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Field Demonstration of Ground-Source Integrated Heat Pump – Part I. Technology and Field Demo System/Site Descriptions, and Preliminary Summer/Fall Performance Analysis for One Site

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OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE US DEPARTMENT OF ENERGY

ORNL/TM-2016/27

Energy and Transportation Science Division

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Preface

This is the first in a series of three reports for the Ground-Source Integrated Heat Pump (GS-IHP) demonstration project.

Report 1: *Field Demonstration of Ground-Source Integrated Heat Pump – Part I. Technology and Field Demo System/Site Descriptions, and Preliminary Summer/Fall Performance Analysis for One Site.*
This volume provides detailed descriptions of the two test sites and the GS-IHP demonstration system. One was located in Knoxville, TN and the second in Oklahoma City, OK. Both are in the small commercial category (under 10,000 ft^2 floor space). A description of the GS-IHP technology is also provided along with details of the measurement and performance analysis plans. Due to a protracted construction schedule for the Oklahoma City site, this report only includes preliminary summer/fall performance data and analysis for the Knoxville site.

Report 2: *Field Demonstration of Ground-Source Integrated Heat Pump – Part 2. Preliminary Winter/Spring Performance Analysis for Two Sites.*
The second volume is planned to provide preliminary heating and spring season performance comparisons for the GS-IHP vs. the baseline in both locations.

Report 3: *Field Demonstration of Ground-Source Integrated Heat Pump – Final Report*
This volume will include annual performance comparisons vs. the baseline to the extent possible. We anticipate that the Knoxville site will have sufficient data to perform an annual energy use estimate. A cost-effectiveness analysis of the GS-IHP vs. the baseline will be included as well.

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I. Executive Summary

ClimateMaster, Inc. (CM) and Oak Ridge National Laboratory (ORNL) jointly developed a new, highly efficient electric integrated HVAC and water heating (WH) system – the ground-source integrated heat pump (GS-IHP). The new GS-IHP system is a combination of a very highly efficient variable-speed (VS) water-source heat pump (WSHP) capable of space heating and cooling and domestic water heating coupled to a geothermal energy source/sink. Most often the geothermal source/sink is a closed-loop ground heat exchanger (GHX loop). The GS-IHP system was developed primarily for residential buildings and is expected to reduce space heating/cooling energy use by ≥50% and WH energy use by ≥75% for that application compared to minimum efficiency electric heat pump and WH systems.[1] GS-IHPs are estimated to have the potential to achieve ≥45% overall energy savings for small commercial buildings with similar building load profiles (e.g., relatively large DHW loads coincident with space heating and cooling loads). They could also reduce peak electric demand by 40% or more compared to the all electric baseline system depending on how coincident the peak air-conditioning and DHW loads are enabling reduced electric demand charges. Reduced electricity consumption would also have other benefits, such as lower NO_x and CO_2 emissions, and reduced water consumption.

Energy savings are achieved primarily by 1) use of the ground vs. outdoor air as the energy source/sink, 2) very efficient hot water production, and 3) its capacity modulation capability for space conditioning and WH. During most of the year and particularly during the peak HVAC load months the ground temperature is more favorable for heat pump operation than the outdoor air resulting in higher efficiency operation for the system. The system can meet DHW loads on demand year-round at heat pump COPs (2.5-3.0 or more), much higher than the maximum overall COP of ~0.9-0.95 that standard electric storage WHs can achieve. When space cooling and DHW demands coincide the GS-IHP system can meet both simultaneously at even higher COPs (5.0 or more). Compared to the single-speed electric RTU baseline, the VS capability of the GS-IHP system allows it to meet off-peak space conditioning (and DHW) demands at much increased efficiency and much reduced electric kW demand. Peak electricity demand is reduced by the same mechanisms.

Even with all these benefits, adoption has been limited due to (1) awareness of the technology which was only recently commercialized (2012) and (2) uncertainty about the relative costs and benefits. This project will address these challenges by (1) quantifying the environmental and energy impacts and costs of the GS-IHP compared to a conventional electric RTU/heat pump and WH; (2) disseminating this information through CBI strategic deployment, and (3) encouraging adoption of GHP-RTUs that provide greater energy savings so that building owners, managers and developers can make more informed choices. By providing funds for a field test of the unit, DOE aids in increasing awareness of this new technology to building owners.

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[1] *Ground-Source Integrated Heat Pump (GS-IHP) Development*, CRADA Final Report, CRADE NFE-07-0100, Oak Ridge National Laboratory, ORNL/TM-2013/194, May 2013.

A site selection evaluation was performed to identify suitable commercial building applications based on the HVAC and DHW load requirements. Based on the evaluation, CM in collaboration with ORNL selected two sites. The first was a commercial kitchen attached to a day care facility located in a large church building in Knoxville, TN (mixed humid climate). The second is a homeless shelter dormitory type building (~8,000 ft^2 total area) in Oklahoma City, OK – climate Zone 3A (warm-humid climate). CM installed GS-IHP systems at both sites. At the Knoxville site the GS-IHP provided HVAC and DHW services for a 463 ft^2 commercial kitchen and an adjoining 60 ft^2 pantry. The occupancy schedule is between 8:00 am to 5:00 pm Monday through Friday. The Oklahoma installation includes two GS-IHP systems each providing HVAC/WH to 10 residential units (total of ~2500 ft^2 each). Two other (non IHP) ground source heat pumps provide HVAC for common areas of the building. All four heat pump systems are connected to a common GHX loop. Only one of the GS-IHPs is instrumented and will be monitored in detail. The residential areas of the building are occupied 24/7.

A data acquisition (DAQ) system was designed and installed at the Knoxville site and will be installed at the Oklahoma City site. (Due to construction delays at the Oklahoma site DAQ installation there has been delayed until January 2016.) The DAQ system at the Knoxville site has been collecting data continuously since August 18, 2015. Data is collected at 15 second intervals, averaged into one minute intervals, and sent to a remote server at ORNL via the internet. An error analysis of the instrumentation was included to determine the overall sensor accuracy of the data collection. During the collection of data to date, the GS-IHP was operated as normal with a wall thermostat to control space heating and cooling operation, and a WH tank thermostat to control DHW operation.

The field study is planned to continue through the 2016 cooling season with the draft final project report due by September 30, 2016. This report provides a description of both installations and preliminary 2015 cooling and fall season performance results for the Knoxville site. For the August 18 through December 14 period, the Knoxville site GS-IHP provided 53.6% total source energy savings compared to a baseline electric RTU/heat pump and electric WH. Peak demand savings ranged from 33% to 59% per month. Energy cost savings of 53.1% have been achieved to date with more than half of that coming from reduced demand charges. Data on installation and maintenance costs are being collected and will be combined with total test period energy savings data for a payback analysis to be included in the project final report. The GS-IHP also saved a significant amount of carbon emissions. The total emission savings for the Knoxville site for the August-December 2015 period were ~0.8 metric tons. If trading for carbon credits ever becomes a reality, additional cost savings would be realized.

