targeted sector for this study spans all sectors and all applications.

With the recent passing of California legislation – including SB 1477 (building decarbonization/space heating/water heating), California Long Term EE Strategic Plan

(CLTEESP), and AB 758 (comprehensive energy efficiency (EE) in existing buildings law), there is a collective push for energy efficiency solutions specifically in the commercial sector.

In California, hydrogen fuel blending is currently being explored through Southern California Gas Company's (SCG) funded hydrogen blending projects. Proposed demonstration projects include blending hydrogen into existing natural gas infrastructure in the City of Orange Cove and at the University of California, Irvine campus [4].

The testing to support EnergyPlus modeling consists of both static performance mapping and transient performance mapping.

Assessment Objectives

The main objective of this laboratory study is to conduct a comprehensive 0-30% hydrogen-natural gas fuel blending analysis on a market-ready GAHP unit to integrate performance mapping curves in EnergyPlus. This is part of an ongoing study to test various market-ready heat pump units to contribute to the EnergyPlus heat pump modeling portfolio and increase its overall accuracy and versatility. EnergyPlus modeling can be used to forecast energy consumption, utility bills, and greenhouse gas emissions. The targeted audience includes California policymakers, program designers, software developers, and manufacturers.

Test Plan

This test plan was designed to split the laboratory testing into three phases – commissioning, steady state evaluation, and load-based (transient) evaluation. The commissioning phase of the system is based on the manufacturer's published performance data per the test point outlined in Table 1. Corresponding testing tolerances for the commissioning phase are outlined in Table 2.

Table 1: Target Conditions for Commissioning Test.

Test Point	Dry Bulb Outdoor Air Temperature (OAT), °F	Return Temperature (RT), °F	Flow Rate, GPM
1	44.6	104	13.6

Table 2: Commissioning Test Tolerances.

Variable	Tolerance
Return and Supply Heating Loop Temperatures	±1.0°F
Heating Loop Flow	±2.0%
Simulated Outdoor Air Dry-bulb Temperature	±1.0°F
Firing Rate	±2.0%
GAHP-A Electrical Power	±1%
% Carbon Dioxide (CO_2) in Exhaust (Initial Commissioning Only)	±0.4%

The steady state evaluation was performed over a range of operating conditions outlined in Table 3. Corresponding testing tolerances for the steady state phase are outlined in Table 4.

Table 3: Target Conditions for Steady State Evaluation.

<table>
<tr><th>Test Point</th><th>Dry Bulb Outdoor Air Temperature (OAT), °F</th><th>Return Temperature (RT), °F</th><th>Flow Rate, GPM</th><th>Hydrogen Blend, %</th></tr>
<tr><td>1-3</td><td>90</td><td rowspan="6">120</td><td rowspan="6">13.6</td><td rowspan="5">10
20
30</td></tr>
<tr><td>4-6</td><td>75</td></tr>
<tr><td>7-9</td><td>47</td></tr>
<tr><td>10-12</td><td>35</td></tr>
<tr><td>13-15</td><td>17</td></tr>
<tr><td>16</td><td>47</td><td>0</td></tr>
</table>

Table 4: Steady State Evaluation Tolerances.

Variable	Tolerance
Return and Supply Heating Loop Temperatures	±2.0°F
Heating Loop Flow	±2.0%
Simulated Outdoor Air Dry-bulb Temperature	±2.0°F
Glycol Concentration	±3.0%
Firing Rate	±2.0%
GAHP A Electrical Power	±1%
% CO_2 in Exhaust (at specified points)	±0.4%

The load-based evaluation was performed over a range of operating conditions outlined in Table 5. Corresponding testing tolerances for the load-based phase are outlined in Table 6.

Table 5: Target Conditions for Load-Based Evaluation.

Test Point	OAT, RT, and Flow Rate Match	Cycle ON-time, hr.	Cycle OFF-Time, hr.	Hydrogen Blend, %
1	47°F / 120°F / 13.6 GPM	0.1 0.2 0.3 0.5 0.7	0.5	10 20 30

Table 6: Load-Based Tolerances.

Variable	Tolerance
Return and Supply Heating Loop Temperatures	±5.0°F
Heating Loop Flow	±2.0%
Simulated Outdoor Air Dry-bulb Temperature	±5.0°F
Glycol Concentration	±3.0%

Equipment Commissioning

The GAHP-A was installed in GTI Energy's thermal heat pump (THP) testbed. Figure 1 shows the installation of the unit from multiple angles [5].

Figure 1: GAHP-A Installation Pictures.

Figure 2 shows the measuring and verification (M&V) instrumentation used for this evaluation, including the THP testbed environmental chamber equipment. Simplified details and tags of the M&V instrumentation are described in Table 7.

Figure 2: Diagram of the M&V instrumentation.

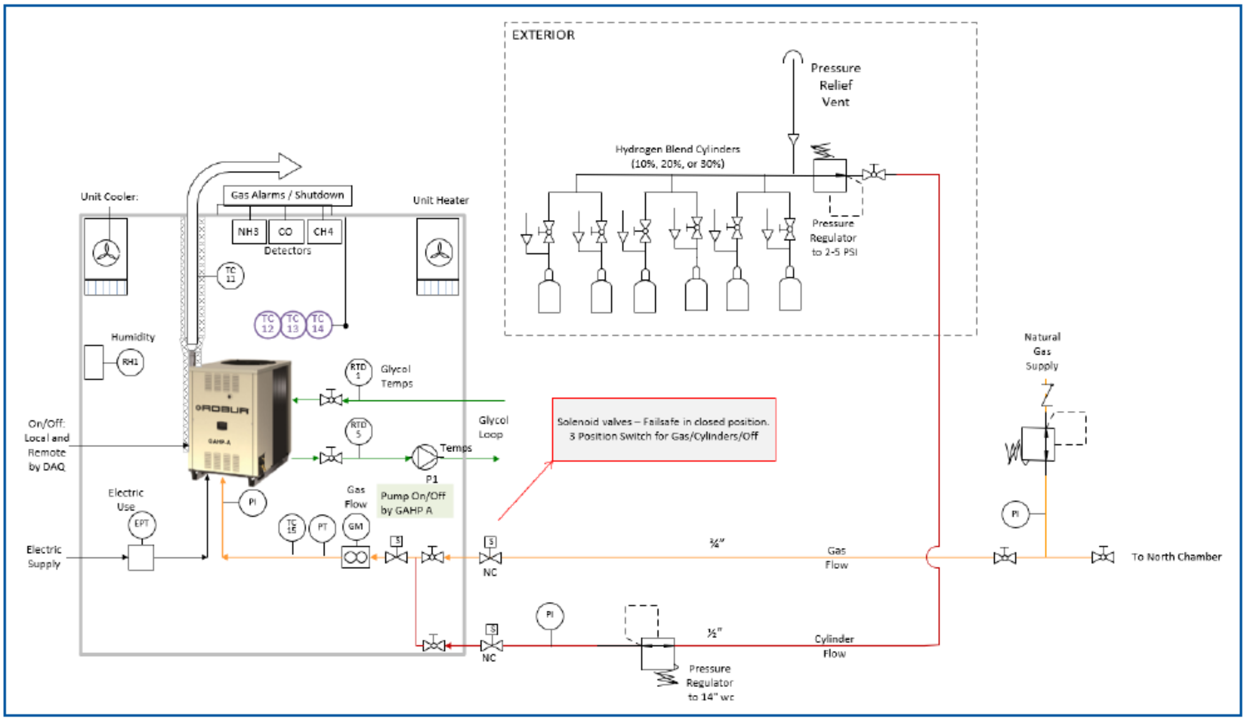


Table 7: Instrumentation Tags and Details.

Tag	Measurement
RTD1	GAHP-A return temperature
RTD5	GAHP-A supply temperature
TC15	Natural gas temperature
TC12, 13, 14	Environmental chamber temperatures
TC11	Exhaust gas temperatures
NG PT	Natural gas inline pressure
FT1	GAHP-A flow rate
GM	Natural gas flow rate
EPT	GAHP power
RH1	Environmental chamber humidity

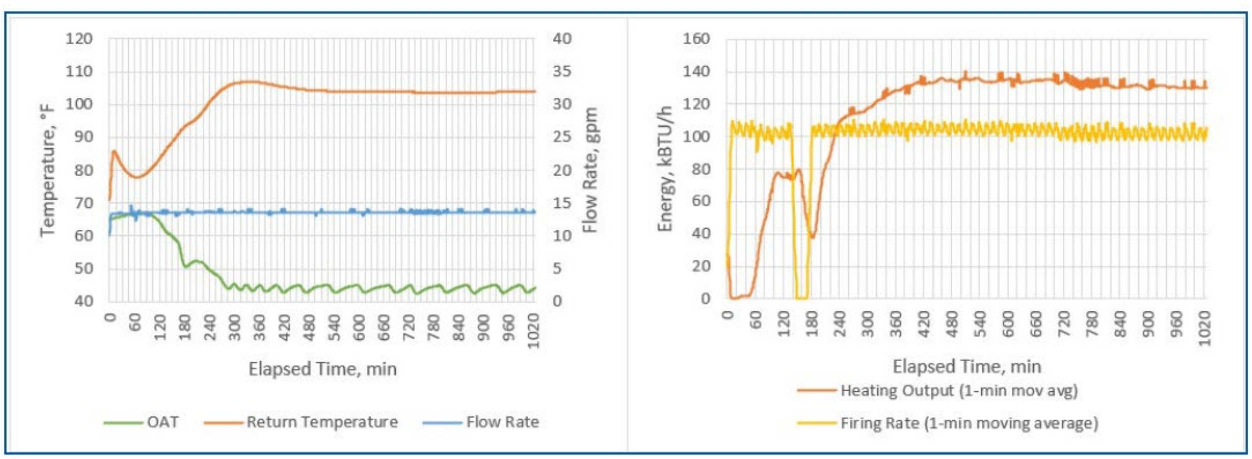
Additional details on the testbed hydronic test rig, gas valve set-up, and hydrogen blend system set-up, which preceded the commissioning test, can be found in Appendix 1.0.

The GAHP-A system was operated at the predefined steady state rating conditions per the conditions and tolerances outlined in Table 1 and Table 2. The commissioning was performed by first running the GAHP-A after calibrating the gas valve manifold pressure. The THP testbed equipment controlled the target simulated OAT and RT and the evaluation took approximately 80 minutes to achieve the target operating conditions. Energy rates were calculated and compared with the manufacturer's specification per the 15-minute average test results and published values outlined in Table 8. Additionally, the time series of the key variables outlined in Table 8 are shown in Figure 3 [5].

Table 8: Test Results Compared to Published Values.

Variables	Test Results	Published Values [6]
Flow Rate	13.6 GPM	13.6 GPM
Outdoor Air Temperature	44.0°F	44.6°F
Return Temperature	103.8°F	104°F
Supply Temperature	123.1°F	122°F
HHV used	1056	1014
Manifold Pressure	2.58 inches (in) water column (WC)	2.77 in WC
Energy Output	94 cubic foot per hour (CFH)	96 CFH
Gas COP	1.32	1.29

Figure 3: Time Series of Commissioning Condition.



Calculations

Steady State and Load-Based Evaluation

The performance results include the energy input, power, heating output, and the COP. The energy input will be calculated using Equation 1.

Equation 1: Energy Input.

$$Q_{in} = \sum V_g \cdot \frac{P_a}{P_s} \cdot \frac{T_s}{T_a} \cdot HHV$$

Where;

Q_{in} = accumulated natural gas energy input, British thermal unit (Btu);
V_g = natural gas volume, cubic foot (CF);
P_a = actual line pressure and barometric pressure, pounds per square inch absolute (psia) (referencing weather data);
P_s = standard pressure of 14.969 pounds per square inch (psi);
T_a = actual line temperature, °R;
T_s = standard temperature of 520°R; and
HHV = natural gas higher heating value (HHV), Btu/cF (values to be measured daily).

Following these calculations in Equation 1, the energy input will be converted to a firing rate as a rolling average over each test point period.

The electricity consumption ($Q_{Elec,GAHP}$) of the GAHP-A unit will be directly measured using a watt node. Each test point will be evaluated and converted to power and energy demand for the given test periods.

The GAHP-A hydronic energy output will be calculated using Equation 2.

Equation 2: Energy Output.

$$Q_{out_f} = \sum \dot{V}_f \cdot C_{p_f} \cdot \rho_f \cdot (T_S - T_R) \cdot \Delta t$$

Where;

Q_{out_f} = GAHP-A accumulated energy output, Btu;
$\dot{V}_f$ = heating loop flow rate, gallons per minute (gpm);
c_{p_f} = heating loop specific heat as a function of average process temperature and volume base glycol water mix %, Btu/pound-mass (lbm)-°F;
ρ_f = heating loop density at the average process temperature and volume base glycol water mix %, lbm/gallon (gal);
T_S = water glycol loop supply temperature (ST), °F;
T_R = water glycol loop return temperature, °F; and
Δt = data logger time-step of 5 seconds, minute (min).

With Equation 1 and Equation 2 defined, the gas only COP and the overall system COP (includes electric power consumption) can be calculated according to Equation 3 and Equation 4, respectively:

Equation 3: Gas Only COP.

$$COP_g = COP\ (gas - only) = \frac{\dot{Q}_{out_f}}{\dot{Q}_{in}}$$

Equation 4: Overall System COP (including electric power consumption).

$$COP_{GAHP} = COP(gas + electric) = \frac{\dot{Q}_{out_f}}{\dot{Q}_{in} + \dot{Q}_{Elec,GAHP}}$$

The COP ratio can be calculated by incorporating both the steady state and load-based results according to Equation 5 and Equation 6, respectively.

Equation 5: Gas Only COP Ratio.

$$COP_g\ Ratio = COP\ (gas - only) Ratio = \frac{COP_{g,load-based}}{COP_{g,SS}}$$

Equation 6: Overall System COP Ratio.

$$COP_{GAHP}\ Ratio = COP(gas + electric) Ratio = \frac{COP_{GAHP,load-based}}{COP_{GAHP,SS}}$$

Where;

$COP_{g,SS}$ = gas only COP at relative steady state testing parameter;
$COP_{GAHP,SS}$ = overall system (gas+electric) COP at relative steady state testing parameter;
$COP_{g,load-based}$ = gas only COP at load-based testing parameter; and
$COP_{GAHP,load-based}$ = overall system (gas+electric) COP at load-based testing parameter.

The part load percentage (PLR) is represented by Equation 7.

Equation 7: PLR.

$$PLR = \frac{\dot{Q}_{out_f,load-based}}{\dot{Q}_{out_f,SS}} \cdot 100\%$$

Where;

$\dot{Q}_{out_f,SS}$ = GAHP-A accumulated energy output at relative steady state testing parameter, Btu/hour (h); and

$\dot{Q}_{out_f,load-based}$ = GAHP-A accumulated energy output at load-based testing parameter, Btu/h.

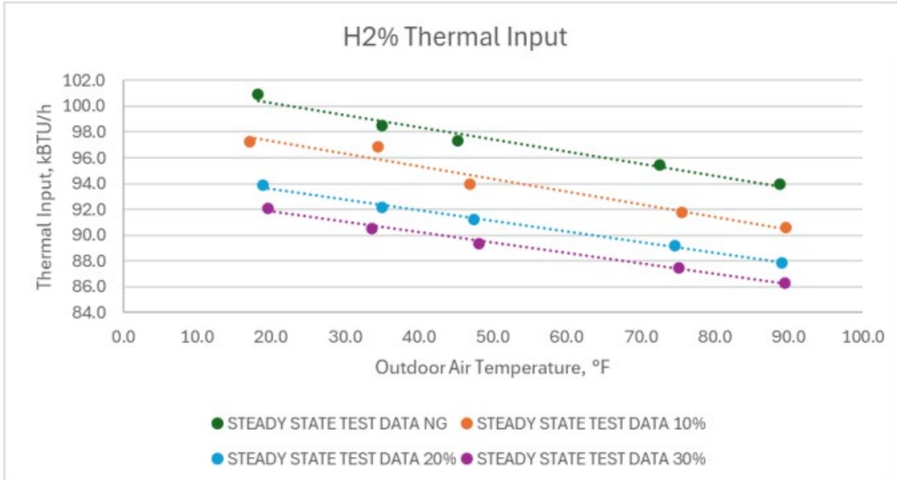
Steady State Evaluation

All resultant test parameters were measured except for the propylene glycol volume % as this was measured and controlled prior to conducting the experiment. A comprehensive snapshot of the target conditions, the test results summarized at a 15-minute average, and the performance results can be found in Appendix 2.0.

Gas Input

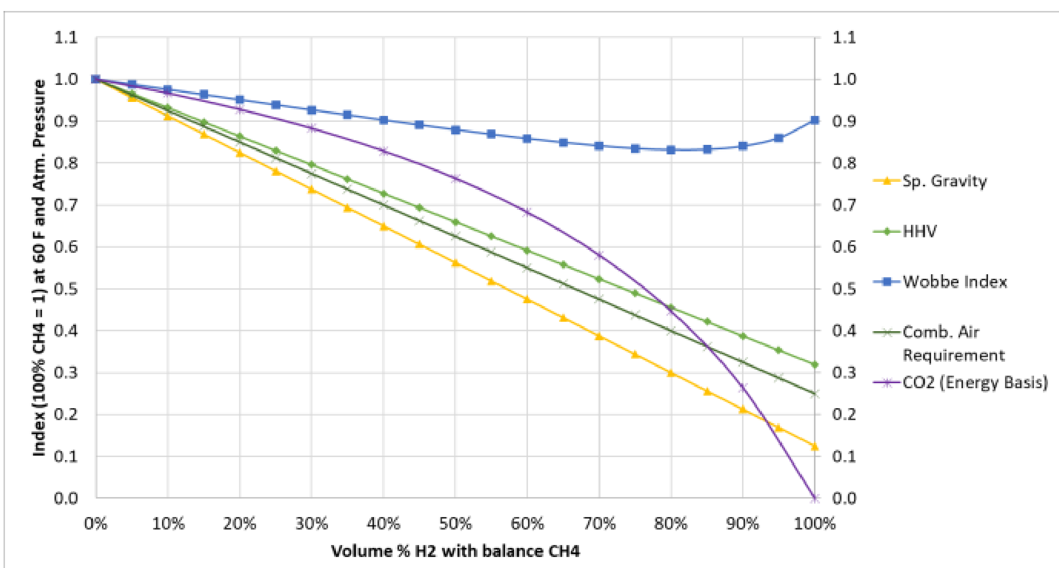
The firing rate was set during commissioning with natural gas and was not modified [1, 11]. Figure 4 shows the firing rate characterization as a function of ambient operating conditions. Due to density changes between air and natural gas in the premix burner, the resultant firing rate changes with varying ambient conditions. This change is convenient as more heating capacity is needed as ambient conditions drop and vice versa.