If deployed widely, GS-IHPs would significantly decrease energy consumption, energy costs, and emissions related to space conditioning and water heating for small commercial buildings and individual commercial building spaces having a good balance between total DHW loads and HVAC loads. Opportunities for deployment include new construction as well as replacements for failing equipment. Applied nationally to all appropriate commercial building spaces, GS-IHPs could save 0.084 quads of source energy vs. a 13 SEER RTU/heat pump and electric WH baseline. The actual utility bill savings for a building owner will depend on a number of factors, most notably the building’s climate region, HVAC and DHW load profiles, and regional utility rates.

The suitability and economics of GS-IHP systems for the small commercial building application will be evaluated and the analyses reported in the final project report (due September 30).

II. Introduction

A. Problem Statement

Reducing energy consumption in buildings is key to reducing or limiting the negative environmental impacts from the building sector. According to the United States (U.S.) Energy Information Administration (EIA), in 2012, commercial buildings consumed 18.1 quads[2] of primary energy, which was 18.6% of the total U.S. primary energy consumption.[3] The primary energy consumption in the commercial sector is projected to increase by 2.8 quads from 2013 to 2040, the second largest increase after the industrial sector.[4] Further space heating, space cooling, and ventilation (HVAC) services accounted for 31% of the energy consumption in commercial buildings.[5] Small commercial buildings (≤10,000 ft^2 floor space) represent about 21% of the commercial floor space in the United States.[6] Many such buildings (and defined spaces within larger commercial and institutional buildings) also have significant domestic hot water (DHW) loads, such as restaurants, laundry facilities, health & fitness centers, etc. The all-electric subset of small commercial buildings consumes approximately 0.160 Quads of primary electricity energy annually for HVAC and WH services.[7]

More than half of U.S. commercial building space is cooled by packaged HVAC equipment, most of which are rooftop units with less than 50 tons of cooling capacity.[8] Existing rooftop HVAC units consume more than 1.3% of total U.S. energy annually.[9] Rooftop units are popular because they are inexpensive, provide zonal control, are easy to install, and can be serviced without disrupting occupants. Given their advantages, their large market share will likely continue.

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[2] Quadrillion (10^{15}) Btus.

[3] U.S. Energy Information Administration, Annual Energy Outlook 2015, available online at http://www.eia.gov/forecasts/aeo

[4] U.S. Energy Information Administration, Annual Energy Outlook 2015, available online at http://www.eia.gov/forecasts/aeo

[5] U.S. Energy Information Administration, Annual Energy Outlook 2015, available online at http://www.eia.gov/forecasts/aeo

[6] EIA, CBECS 2003 Table C1, the percent commercial floor space in buildings ≤10,000 ft^2 (total floor space in buildings ≤10,000 ft^2 / total building floor space), http://www.eia.gov/consumption/commercial/data/archive/cbecs/cbecs2003/detailed_tables_2003/2003set9/2003html/c1.html

[7] EIA, CBECS 2003 Table E3, electricity consumption by end use for non-mall buildings, http://www.eia.gov/consumption/commercial/data/archive/cbecs/cbecs2003/detailed_tables_2003/2003set19/2003html/e03.html

[8] Shen, B. and Rice, C.K., “Next generation rooftop unit (RTU) development – final report”, ORNL/TM-2015, Oak Ridge National Laboratory, 2015.

[9] Shen, B. and Rice, C.K., “Next generation rooftop unit (RTU) development – final report”, ORNL/TM-2015, Oak Ridge National Laboratory, 2015.

Today's RTUs are inefficient for a host of reasons. Many are oversized to handle peak ambient temperatures. Undersized/dirty evaporator coils reduce compressor efficiency. Capacity is also wasted by over-drying indoor air in dry climates. Single-speed blowers run for ventilation during all occupied hours, using about half of annual rooftop unit energy. Improving their operational efficiency is essential for enhancing overall commercial building energy performance. Recent advancements in component technology enable inefficiencies to be reduced. Conventional storage WHs particularly electric WHs are approaching thermodynamic limits to their efficiency potential. Storage WHs of the type used in small commercial buildings are subject to DOE minimum efficiency requirements. For instance, a 50 gallon electric WH must have an energy factor (EF, an annual efficiency metric) of ≥0.94. Significant increases in WH efficiency will need to come from use of heat pumping technologies; either combined or integrated heat pumps (IHP) or standalone heat pump water heaters (HWPH).

ClimateMaster, Inc. (CM) and Oak Ridge National Laboratory (ORNL) jointly developed a new, highly efficient electric integrated HVAC and water heating (WH) system – the ground-source integrated heat pump (GS-IHP). The new GS-IHP system is a combination of a very highly efficient variable-speed (VS) water-source heat pump (WSHP) capable of space heating and cooling and domestic water heating coupled to a geothermal energy source/sink. Most often the geothermal source/sink is a closed-loop ground heat exchanger (GHX loop).

The WSHP unit was tested at Air-conditioning, Heating, and Refrigeration Institute (AHRI) standard conditions[10] and achieved the highest rated efficiencies of any commercially available WSHP unit - heating coefficients of performance (COP) of 5.1 and 3.3 at minimum and maximum speeds, respectively, and cooling energy efficiency ratios (EER) of 45.1 and 21.6 at min and max speeds.[11] Because tests at standard conditions do not represent the "true" seasonal energy efficiency, field tests and demonstrations are needed to show the potential savings potential of the GS-IHP. Field demonstrations provides performance comparisons in "real" conditions and allow for: 1) comparison of annual energy savings of the GS-IHP to a standard efficiency electric rooftop unit heat pump (RTU/heat pump) and electric WH; 2) identification of non- performance related issues, such as maintenance requirements; and 3) capturing lessons learned and how-to guidance in a concise case study for market deployment.

B. Opportunity

The GS-IHP system was developed primarily for residential buildings and is expected to reduce space heating/cooling energy use by ≥50% and WH energy use by ≥75% for that application compared to

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[10] Air-conditioning, Heating, and Refrigeration Institute, ANSI/AHRI/ASHRAE/ISO Standard 13256-1, "*Water-to-Air and Brine-to-Air Heat Pumps — Testing and Rating for Performance,*" 1998.
[11] ClimateMaster catalog for Trilogy Q-mode (QE) series water source heat pump products, September 2014.

minimum efficiency electric heat pump and WH systems.[12] GS-IHPs are estimated to have the potential to achieve ≥45% overall energy savings for small commercial buildings or special purpose spaces within larger buildings with similar building load profiles (restaurants, commercial/institutional building kitchen facilities, hotel/motel/dormitory type buildings, laundry facilities, health/fitness centers, etc.). They could also reduce peak electric demand by 40% or more compared to the baseline electric system depending on how coincident the peak air-conditioning and WH loads are enabling reduced electric demand charges. Reduced electricity consumption would also have other benefits for power plants, such as lower NO_x and CO_2 emissions, and reduced cooling water consumption. Even with all these benefits however, adoption has been limited due to (1) awareness of the technology which was only recently commercialized (2012) and (2) uncertainty about the relative costs and benefits. This project will address these challenges by (1) quantifying the energy savings and costs of the GS-IHP compared to the minimum efficiency electric baseline system; (2) disseminating this information through strategic deployment channels, and (3) encouraging adoption of GS-IHPs that provide greater energy savings so that building owners, managers and developers can make more informed choices.

Energy savings are achieved primarily by very efficient hot water production and its capacity modulation capability for space conditioning and WH. The system can meet WH loads on demand year-round at heat pump COPs (2.5-3.0 or more), much higher than the maximum overall COP of ~0.9 that standard electric storage WHs can achieve. Additionally, coincident WH and space cooling demands can be met simultaneously at even higher COPs (5.0 or more). Compared to the single-speed electric RTU baseline, the VS capability of the GS-IHP system allows it to meet part-load space conditioning (and WH) demands at much increased efficiency and much reduced electric kW demand. Peak electricity demand is reduced by the same mechanisms. By meeting the technical project objectives, life cycle costs will be more favorable, compared to traditional HVAC and WH equipment, as the result of reduced energy costs.

C. Technical Objectives

The technical objective of this project is to demonstrate the capability of a new ground-source integrated heat pump (GS-IHP) system to reduce overall energy use for space heating, space cooling, and water heating by at least 45% vs. a conventional electric RTU and electric WH in a light commercial building application. This project supports the DOE-BTO goals of reducing HVAC energy use by 20% and water heating by 60%.

[12] *Ground-Source Integrated Heat Pump (GS-IHP) Development*, CRADA Final Report, CRADE NFE-07-0100, Oak Ridge National Laboratory, ORNL/TM-2013/194, May 2013.

D. Technology Description

The demonstrated GS-IHP system is comprised of a nominal 4-ton (cooling) WSHP packaged unit coupled to an external geothermal source/sink system and a domestic hot water (DHW) storage tank. For the demonstration systems in this study the geothermal system was a closed-loop ground heat exchanger (GHX loop). Other geothermal source/sink systems are possible as well – e.g., closed-loop heat exchanger submerged in a pond, lake, or river; etc. The WSHP package was CM's Trilogy 45 Qmode IHP product (http://www.climatemaster.com/residential/climatemaster-trilogy-45-mode-series-heat-pump/). Table 1 summarizes the Trilogy/GS-IHP system rated/design performance compared to that of a conventional electric RTU/heat pump with a conventional electric storage water heater (WH).

The Trilogy WSHP features a variable-speed (VS) compressor along with a VS blower for indoor air circulation and VS pumps for GHX loop and DHW loop circulation. The system provides variable space cooling, space heating, and water heating capacity as needed by modulating over set point temperature ranges. Four different operating modes are available as listed below:

- Space cooling (factory set at 1½ to 4 tons for 4-ton size unit; installer adjustable to maximum 5 ton capacity)
- Space heating (1½ to 5 tons for 4-ton size unit)
- Combined WH plus space cooling
- Dedicated water heating year-round

In addition, the VS compressor and blower allow the unit to increase/decrease dehumidification (moisture removal) capacity as needed in response to space RH level when in space cooling modes to maintain comfort levels in the conditioned without sacrificing efficiency. Similarly the air delivery temperature can be adjusted as needed in space heating mode. Compact HX designs are used for the air/refrigerant space heating/cooling coil and the GHX loop/refrigerant and hot water/refrigerant coils. This reduces the required system refrigerant charge and associated environmental risks.

The Trilogy systems include a "smart" hot water tank which includes electric elements for back-up or emergency water heating and HW fittings to minimize mixing of tank water during heat pump WH operation in order to maintain tank stratification. Tank controls are integrated with the heat pump unit controls.[13]

Table 1. Summary of GS-IHP versus conventional RTU + Electric Storage WH

	Base (electric RTU/heat pump & WH)	GS-IHP
Compressor/number	Scroll/1-speed	Scroll/variable speed
Refrigerant type	R410A	R410A
Design Cooling rating	48,000 Btu/hr at 95°F outdoor temp[a]	18,000 Btu/hr @ min speed[b] 48,000 Btu/hr @ max speed[b]

[13] ClimateMaster, Inc. product brochure, "Trilogy® 45 Geothermal Systems," March 2015.

	Base (electric RTU/heat pump & WH)	GS-IHP
Design Heating rating	45,000 Btu/hr at 47°F outdoor temp[a] 28,000 Btu/hr at 17°F outdoor temp[a]	24,000 Btu/hr @ min speed[b] 60,000 Btu/hr @ max speed[b]
Design water heating capacity; dedicated WH	4.5 kW (conventional electric WH)	~28,000 Btu/hr, low speed ~40,000 Btu/h, high speed (110°F entering HW temperature; 35-80°F entering water temperature from GHX loop)[c]
Design cooling plus WH capacity; combined mode	na	18,000 Btu/hr cooling + 24,000 Btu/hr WH, low speed 48,000 Btu/hr cooling + 69,000 Btu/hr WH, high speed (110°F entering HW temperature)[c]
Rated cooling efficiency	11.4 EER at 95°F outdoor temperature[a] 13.0 SEER[a]	45.1 EER @ min speed[b] 21.6 EER @ max speed[b]
Rated heating efficiency	3.05 COP at 47°F outdoor temperature[a] 2.26 COP at 17°F outdoor temperature[a]	5.1 COP @ min speed[b] 3.3 COP @ max speed[b]
Design water heating efficiency; dedicated WH	1.0 COP (conventional electric WH)	2.5-5.0 COP (110°F entering HW temperature; 35-80°F entering water temperature from GHX loop)[c]
Design cooling plus WH efficiency; combined mode	na	Up to 30 EER combined, low speed Up to 19 EER combined, high speed (110°F entering HW temperature)[c]
Unit dimension (in)	45 L X 47 H X 76 W	25.4 L X 56 H X 30.6 W
Unit weight	590 lb, RTU	448 lb, Trilogy WSHP
Electrical	13.0 kW, RTU 4.5 kW, WH tank	8.5 kW, heat pump unit 4.5 kW, WH tank

[a]Certified per ANSI/AHRI Standard 210/240

[b]Certified per ANSI/AHRI/ISO/ASHRAE Standard 13256-1

[c]ClimateMaster product catalog [September, 2014]

III. Project Scope

A new technology (GS-IHP) based on a DOE funded concept development is estimated to reduce both site and source energy consumption for HVAC and water heating (WH) by at least 45% overall compared to minimum efficiency electric HVAC/WH systems. This would also have other benefits, such as reduced electrical demand and lower NO_X and CO_2 emissions associated with the lower electricity consumption. Even with all these benefits, adoption has been limited due to (1) awareness of the technology which was only recently commercialized (2012) and (2) uncertainty about the relative costs and benefits. This project will address these challenges by (1) quantifying the environmental and energy impacts and costs of the GS-IHP compared to a conventional electric RTU and electric WH; (2) disseminating this information through CBI strategic deployment, and (3) encouraging adoption of the technology so that building owners, managers and developers can make more informed choices.