Figure 4: Firing Rate Variation with Temperature.



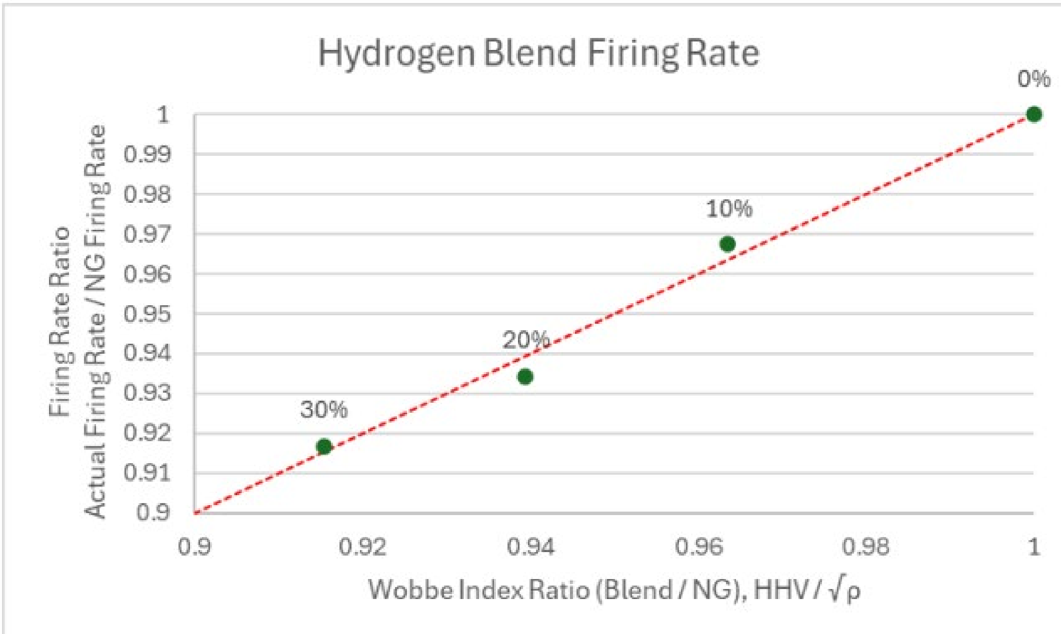
When hydrogen is blended with natural gas or methane, the energy content of the blend decreases on a volumetric basis. This is shown as the HHV curve in Figure 5 below. The HHV of the blend decreases from a relative value of 1.0 (100% methane) to 0.80 at 30% H_2 by volume. However, the energy input rate of a blend is also affected by the gas density, which results in higher flow at a given gas regulator setting. This additional flow offsets a portion of the decrease in energy content of the blended hydrogen. Thus, the reduction in capacity when firing blends is less than the direct comparison to the energy content, and more closely follows the Wobbe Index (WI). The WI is used to denote gas replacement equivalency [12]. At a blend of 30%, the WI ratio is 0.92, indicating that the expected capacity would be 92% that of pure methane. The WI is defined as the ratio of HHV to the square root of specific gravity per Equation 9.

Figure 5: Index of Key Parameters vs. Blend Percent.



Experimental results show that the capacity decreases at increasing blend percentages correlates closely with the WI ratio, relative to baseline performance data with natural gas at 1056 BTU/cf HHV represented by the 0% data point in Figure 6. All comparisons were performed at 47°F OAT in the environmental chamber.

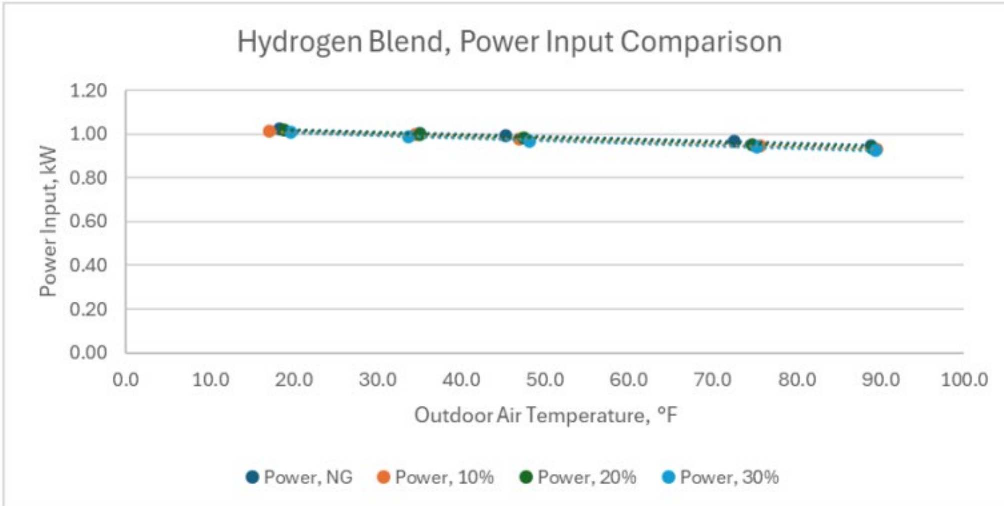
Figure 6: Firing Rate Ratio to Wobbe Index.



Electricity Input

The GAHP A unit requires electrical power for the solution pump, the air coil fan, and the controls. The electricity input was characterized similarly to the gas input. As can be seen from Figure 7, the electricity input is nearly constant at 1 kilowatt (kW) and increases slightly as the ambient conditions drop. The power to the external pump was excluded from this evaluation as it depends on the installation. There is less than 2% variation between the blends.

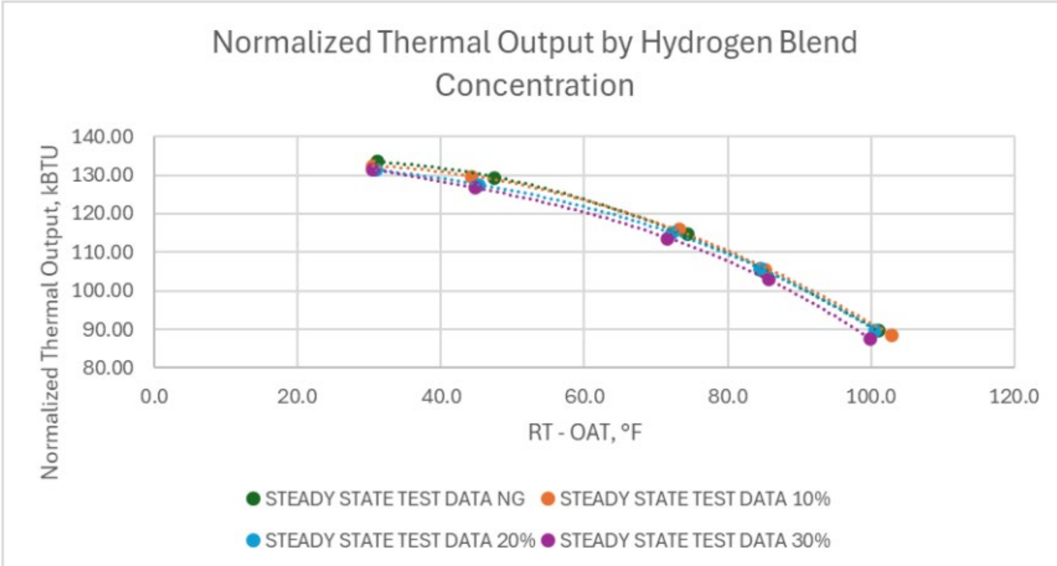
Figure 7: Electricity Input Rate Characterization.