This report is not intended to be used as a recommendation for using a GS-IHP based purely on the current results; rather this report emphasizes the potential savings opportunities when favorable conditions exist. When selecting HVAC equipment for particular applications, additional considerations of applicability, installation methods, electricity and gas costs, necessity for water heating, etc., are needed.

IV. Project Approach

A. Field Site Selection and Installation

A site selection evaluation was performed to identify suitable commercial building applications based on the HVAC and water heating load requirements. Based on the evaluation, CM in collaboration with ORNL selected two sites. The first was a commercial kitchen attached to a day care facility located in a large church building in Knoxville, TN. Knoxville is located in climate Zone 4A (Mixed-Humid per Figure 1 and Table 2 below). The second is a homeless shelter dormitory type building (~8,000 ft^2 total floor space) in Oklahoma City, OK – climate Zone 3A (Warm-Humid). CM and its subcontractors (City Heat & Air of Knoxville and Comfortworks, Inc. of Oklahoma City) designed and installed GS-IHP systems at both sites based on their Trilogy 45 IHP Qmode product. Figures 2-10 provide photos and GHX schematics for the two installations. At the Knoxville site (Figures 2-6) a single GS-IHP provided HVAC and DHW services for the 463 ft^2 kitchen and adjoining 60 ft^2 pantry. The occupancy schedule is between 8:00 am to 5:00 pm Monday through Friday. The Oklahoma installation (Figures 7-10) includes two Trilogy-based GS-IHP systems each providing HVAC/WH to 10 residential units (total of ~2500 ft^2 each). Two other (non IHP) ground source heat pumps provide HVAC for common areas of the building. All four heat pump systems are connected to a common GHX loop. Only one of the GS-IHPs is instrumented and will be monitored in detail. The residential areas of the building are occupied 24/7.

There were strong advocates onsite to serve as the primary point of contact with access to the space, equipment, and operations. The areas or spaces being considered for demonstration are representative of the conditions and functions for the expected application of the technology.

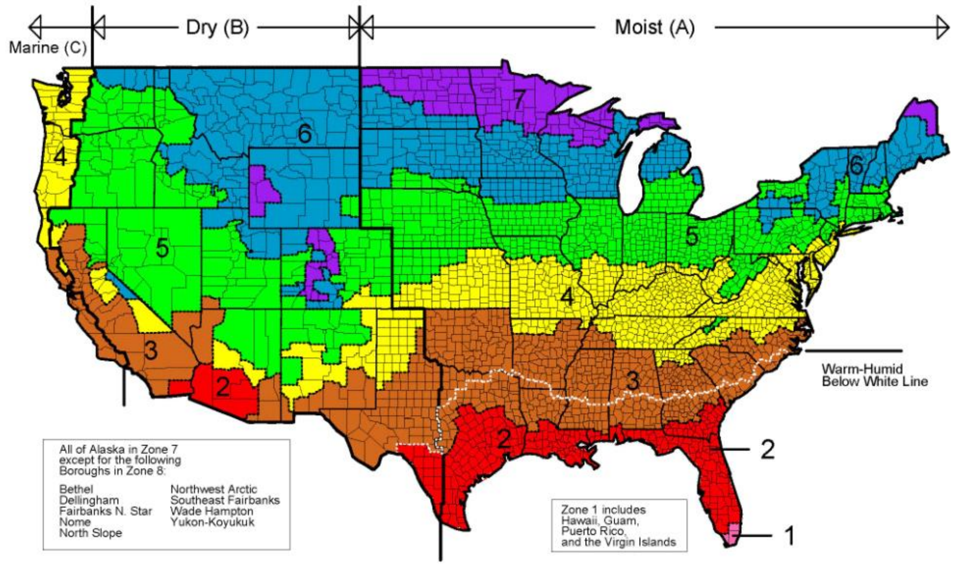

Figure 1. Map of USA climate zones (Source: ANSI/ASHRAE/IESNA Standard 90.1-2007)

Table 2. Description of USA climate zones (Source: ANSI/ASHRAE/IESNA Standard 90.1-2007)

Zone Number	Name	Thermal Criteria
1	Very Hot – Humid (1A), Dry (1B)	5000 < CDD10°C
2	Hot – Humid (2A), Dry (2B)	3500 < CDD10°C ≤ 5000
3A and 3B	Warm – Humid (3A), Dry (3B)	2500 < CDD10°C ≤ 3500
3C	Warm – Marine	CDD10°C 2500 AND* HDD18°C 2000
4A and 4B	Mixed – Humid (4A), Dry (4B)	CDD10°C ≤ 2500 AND 2000 < HDD18°C ≤ 3000
4C	Mixed – Marine	2000 < HDD18°C ≤ 3000
5A, 5B and 5C	Cool– Humid (5A), Dry (5B), Marine (5C)	3000 < HDD18°C ≤ 4000
6A and 6B	Cold – Humid (6A), Dry (6B)	4000 < HDD18°C ≤ 5000
7	Very Cold	5000 < HDD18°C ≤ 7000
8	Subarctic	7000 < HDD18 °C

*CDD (cooling degree C-days) ≤2500 AND HDD (heating degree-C days) ≤2000

Figure 2. Aerial view of the Knoxville, TN test site (Photo source: Google Maps)

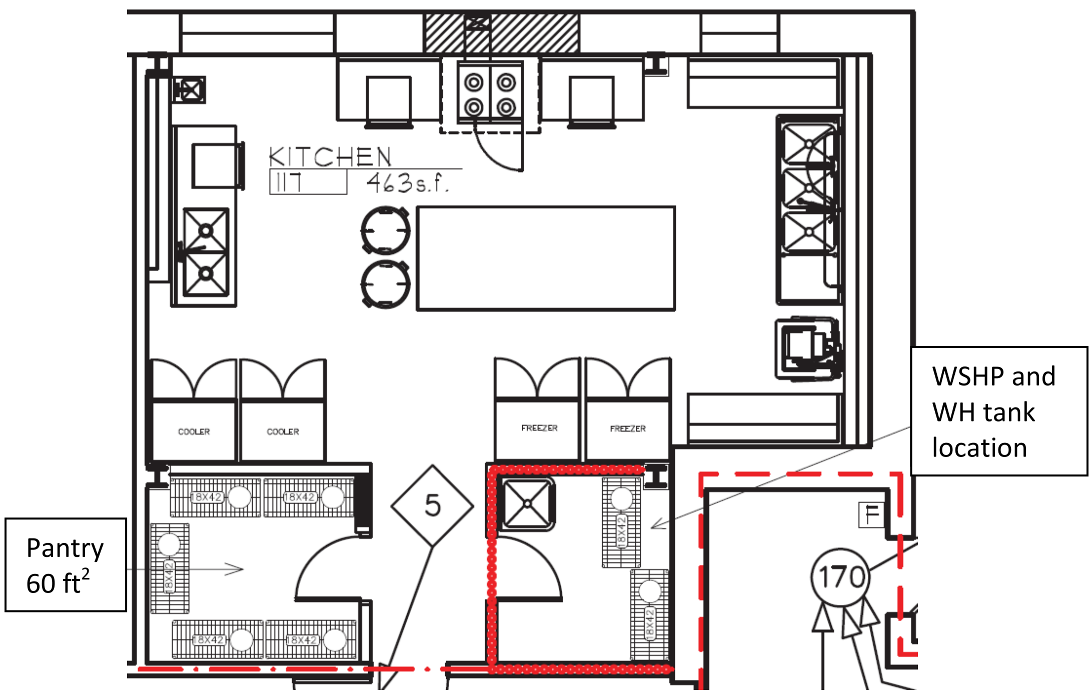

Figure 3. Kitchen floor plan, Knoxville, TN test site

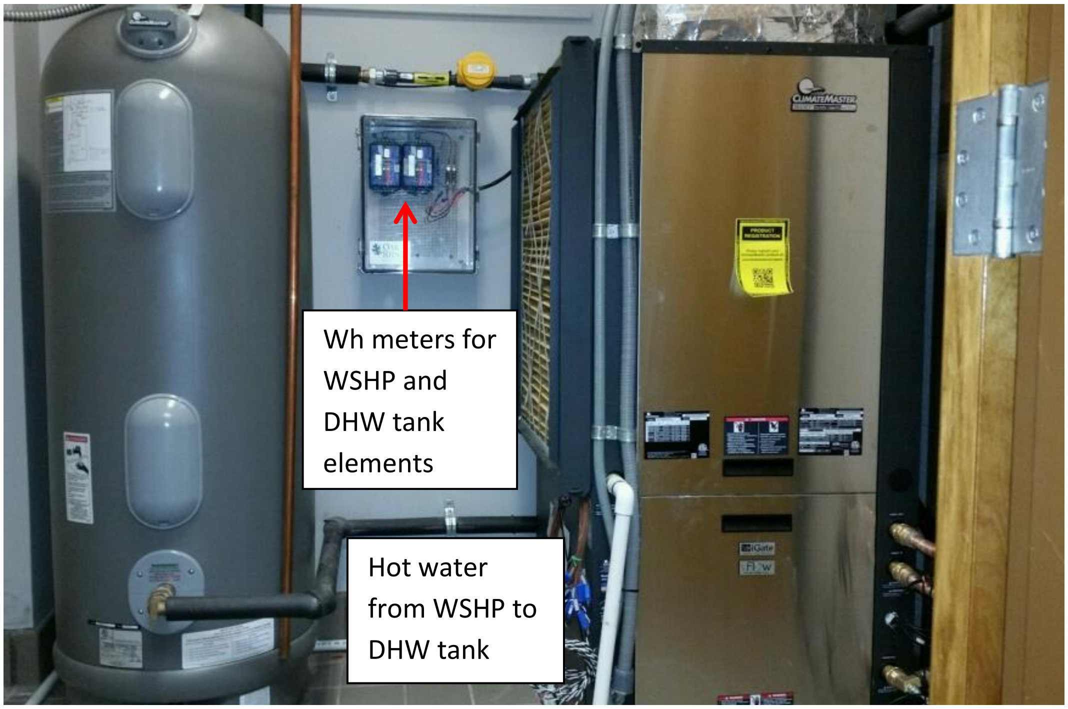

Figure 4. Trilogy WSHP system as installed at the Knoxville, TN test site

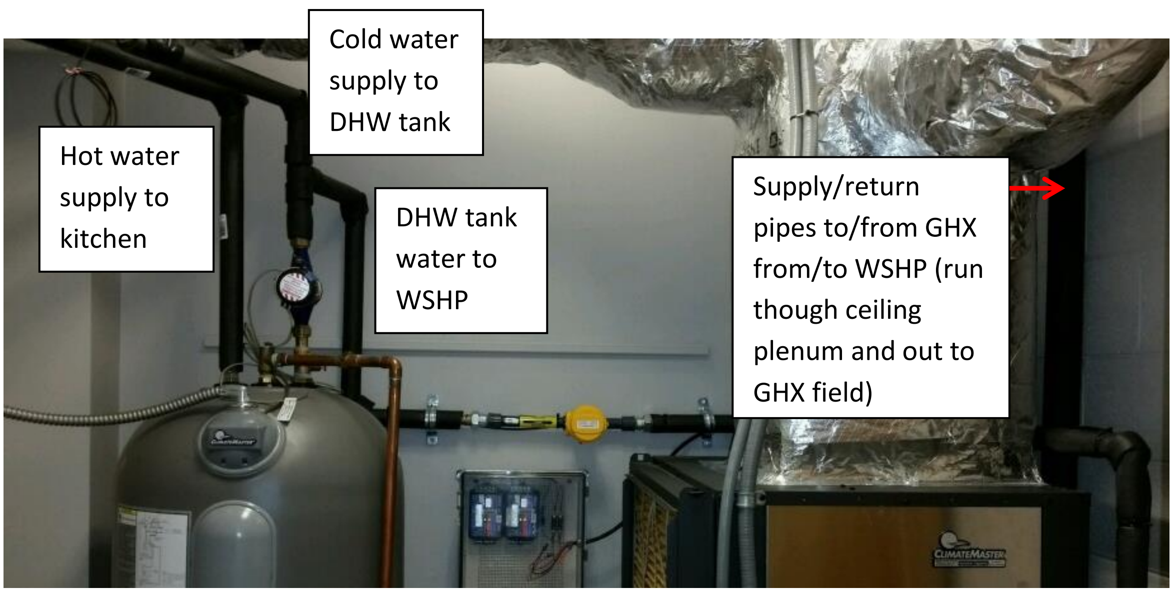

Figure 5. WH piping connections and flowmeters at Knoxville site.

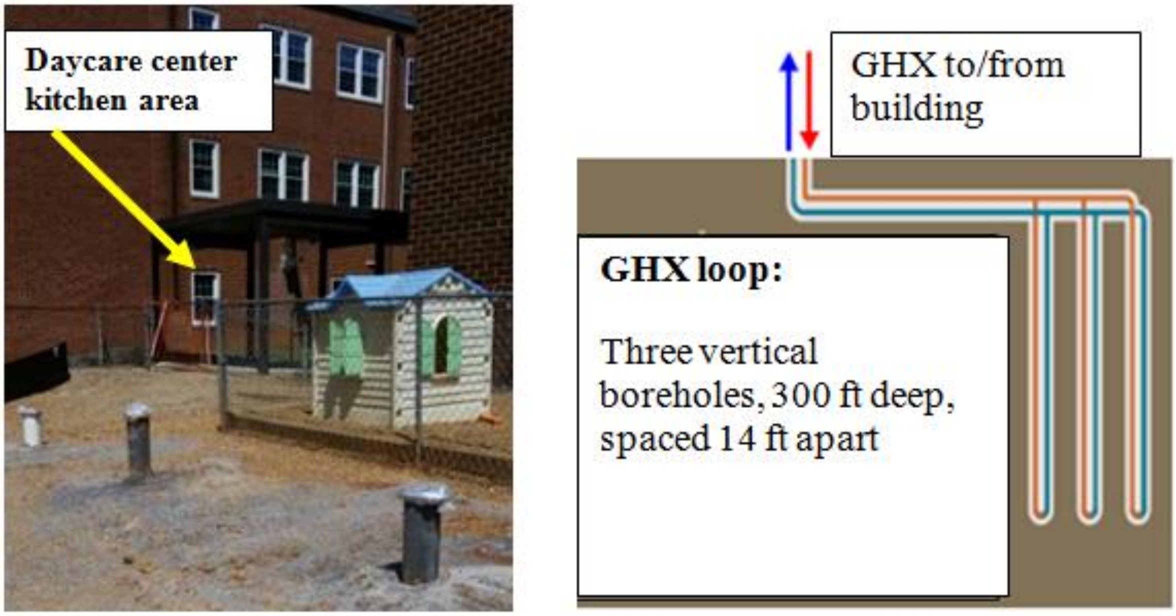

Figure 6. GHX loop location and schematic for Knoxville, TN test site (graphic source: ClimateMaster)