Manufacturer Heat Capacity Comparison

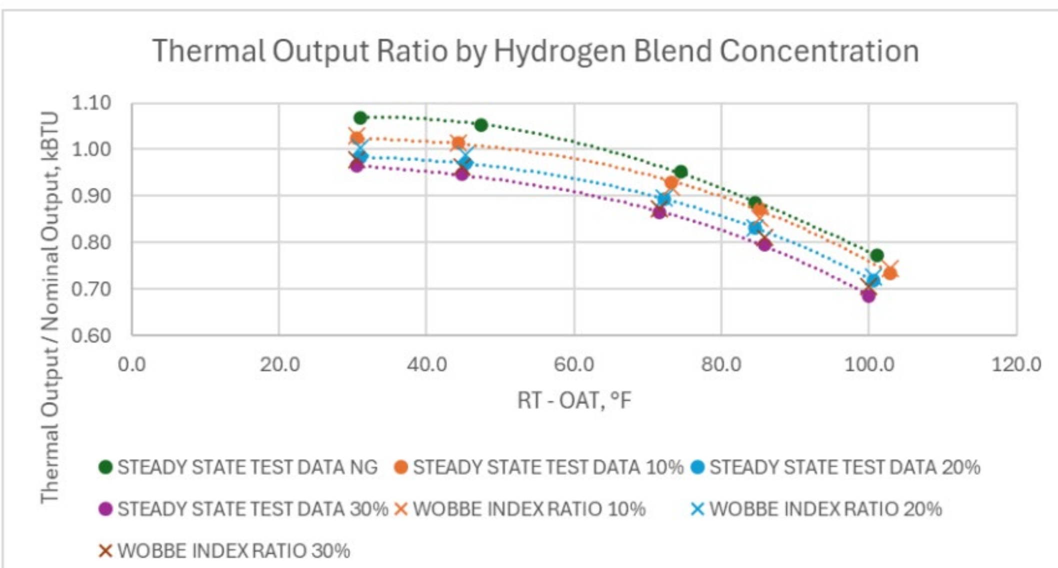
Results were compiled and compared to prior testing with natural gas at the five outdoor air temperatures, 120°F return temperature and 13.6 gpm flow rate. The heating output was normalized to the rating conditions as described in the commissioning test. This normalized output uses the ratio between the actual gas input, which varies with the ambient conditions, over the rated gas input of 95.5 kBtu/h. This approach helps normalize the energy output with fixed energy input. This was plotted against the combined variable of the difference of return temperature and ambient temperature (RT-OAT). The combined variable facilitates performance normalization and can be explained as follows: the temperature difference between the heat source (ambient) and the heat sink (hydronic return temperature). Results are shown in Figure 8, where the close correlation between the results with natural gas and the hydrogen blend concentrations can be noted with the normalized output.

Figure 8: Heating Output Comparison.



A further comparison, Figure 9, shows the effect of blending 10%, 20%, and 30% concentrations of hydrogen into natural gas with the actual thermal output. For a given gas pressure at the GAHP gas valve manifold, the thermal output derates with increasing hydrogen concentration. Similar to the thermal input discussed previously, the derate correlates with the WI. Table 17 in Appendix 4.0 provides the actual values from the test results.

Figure 9: Heating Output Ratio with Hydrogen Blend Concentration.



Coefficient of Performance

Test results were further analyzed, and COPs were calculated per the test plan in Appendix A. Figure 10 and Figure 11 shows the steady-state COPs from the steady-state evaluations. Results indicated that COP (gas-only) is consistent with each hydrogen blend concentration.

Figure 10: COP (gas-only) Characterization.

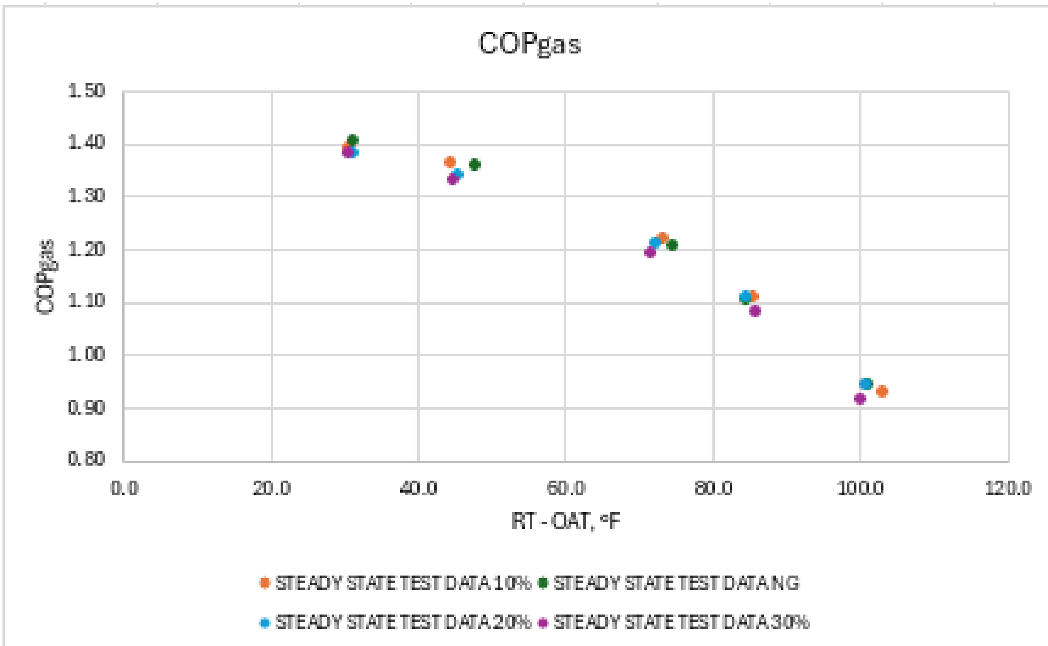
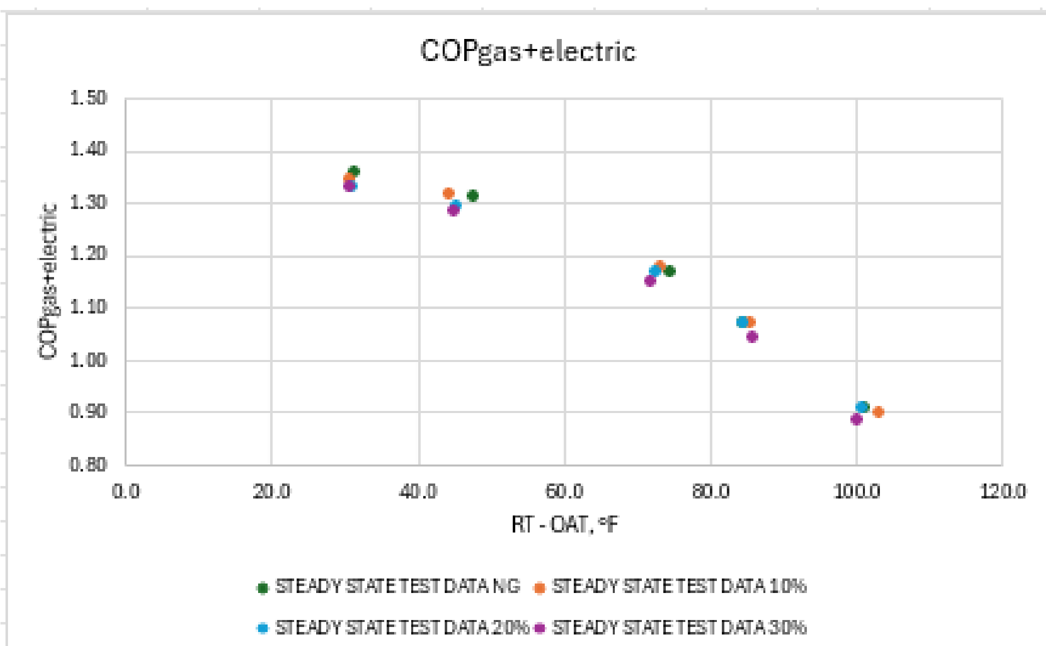


Figure 11: COP (gas+electric) Characterization.



From the commissioning test, it was noted that COP (gas-only) was 1.29 at the rating condition (44.6 °F OAT and 104 °F RT). At the same condition, system COP (gas+electric) was 1.25. Figure 10 and Figure 11 shows the difference between COP (gas only) and COP (gas+electric), which is generally 0.05 less. As expected, COP drops under higher lift conditions (RT-OAT).

Emissions

With each hydrogen blend, an emissions sample was recorded at the same operating conditions, 47°F OAT and 120°F RT. Results are presented in Table 9, showing an improving trend with higher concentrations of hydrogen. The benefits of improved emissions need to be considered with the derate in thermal output when assessing the overall impact of implementing hydrogen blends into the natural gas supply.

Table 9: Emissions results summary.