Figure 7. Oklahoma City, OK test site host building

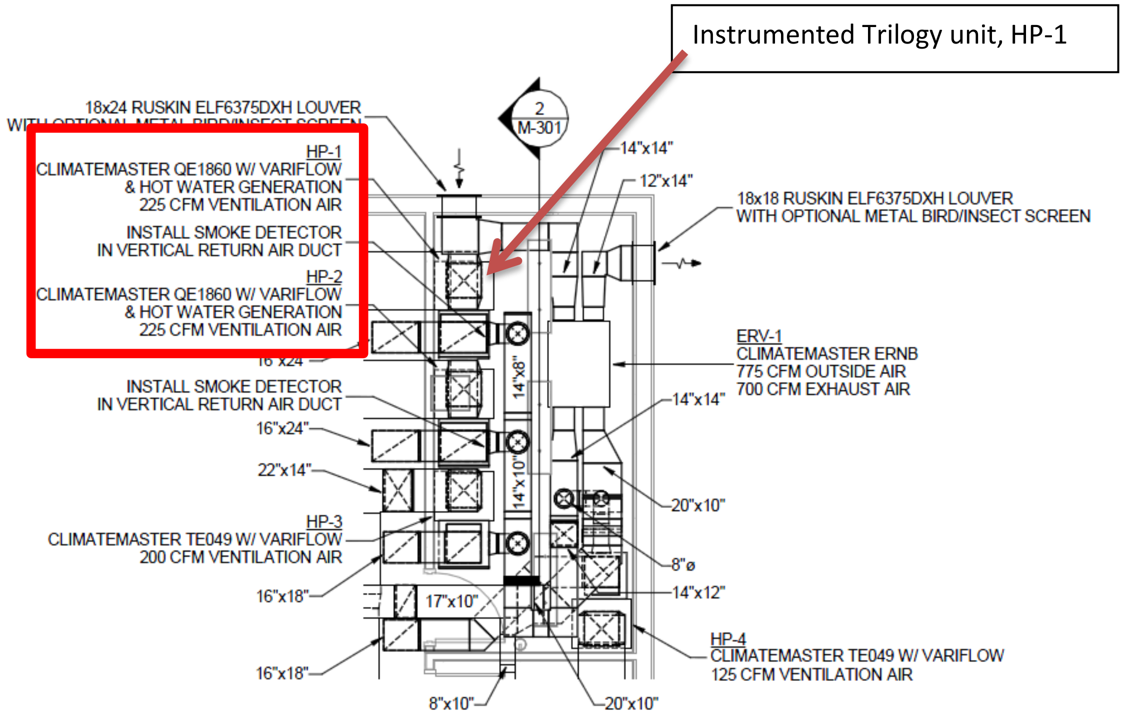

Figure 8. Oklahoma City, OK building mechanical room floor plan; Trilogy units are HP-1 and HP-2 (Source: ClimateMaster)

Figure 9. Oklahoma City host building mechanical room; instrumented Trilogy is on rh side against back wall; Trilogy HW tanks at left (Source: ClimateMaster)

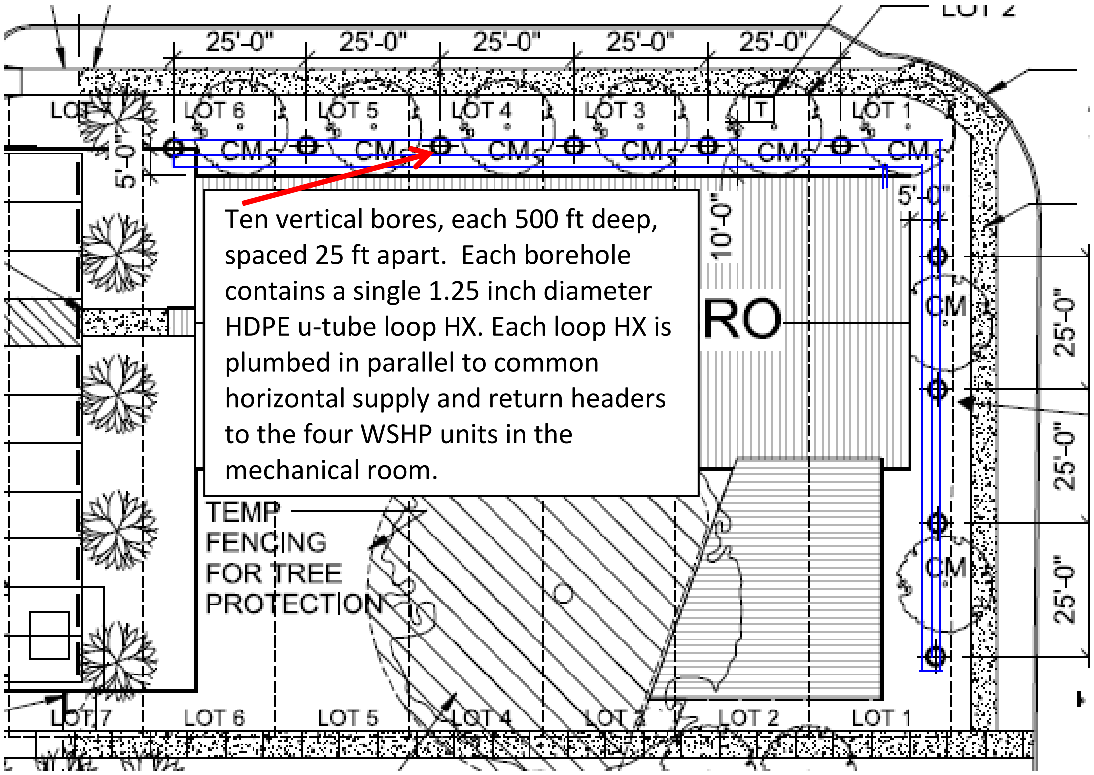

Figure 10. GHX loop location and details for Oklahoma City, OK test site (Source: ClimateMaster)

E. Metering and Monitoring Plan

The test systems have been installed and commissioned to ensure proper operation at both sites. A data acquisition (DAQ) system was designed and installed at the Knoxville site and will be installed at the Oklahoma City site. (Due to construction delays at the Oklahoma site DAQ installation there has been delayed until January 2016.) The DAQ system at the Knoxville site has been collecting data continuously since August 18, 2015. Data is collected at 15 second intervals, averaged into one minute intervals, and sent to a remote server at ORNL via the internet. An error analysis of the instrumentation (Table 3) was included to determine the overall sensor accuracy of the data collection. During the collection of data, the GS-IHP was operated as normal with a wall thermostat to control space heating and cooling operation, and a WH tank thermostat to control WH operation.