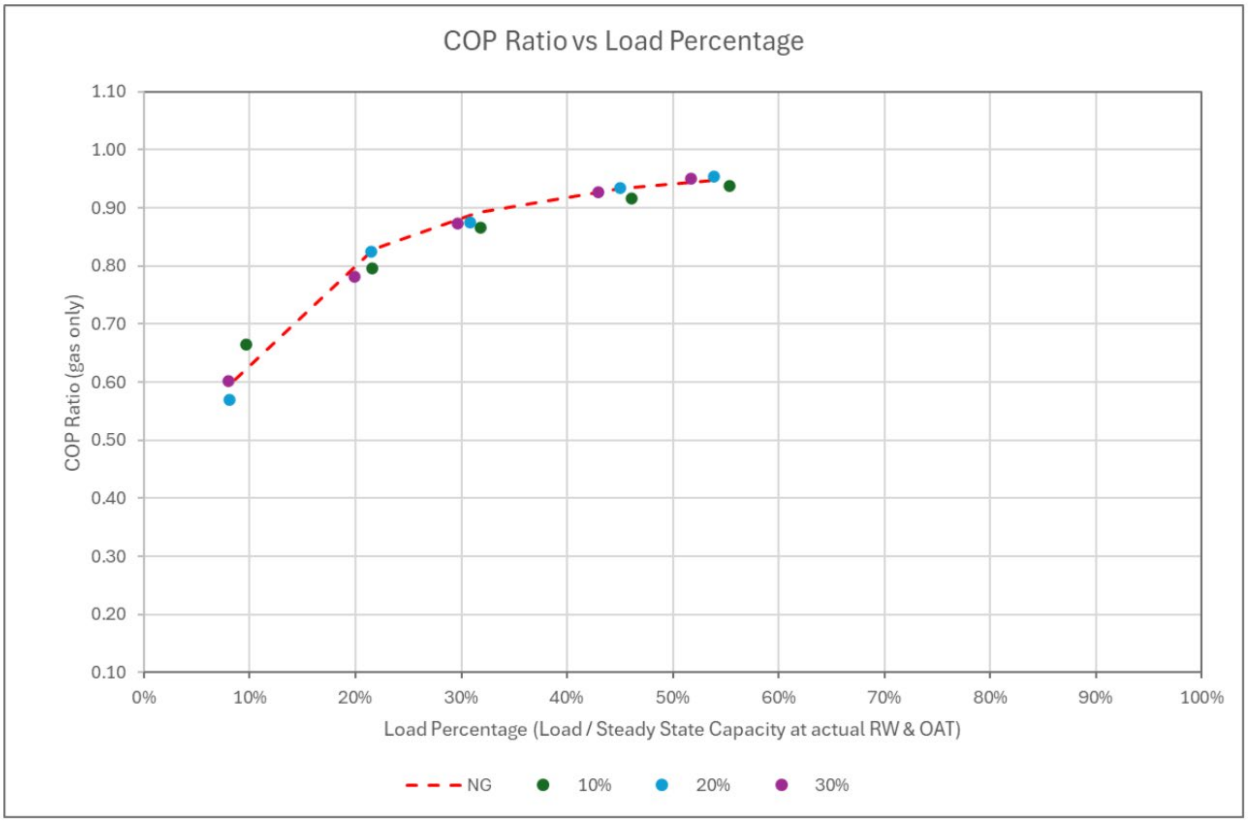
Blend	Corr NOx (3% Air), ppm	Corr CO (3% Air), ppm	CO2, % vol	O2, %vol
Natural Gas	17.6	21.1	8.77%	5.65%
10%	11.5	13.9	7.77%	6.70%
20%	8.4	10.4	7.33%	7.09%
30%	7.0	8.3	6.64%	7.92%

Load-Based Evaluation

All resultant test parameters were measured except for the propylene glycol volume % as that was measured and controlled prior to conducting this part of the experiment. A comprehensive snapshot of the target conditions, the test results summarized at a 15-minute average, and the performance results for the load-based testing can be found in Appendix 3.0.

The goal of part load testing was to compare the performance degradation curve from natural gas to the hydrogen blends, providing a correlation between load percentage and reduction in the unit COP with fuel source. The trend is presented in Figure 12. The load percentage is based on the steady state thermal output for each blend concentration and outdoor air temperature.

Figure 12: Part-load Degradation Curve.



Upon completion of the hydrogen blend testing with blends up to 30%, there were no apparent system issues. This is an overall positive result. The COP ratio (part-load / steady state capacity of each blend) was shown to be independent of the blend and is in close alignment with the baseline natural gas testing.

EnergyPlus Modeling

Results from the steady state and load-based laboratory testing have been used to develop performance characterizations for EnergyPlus modeling. GTI Energy developed these curves using the "Pathways to Decarbonization of Residential Heating" [10]. Calculations used to develop these curves are outlined in the following section and the corresponding constants derived can be found in Appendix 4.0. Based on the designed test plan, limitations in the modeling equations include:

- Heat transfer fluid properties are based on a water-propylene glycol mix with a concentration of 35% flowing between 7.0 and 13.6 GPM.
- Ambient temperature ranges between 0°F and 110°F.

The EnergyPlus module has two independent input variables: ambient dry bulb temperature (T_{amb}) and hydronic return temperature (T_{ret}). Within the range of test results, a function (CAPFT) of these two variables outputs the maximum capacity of the GAHP A when multiplied by the rated capacity at standard operating conditions (47 °F ambient and 95 °F RT). When blending hydrogen into the natural gas fuel supply, a derate function needs to be applied to the manufacturer's rated capacity. At each time step in an EnergyPlus simulation, the load demand is given and used with the maximum capacity to set a PLR. Several functions are provided to determine the overall gas usage as a function of the two input variables, T_{amb} and T_{ret} (EIRFT), as a function of the PLR (EIRFPLR), and defrost cycle derate (EIRDEFROST) when ambient temperatures are between -8.89°C and 3.33°C (16°F and 38°F). The COP (gas-only) can be determined from the gas usage and heat delivered at any given operating conditions of the input variables and PLR. Similar to gas usage, electric consumption is determined as a function of the two input variables, T_{amb} and T_{ret}, ($AUX_{ELEC,EIRFT}$) and a function of the PLR ($AUX_{ELEC,EIRFPLR}$). The COP (gas+electric) with combined gas and electric consumption equals the rate of heat delivered (kBTU/h) divided by the sum of the energy consumed (gas and electricity converted to kBTU/h) [5].

EnergyPlus Performance Curve Development

Heating Output Rate

The following outlines the equations used to develop the EnergyPlus performance curves based on the lab data and analysis. The GAHP-A heating capacity outlined in Equation 8 is used to calculate the part-load performance in EnergyPlus. The capacity is also used to estimate the gas input and power utilization of the GAHP which are both outlined in Equation 11 and Equation 15, respectively. Note the addendum included in the ET23SWG0015 report to update the GAHP input outlined below for Equation 11. This addendum adds the nominal fuel-based COP for the Robur GAHP A to the derivation of coefficients for integration into EnergyPlus [1, 11].

Equation 8: Heating Output Rate.

$$GAHP\ Heating\ Capacity = RatedCapacity \cdot CAPFT$$

Where;

$GAHP\ Heating\ Capacity$ = heating capacity output rate, kilo British thermal unit (kBtu)/h.
$RatedCapacity$ = 126.95, kBtu/h; and
$CAPFT$ = heating capacity correction factor as a function of ambient and return temperature (Equation 10).

Note that the rated capacity will need a derate factor applied to correspond with the fuel supply and WI ratio. The WI represents the heating value of natural gas arriving from the gas line at the orifice where a burner is located. The higher the WI, the greater the heating value of the quantity of gas that will flow through a hole of a given size in a given amount of time [12]. Corresponding values can be found in Appendix 4.0 (Table 17).

Where Equation 9 is used to calculate the WI Ratio.

Equation 9: Rated Capacity Correction.

$$Wobbe\ Index\ Ratio = \frac{Wobbe\ Index_{actual}}{Wobbe\ Index_{nominant}}$$

Where;

$Wobbe\ Index\ Ratio$ = rated capacity derate factor as a function of fuel supply;
$Wobbe\ Index_{actual}$ = fuel supply Wobbe Index (HHV/$\sqrt{SG}$); and
$Wobbe\ Index_{nominal}$ = rated fuel Wobbe Index (HHV/$\sqrt{SG}$).

The heating capacity correction factor (CAPFT) is calculated using Equation 10.

Equation 10: CAPFT.

$$CAPFT = a1 + b1 \cdot Tret + c1 \cdot Tamb + d1 \cdot Tret^2 + e1 \cdot Tret \cdot Tamb + f1 \cdot Tamb^2 + g1 \cdot Tret^3 + h1 \cdot Tret^2 \cdot Tamb + i1 \cdot Tret \cdot Tamb^2 + j1 \cdot Tamb^3$$

Where;

$Tamb$ = heating capacity output rate, kBtu/h;
$Tret$ = 123.5, kBtu/h; and
i_1 = coefficients listed in Appendix 4.0 (Table 18).

Gas Input Utilization

The GAHP-A gas input utilization is calculated according to Equation 11, including the nominal fuel-based COP. Nominal fuel based COP is an input in the *HeatPump:AirToWater:FuelFired* module in EnergyPlus 23.1.

Equation 11: Gas Input Utilization.

$$GAHP\ Gas\ Use = \frac{\frac{Load}{COP_{nom}} \cdot EIRFT \cdot EIRFPLR \cdot EIRDEFROST}{CRF}$$

Where;

$GAHP\ Gas\ Use$ = gas utilization, kBtu;
$Load$ = EnergyPlus heating load as a function of time, kBtu;
COP_{nom} = Rated GAHP capacity / Rated Gas Input, equivalent to 1.327;
$EIRFT$ = gas utilization operating conditions correction factor (Equation 12);
$EIRFPLR$ = gas utilization cycling correction factor (Table 20);
$EIRDEFROST$ = defrost factor (Equation 13); and
CRF = gas input utilization correction factor as a function of cycling operation for modulating equipment (Equation 14).

The gas input utilization operating conditions correction factor (EIRFT) is calculated using Equation 12.

Equation 12: EIRFT.

$$EIRFT = a2 + b2 \cdot Tamb + c2 \cdot Tamb^2 + d2 \cdot Tret + e2 \cdot Tamb \cdot Tret + f2 \cdot Tamb^2 \cdot Tret$$

Where;

i_2 = coefficients listed in Appendix 4.0 (Table 19).

The gas input utilization correction factor (EIRFPLR) is calculated using an interpolation method as a function of PLR. PLR is calculated according to Equation 7. The resultant table can be found in Appendix 4.0 (Table 20).

The defrost factor (EIRDEFROST) is calculated using Equation 13 [8]. Note that GTI Energy recommends implementation of this equation as it is referenced in the "Pathways to Decarbonization of Residential Heating" source [10].

Equation 13: Defrost Factor.

$$EIRDEFROST = -0.0011 \cdot Tamb^2 - 0.006 \cdot Tamb + 1.0317\ for - 8.89℃ \leq Tamb \leq 3.333℃$$

The gas input utilization cycling correction factor (CRF) is calculated using Equation 14.

Equation 14: Gas Input Cycling Correction Factor.

$$CRF = 0.4167 \cdot CR + 0.5833$$

Where;

CR = the cycling modulating derate factor that needs to be set to 1 for the GAHP-A.

Power Input Utilization

The GAHP-A power input utilization is calculated using Equation 15.

Equation 15: Power Utilization.

$$Electric\ Power\ Consumption = RatedPower \cdot Aux_{Elec,EIRFT} \cdot Aux_{Elec,EIRFPLR}$$

Where;

$Electric\ Power\ Consumption$ = power input utilization, kWh;
$RatedPower$ = 0.985, kWh;
$Aux_{Elec,EIRFT}$ = power input utilization correction as a function of return and ambient temperatures; and
$Aux_{Elec,EIRFPLR}$ = power input utilization correction factor as a function of part-load.

The power input utilization operating conditions correction factor ($Aux_{Elec,EIRFT}$) is calculated using Equation 16.

Equation 16: Power Utilization Operating Conditions Correction Factor.

$$Aux_{Elec,EIRFT} = a4 + b4 \cdot Tamb + c4 \cdot Tamb^2 + d4 \cdot Tamb^3 + e4 \cdot Tret + f4 \cdot Tamb \cdot Tret$$

Where;

i_4 = coefficients listed in Appendix 4.0 (Table 21).

The power input utilization cycling correction factor ($Aux_{Elec,EIRFPLR}$) is calculated using Equation 17.

Equation 17: Power Utilization Cycling Correction Factor.

$$Aux_{Elec,EIRFPLR} = a5 \cdot PLR + b5$$

Where;

i_5 = coefficients listed in Appendix 4.0 (Table 22).

Modeling Strategy Accuracy

The performance characterizations presented in EnergyPlus Performance Curve Development Section were used to model the GAHP A performance and compared with measured test data in the following section. Generally, these parameters can be predicted within ±5% (Figure 13). The overall modeling accuracy is about ±5% above 25%-part load ratio shown in the computation of the GAHP A COP (gas only) at part-load operation in Figure 14.

Figure 13: Error Between Measured and Model Data for Modeling Parameters.

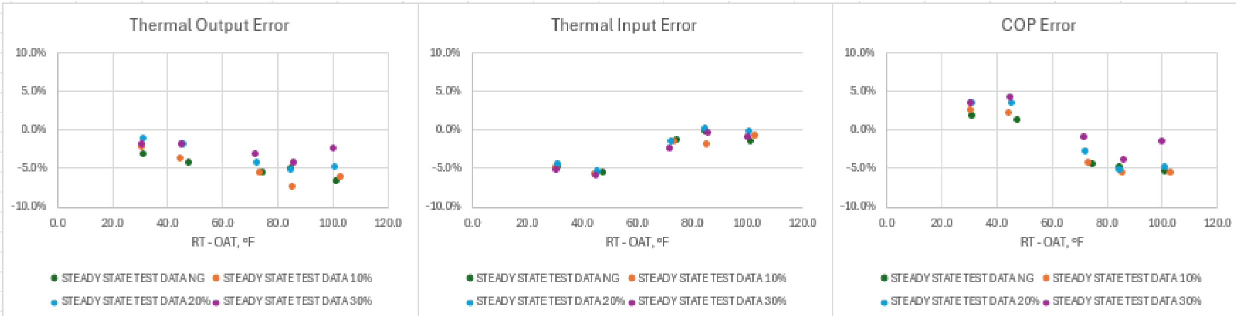
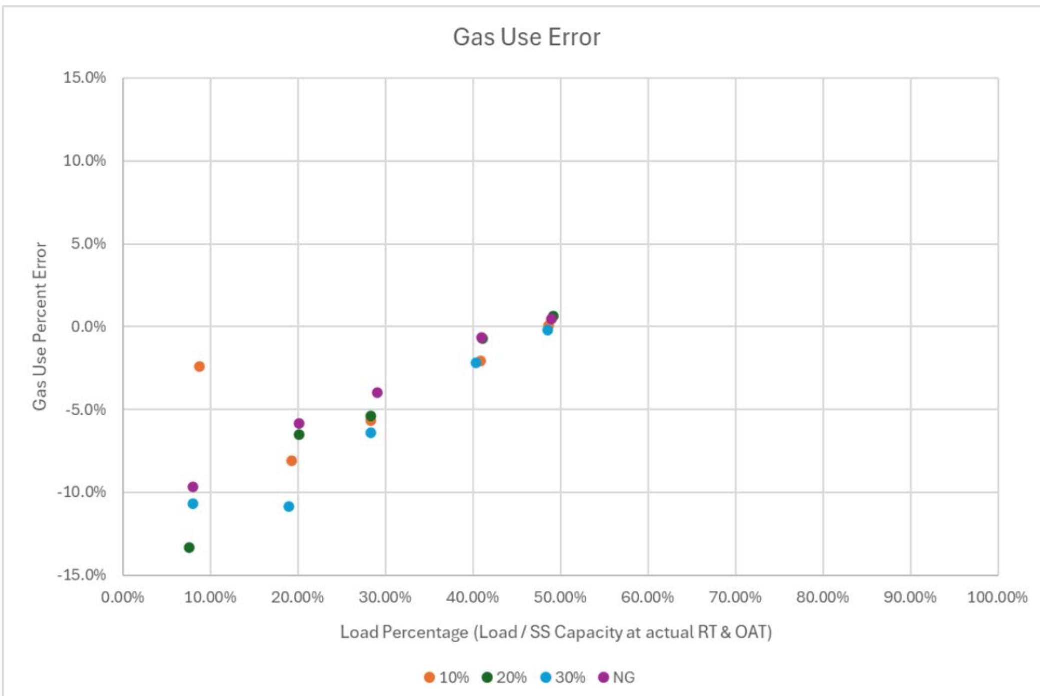


Figure 14: COP (gas-only) Comparison and Error between Measured and Modeled Data.



No additional defrost testing was performed with the hydrogen blends. Once derating rated capacity, all other formulations previously developed are valid to continue using, including defrost characterization. The EnergyPlus model includes a factor to account for the defrost performance penalty (up to 4% near 27°F). Testing performed with natural gas during prior testing of the GAHP A unit showed an average performance impact at a temperature of 35°F in the same range. More extensive testing would be required to revise the modeling tools' default defrost performance curve. Until further testing is performed, the recommendation is to use the default defrost performance curve currently in EnergyPlus.

Conclusions

A comprehensive test matrix was established to gain a thorough understanding of how the GAHP-A unit operates with hydrogen-fuel blending under various steady state and load-based conditions. The key independent variables across both tests were the propylene glycol flowrate, OAT, RT, cycle on runtimes, and cycle off times.