Table 3. Instrumentation

Monitoring point	Manufacturer	Model No.	Error
Trilogy WSHP unit & WH tank element Watts	Continental Control Systems	WattNode models WNC-3Y-208-MB and WNB-3Y-208-P, respectively	±0.5% W reading for 5-100% rated current (±1% of reading for 1-5% rated current)
Line voltage	Continental Control Systems	WattNode model WNC-3Y-208-MB	±0.5% V reading
Supply/Return Temperatures, Trilogy to/from GHX loop	Omega	PM-1/10-1/8-6-1/8-P-3; platinum resistance temperature device (RTD), immersion	±(0.03 + 0.0005 |t|)°C From **0 to 100°C**[a]
Supply/Return Temperatures, Trilogy to/from DHW tank	Omega	PM-1/10-1/8-6-1/8-P-3; platinum RTD, immersion	±(0.03 + 0.0005t)°C From **0 to 100°C**[a]
Supply/Return Temperatures, DHW tank to/from building HW distribution network	Omega	PM-1/10-1/8-6-1/8-P-3; platinum RTD, immersion type	±(0.03 + 0.0005t)°C From **0 to 100°C**[a]
Flow; GHX loop	Omega	FMG3001-PP	±0.8%, max[b] (~1-20 gpm)
Flow, DHW tank loop	Omega	FMG3001-PP	±0.8%, max[b] (~1-10 gpm)
Flow, building water supply to DHW tank	Omega	FTB8007B-PT	±1.5% (0.22-22 gpm)
ID space temperature	Trilogy onboard sensor	Thermistor included with CM thermostat	±0.56 °C (±1.0°F)
ID space RH (%)	Trilogy onboard sensor	Johnson Controls model HT-6703	±3 %RH
Temperature in/out Trilogy air coil	Omega	Type T TC	0.75% Full Scale
RH% in/out Trilogy air coil	Omega	HX92AC-D	±2.5% RH from 20 to 80% RH; ±3.1% RH below 20 and above 80% RH @ 22°C with temp coefficient of ±0.1% RH/°F Output
Ambient Temp	Local airport weather data	Ecobee web site accessed via Trilogy control system	na

[a]All RTDs underwent 5 point calibration over expected temperature operating range (30 to 140 °F) against NIST traceable thermometer; linear fit to temperature standard with R^2 of 1.000.
[b]Results of factory calibration against NIST traceable standard over expected operating flow ranges.

Figure 11 shows a schematic of the GS-IHP system, including the critical sensor locations.

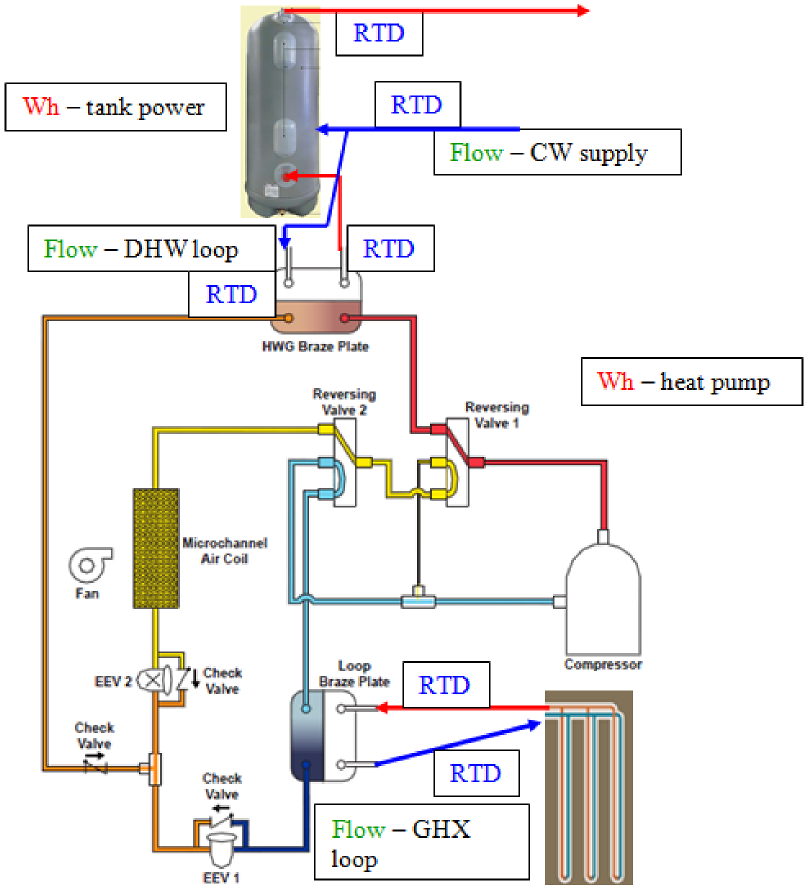

Figure 11. GS-IHP schematic with critical sensor locations (Graphic source: ClimateMaster)

ORNL pulls the data files from the test sites and stores them on file storage resources at ORNL. The data is subsequently loaded into a searchable database. This facilitates access to the data since it can be queried on any number of constraints (i.e., date ranges, parameter values, etc.) by most data analysis packages. MATLAB and Excel were used to analyze the data for this report.

A log was maintained at the site of any performance-related issues such as failure to start, failure to maintain indoor air temperatures, or loss of refrigerant charge. Cost data (for repair, installation, and any routine maintenance) are being collected and will be used for the cost analyses to be included in the project final report (due September 30, 2015).

F. Energy Savings Estimation Approach

The goal of the GS-IHP demonstration is to estimate its annual energy savings and costs versus a standard efficiency electric RTU and electric water heater.

The site measured data (loop temperatures and flow rates) are post-processed and used to compute space heating, space cooling, and water heating energy loads delivered by the GS-IHP for each mode using the equations below. These calculated values are stored along with the measured data for each 15-second data scan.

Space cooling delivered (SC Mode)

$$Q_{SC} = V_{GroundLoop}\rho_{GroundLoop}c_{GroundLoop}(LWT - EWT) - W_{IHP}$$

Space cooling delivered (SC +WH Mode)

$$Q_{SC} = Q_{WH,IHP} - W_{IHP}$$

Space heating delivered

$$Q_{SH} = V_{GroundLoop}\rho_{GroundLoop}c_{GroundLoop}(EWT - LWT) + W_{IHP}$$

Water heating delivered by IHP

$$Q_{WH,IHP} = V_{DHWLoop}\rho_{DHWLoop}c_{DHWLoop}(LDHWT - EDHWT)$$

Water heating delivered to building

$$Q_{WH} = V_{Hot}\rho_{Hot}c_{Hot}(T_{Hot}{}^{a} - T_{Cold}) + Wtank$$

([a]Due to the numerous small volume hot water draws and the response time of the hot water temperature sensor, T_{Hot} was taken to be the tank temperature measured at the upper element.)