For the steady state testing conditions:

1) The hydrogen blend firing rate correlates closely with the Wobbe Index Ratio (Blend/NG), therefore, drawing a correlation between adjustments in HHV and the density of the tested hydrogen-natural gas blends relative to pure methane.
2) The thermal output, power input, and COP are minimally affected by an increase in hydrogen blending. This is a positive finding in that these variables are not negatively impacted by hydrogen blends up to 30%.
    a. Power input is nearly held constant at 1 kW at the tested hydrogen-natural gas blends.
    b. The thermal output ratio correlates well with the Wobbe Index Ratio at the tested hydrogen-natural gas blends. Note that the normalized data shows a minimal difference in output amongst the tested hydrogen-natural gas blends.
    c. There was a minimal difference found between the COP (gas-only) and the COP (gas+electric).
3) Emissions testing of the blends demonstrated positive impact of reducing NOx and CO, with a 61% reduction using 30% hydrogen blend relative to natural gas alone. Increasing the concentration of hydrogen in the natural gas fuel supply also reduces CO_2 emissions, offering significant emissions benefits.

For load-based testing conditions:

1) The COP (gas-only) ratio shows close alignment with the baseline natural gas testing. This implies that the COP ratio is independent of the hydrogen blend percentage.
2) Performance of the GAHP at part loads was independent of the fuel supply.

Close alignment of the model prediction data to the measured data of about ±5% accuracy above 25% part-load provides sufficient confirmation for integration of the GAHP-A hydrogen-blend laboratory data into EnergyPlus. The decrease in accuracy below part-loads of 25% can be attributed to the resultant experimental data. To increase the accuracy at lower part-loads, the recommendation would be to increase the testing average per point of data in the test matrix.

Recommendations

This study provided the following recommendations based on the laboratory study and EnergyPlus performance curve development:

1. Adoption of the updated EnergyPlus performance mapping input curves per the addendum outlined in the ET23SWG0015 should be implemented across similar projects [1, 11].
2. Additional experimental defrost testing with the GAHP-A unit should be conducted to provide additional input on the default defrost performance curve currently in EnergyPlus.
3. To further contribute to the EnergyPlus GAHP modeling portfolio, additional prototype and commercially available GAHP units should be tested. It is recommended that a similar test plan as the GAHP-A unit, where applicable, be developed to draw comparison conclusions related to the parameters analyzed in this study.

Appendices

Appendix 1.0 Test Rig Setup

Testbed Hydronic Test Rig

Note that the plumbing for the GAHP A was not changed from prior testing with natural gas [1, 11]. The propylene glycol percentage in the heat recovery fluid was 37%, with deviations in density and specific heat from water, as shown in Table 10. These 37% propylene glycol water mix properties were used in the resulting energy input and output calculations shown in Equipment Commissioning of this report.

Table 10: Fluid Properties.

Temperature, °F	Density, lbm/cF			Specific Heat, Btu/lbm-°F		
	Water	PG @ 37%	% Diff.	Water	PG @ 37%	% Diff.
40	8.34	8.89	6.54%	1.000	0.895	-10.49%
60	8.33	8.82	5.87%	0.998	0.916	-8.21%
80	8.31	8.76	5.36%	0.998	0.934	-6.40%
100	8.29	8.70	4.89%	0.998	0.949	-4.87%
120	8.25	8.64	4.71%	0.999	0.962	-3.74%
140	8.21	8.59	4.57%	1.001	0.971	-2.99%
PG = propylene glycol Diff. = difference						

Gas Valve Set-up

In the GAHP A natural gas testing project, the gas valve was adjusted to account for site-specific conditions before the initial test period, following guidelines in the GAHP A Installation Manual shown in Figure 15 [1, 6]. For the current hydrogen-natural gas blend testing, no further adjustments were made. This was done to maintain consistency from previous natural gas tests to the current blend testing. The regulator installed in the test rig was adjusted until the primary field setting, manifold pressure, was 2.58 in WC, corresponding to 94 CFH inlet gas flow. The gas supply for the hydrogen blends from installed cylinders matches the same manifold pressure.

Figure 15 shows the resulting carbon dioxide emissions, gas flow, and firing rate at the measured manifold pressure based on the building gas supply HHV 1,056 BTU/cu ft. Figure 16 compares the measurement of manifold pressure and exhaust gas constituents during the gas manifold pressure tests outlined in Table 11. It should be noted that the Robur manufacturer's instructions assume the technician performing the installation will know the gas input HHV and specific gravity. Both are variables, and it is likely that the technician will not know these values at the time of installation, so the firing rate in actual practice could vary significantly.

Figure 15: GAHP-A Exhaust Gas Specifications and Gas Manifold Pressure Settings.

Table 3.3 *Flue gas exhaust characteristics*

Natural gas	Fumes flow rate	SCF	1750
	Flue temperature	°F	293
	CO_2 percentage in fumes	%	9.2

Table 5.1 *Manifold pressure [inch WC] based on gas input (HHV) of 95.500 Btu/hr using a 0.21" nozzle*

MJ/m³	Btu/CU.FT.	Specific gravity of natural gas			
		0.55	0.60	0.65	0.70
35.40	950	3.15	3.43	3.72	4.01
36.33	975	2.99	3.26	3.53	3.80
37.26	1000	2.84	3.10	3.36	3.61
38.19	1025	2.70	2.95	3.20	3.44
39.12	1050	2.58	2.81	3.04	3.28
40.05	1075	2.46	2.68	2.90	3.13
40.98	1100	2.35	2.56	2.77	2.99
41.92	1125	2.24	2.45	2.65	2.86
Our reference:					
MJ/m³	Btu/CU.FT.	Specific gravity of natural gas 0.555			
37.78	1014	2.77			

Table 11: Gas Manifold Pressure Tests.

Manifold Pressure, inWC	Exhaust Gas CO_2 %	Measured Gas Flow, cfh	Firing Rate, Btu/h
2.58	8.8	94.0	99,400

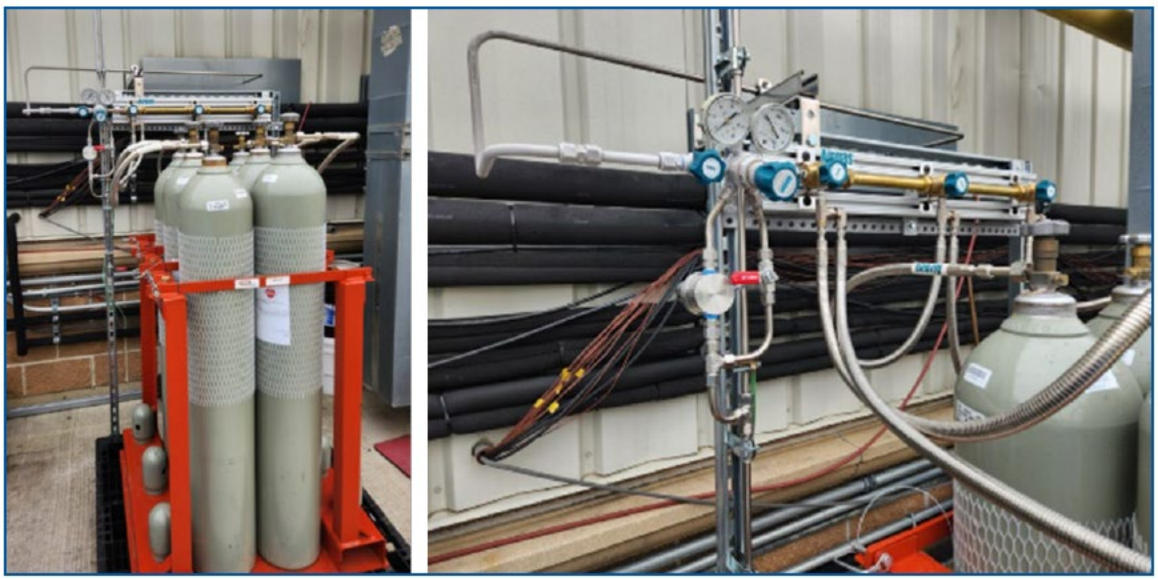
Figure 16: Exhaust Gas Constituents [left] and Manifold Pressure [right].

Hydrogen Blend System

When originally proposed, GTI Energy planned to use a blending station to test the GAHP A at 10%, 20%, and 30% blends (by volume, hydrogen to natural gas). However, the mixing station installation was delayed, and it was decided to test with pre-mixed cylinders provided by gas suppliers. Test cylinders were sourced from a gas supplier, with 10%, 20%, and 30% blends (by volume, hydrogen to methane). Testing with hydrogen/methane blends, rather than hydrogen/natural gas, is a slight variation of what would be experienced in the field, but allows consistent gas mixture, without the variations inherent in natural gas. For example, HHVs will be consistent based on blend concentration and independent of natural gas HHV variation. To perform the hydrogen blend testing, GTI Energy designed and installed the system as shown in Figure 2 and Figure 17.

The blend system has been installed and leak checked. Initial testing with a hydrogen blend has been performed. Dynamic pressure measured at the gas meter inside the environmental chamber and manifold pressure measured at the gas valve inside the GAHP will be tuned to the same measurements as the natural gas commissioning.

Figure 17: Installation of Cylinders, Manifold, and Pressure Regulator.



Appendix 2.0 Steady State Results

Table 12: Steady State Results Summary – Natural Gas.

Target Conditions			Test Results, 15-min average			Cycling Rates and Performance				
Outside Air Temp, °F	Flow Rate, gpm	Return Temp., °F	Outside Air Temp., °F	Flow Rate, gpm	Return Temp., °F	Heating Output, kBtu/h†	Thermal Input, kBtu/h†	Power, kW†	COP (Gas-Only)	COP (Gas + Electric)
44.6	13.6	104	44.0	13.6	103.8	130.81	99.4	0.98	1.32	1.27
17	13.6	120	18.3	13.7	119.3	95.37	100.9	1.02	0.94	0.91
35	13.6	120	35.1	13.6	119.6	109.30	98.5	1.01	1.11	1.07
47	13.6	120	45.3	13.6	119.7	117.71	97.3	1.00	1.21	1.17
75	13.6	120	72.5	13.6	120.0	129.96	95.5	0.97	1.36	1.32
90	13.6	120	88.9	13.6	119.9	132.03	93.9	0.95	1.41	1.36

Table 13: Steady State Results Summary – 10% Hydrogen Concentration.

Target Conditions			Test Results, 15-min average			Cycling Rates and Performance				
Outside Air Temp, °F	Flow Rate, gpm	Return Temp., °F	Outside Air Temp., °F	Flow Rate, gpm	Return Temp., °F	Heating Output, kBtu/h†	Thermal Input, kBtu/h†	Power, kW†	COP (Gas-Only)	COP (Gas + Electric)
17	13.6	120	17.1	13.6	119.9	90.6	97.2	1.01	0.93	0.90
35	13.6	120	34.5	13.6	119.7	107.6	96.9	1.00	1.11	1.07
47	13.6	120	46.9	13.6	120.1	114.8	94.0	0.98	1.22	1.18
75	13.6	120	75.6	13.6	119.9	125.2	91.8	0.95	1.36	1.32
90	13.6	120	89.6	13.6	120.1	126.4	90.6	0.93	1.39	1.35

Table 14: Steady State Results Summary – 20% Hydrogen Concentration.

Target Conditions			Test Results, 15-min average			Cycling Rates and Performance				
Outside Air Temp, °F	Flow Rate, gpm	Return Temp., °F	Outside Air Temp., °F	Flow Rate, gpm	Return Temp., °F	Heating Output, kBtu/h†	Thermal Input, kBtu/h†	Power, kW†	COP (Gas-Only)	COP (Gas + Electric)
17	13.6	120	18.9	13.7	119.5	88.65	93.8	1.02	0.94	0.91
35	13.6	120	35.0	13.6	119.5	102.64	92.2	1.00	1.11	1.07
47	13.6	120	47.5	13.6	119.8	110.48	91.2	0.98	1.21	1.17
75	13.6	120	74.7	13.6	120.0	119.74	89.2	0.95	1.34	1.29
90	13.6	120	89.1	13.6	120.0	121.55	87.9	0.94	1.38	1.33

Table 15: Steady State Results Summary – 30% Hydrogen Concentration.

Target Conditions			Test Results, 15-min average			Cycling Rates and Performance				
Outside Air Temp, °F	Flow Rate, gpm	Return Temp., °F	Outside Air Temp., °F	Flow Rate, gpm	Return Temp., °F	Heating Output, kBtu/h†	Thermal Input, kBtu/h†	Power, kW†	COP (Gas-Only)	COP (Gas + Electric)
17	13.6	120	19.6	13.5	119.5	84.78	92.1	1.01	0.92	0.89
35	13.6	120	33.7	13.5	119.5	98.16	90.5	0.99	1.08	1.05
47	13.6	120	48.1	13.5	119.7	106.78	89.3	0.97	1.20	1.15
75	13.6	120	75.2	13.5	120.0	116.83	87.5	0.94	1.34	1.29
90	13.6	120	89.5	13.5	119.9	119.25	86.3	0.93	1.38	1.33

Figure 18: GAHP A Steady State Capacities with Fixed OAT and Supply and Return Temperatures [6].

Table 1.3 *GAHP-A heat capacity [kBtu/hr]*

External air temperature (dry bulb) [°F]	Hot water outlet temperature [°F]			
	86	113	122	140
	ΔT = 18 °F			ΔT = 27 °F
-20.0	97.6	88.7	85.0	83.6
-13.0	98.6	89.7	86.0	84.6
-4.0	99.6	90.8	87.0	85.6
5.0	102.0	93.5	90.1	88.4
14.0	111.6	102.4	95.9	92.8
19.4	117.0	108.2	100.0	96.2
35.6	126.9	122.2	**114.0**	105.8
44.6	132.4	130.7	123.5	115.3
50.0	134.8	134.4	128.0	120.1
59.0	136.5	136.5	132.0	123.5
68.0	138.2	138.2	133.8	127.3
77.0	139.2	139.2	134.8	128.0

The highlighted value corresponds to the nominal heating capacity.

Appendix 3.0 Load Based Results

Table 16: Load-based Evaluation Test Results.

Test Results						Performance Results				
Hydrogen Blend Concentration	On Time, hr	Off Time, hr	OAT, °F	Flow Rate, gpm	RT, °F	Heating Output, kBtu/h	Thermal Input, kBtu/h	Power, kW	COP (Gas-Only)	COP (Gas + Electric)
NG	0.1	0.5	49.0	13.6	115.3	10.14	13.9	0.26	0.73	0.68
NG	0.2	0.5	47.6	13.6	115.3	25.73	25.7	0.37	1.00	0.95
NG	0.3	0.5	47.5	13.6	116.4	37.31	34.7	0.45	1.07	1.03
NG	0.5	0.5	46.3	13.6	117.6	53.34	47.5	0.56	1.12	1.08
NG	0.7	0.5	46.2	13.6	118.2	63.96	56.0	0.63	1.14	1.10
10%	0.1	0.5	48.5	13.6	114.3	10.86	13.4	0.25	0.81	0.76
10%	0.2	0.5	48.1	13.6	115.7	24.12	24.8	0.36	0.97	0.93
10%	0.3	0.5	47.9	13.6	116.4	35.48	33.6	0.43	1.06	1.01
10%	0.5	0.5	47.8	13.6	117.6	51.40	45.9	0.54	1.12	1.08
10%	0.7	0.5	47.1	13.6	118.2	61.68	53.8	0.61	1.15	1.10
20%	0.1	0.5	49.6	13.6	115.4	9.08	13.1	0.26	0.69	0.65
20%	0.2	0.5	48.5	13.5	115.1	24.12	24.2	0.36	1.00	0.95
20%	0.3	0.5	47.9	13.5	116.5	34.36	32.4	0.44	1.06	1.01
20%	0.5	0.5	47.4	13.5	117.6	50.16	44.3	0.55	1.13	1.09
20%	0.7	0.5	47.4	13.6	118.2	60.13	52.1	0.62	1.15	1.11
30%	0.1	0.5	49.5	13.4	113.6	9.10	12.7	0.25	0.72	0.67
30%	0.2	0.5	47.3	13.5	115.2	22.18	23.7	0.36	0.94	0.89
30%	0.3	0.5	47.6	13.5	116.4	33.04	31.6	0.44	1.05	1.00
30%	0.5	0.5	46.8	13.5	117.6	47.66	43.0	0.55	1.11	1.06
30%	0.7	0.5	46.7	13.5	118.2	57.44	50.5	0.62	1.14	1.09

Appendix 4.0 Energy Plus Modeling Coefficients

Table 17: Hydrogen Blend WI Ratio to Thermal Performance (Equation 9).

Blend	HHV, BTU/cf	Density, lbm/ft^3	Wobbe Index Ratio	Thermal Input Ratio	Thermal Output Ratio
NG	1056	0.045	1	1	1
10%	943.2	0.039	0.964	0.977	0.968
20%	874.4	0.035	0.926	0.932	0.931
30%	805.6	0.031	0.904	0.913	0.901

Table 18: CAPFT Coefficients (Equation 10).

Coefficients	Values
a1	-5.253E+01
b1	1.499E+00
c1	-6.346E-03
d1	-1.399E-02
e1	2.554E-04
f1	-5.878E-05
g1	4.319E-05
h1	-1.023E-06
i1	6.043E-08
j1	2.358E-08

Table 19: EIRFT Coefficients (Equation 12).

Coefficients	Values
a2	6.908E-01
b2	5.850E-05
c2	2.336E-05
d2	9.276E-03
e2	-1.612E-04
f2	6.896E-07

Table 20: EIRFPLR Values.

PLR	Values
1%	2.250
5%	1.700
10%	1.450
15%	1.250
20%	1.150
30%	1.070
50%	1.035
75%	1.020
100%	1.000

Table 21: $Aux_{Elec,EIRFT}$ Coefficients (Equation 16).

Coefficients	Values
a4	1.007E+00
b4	-7.961E-04
c4	-8.439E-06
d4	5.926E-08
e4	5.889E-04
f4	7.167E-07

Table 22: $Aux_{Elec,EIRFPLR}$ Coefficients (Equation 17).

Coefficients	Values
a5	8.421E-01
b5	1.714E-01

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