Where –

- EWT: GHX loop fluid temperature entering WSHP (RTD)
- LWT: GHX loop fluid temperature leaving WSHP (RTD)
- $EDHWT$: domestic hot water temperature entering WSHP (RTD)
- $LDHWT$: domestic hot water temperature leaving WSHP (RTD)
- T_{Cold}: cold water supply temperature to WH tank (RTD)
- T_{Hot}: WH tank wall temperature at upper element location (type T thermocouple)
- V: fluid flow rate
- ρ: fluid density
- c: fluid specific heat

Energy consumption for the GS-IHP is measured directly by two watt-hr meters, one for the Trilogy unit (W_{IHP}) and one for the WH tank back up elements (W_{tank}). The energy consumption is apportioned to each operating mode by a data analysis program and stored along with the loads data for each time step.

The energy delivery and measured energy use for the GS-IHP in each mode are totaled for each month/season and compared with the estimated energy used by the baseline RTU/electric WH to meet the same loads. Energy savings and carbon emission reductions for the GS-IHP are computed as the difference in these values vs. the Baseline.

G. Cost Savings Approach

The electricity rates for the test sites along with the measured energy use of the GS-IHP and the estimated energy use of the baseline system are used to determine annual energy related costs. In addition, an estimate of demand charges for both systems is calculated based on the measured hourly energy use of the GS-IHP and the estimated hourly energy use of the baseline system. Annual energy savings for the GS-IHP are estimated from the differences in these two metrics.

H. Installation Cost

Actual system installation cost data are being compiled for each site and will be included with the final project report. In addition to the actual cost an estimated “mature market” installation cost estimate will be made for use in a payback analysis for the final project report.

I. GS-IHP Control Verification, Performance-Related Issues, and Installation and Maintenance

The Trilogy WSHP for the GS-IHP system includes an advanced, onboard control system that features VS compressor, indoor blower, GHX loop pump, and DHW loop pump capability. It also features recovery of normally rejected heat from the space cooling operation to provide domestic hot water for the building and year-round water heating capability at heat pump efficiency levels. These control strategies have successfully enabled the Knoxville system to function as designed and maintain space and hot water temperatures in the building with no complaints.

The only reported maintenance issue for the Knoxville site was failure of a main system control board at installation. CM provided a replacement board under warranty within a week and no further issues were encountered. There have been no reported installation/maintenance issues for the Oklahoma City site.

The only routine maintenance required for the Trilogy unit is air filter change out twice per year at an estimated cost of $40 each change ($80/y).

The major variable impacting GS-IHP system installation cost is the external geothermal heat source/sink. As noted earlier, in most cases this involves drilling/excavation and installation of a GHX loop (usually of the vertical bore field type). For the Knoxville site, two "out of normal" installation issues were experienced. First the space available for the GHX field was limited such that the individual boreholes had to be spaced at 14 ft apart instead of CM's normally recommended 20 ft spacing. This did not impact installation cost but could impact long term performance if the annual loads on the loop are significantly unbalanced (e.g. annual heat rejection to the ground is much greater than annual heat extraction). The other issue was that the ground HX header piping connecting to the WSHP had to be partly exposed to ambient air. This was because it was not possible to run headers completely under the building to the WSHP location next to the kitchen facility in the building. The header piping had to be run up the outside wall and then through a ceiling plenum above the WSHP (see Figure 12, below, and Figure 5). This situation occurs only rarely in the experience of the installing contractors. It required that an antifreeze solution be added to the water in the GHX loop in early January 2016 to avoid any potential loop freeze problems. This added an estimated $700 to the system cost (cost of the antifreeze plus additional site visit) No "out of normal" GHX installation issues occurred for the Oklahoma City site.

Figure 12. GHX loop headers attached to wall outside kitchen facility, Knoxville site

V. Preliminary Results – Knoxville site

Table 4 summarizes the overall GS-IHP performance monitoring results for the period of 8/18/2015 to 12/14/2015 along with the assumptions/limitations of the comparison. For the August to December period, no space heating operation was required at the Knoxville site.

Table 4. GS-IHP summary performance comparison vs. baseline system

	GS-IHP	Baseline RTU + electric WH
Space Cooling (from SC and SC+WH modes)		
Total Space Cooling Delivered (kWh)	5943	5943
Sensible Cooling Delivered (kWh)	~4946	--
Sensible heat ratio (SHR)	~0.832	
Space Cooling Energy Use (kWh)	766	1382
Space Cooling COP	7.75	4.30
Water Heating (from demand WH and SC+WH modes)		
WH output from WSHP to WH tank (kWh)	863	--
Water Heating Delivered to Building (kWh)	703	703
Total Water Heating Energy Use (kWh)	197	748
GS-IHP backup tank element energy use (kWh)	0.8	--
Water Heating COP	3.57	0.94[14]
Water heating COP excluding tank/line losses	4.38	1.00
Misc. energy consumption from controls, etc. (kWh)	48	48
Overall		
Energy Use (kWh)	**1011**	**2178**
% Energy savings	**53.6%**	**--**
Carbon Equivalent Emissions (CO_2 metric tons)[15]	**0.70**	**1.50**
CO_2 Emission Savings (metric tons)	**0.80**	**--**

Assumptions

1) Baseline RTU SHR is the same as that estimated for Trilogy WSHP.
2) Baseline RTU is a 48,000 Btu/h rated cooling capacity unit (see Table 1 for other ratings)
3) Baseline RTU fan power is 365 W/1000 cfm (taken from the current AHRI 210/240 ratings procedure[16])
4) Baseline RTU misc. energy use is the same as that measured for the Trilogy WSHP
5) Energy use for the combined SC+WH mode is divided between SC and WH proportional to the output capacities.

[14] Minimum energy factor for 50 gal electric storage WH manufactured after April 15, 2015 as rated per DOE test procedure https://www1.eere.energy.gov/buildings/appliance_standards/product.aspx/productid/27.

[15] 6.89 x 10^{-4} metric tons/kWh; taken from Energy Prices and Carbon Content (8/3/15 version) by Colin Weber.

[16] Air-conditioning, Heating, and Refrigeration Institute, ANSI/AHRI Standard 210/240-2008 with Addenda 1 and 2, "*Performance Rating of Unitary Air-Conditioning & Unitary Heat Pump Equipment,*" March 2012.

6) The Trilogy sensible cooling and subsequent SHR are calculated based on the cfm provided by the trilogy unit, an assumption of 0.075 lbm/ft^3 air density, and measured return and supply air temperatures.

Table 5 provides a summary of the monthly average COPs for the GS-IHP system for each of its active operating modes during the summer/fall test period (August 18 through December 14). Note that the overall SC COP for the GS-IHP system in Table 4 (8.00) does not include the impact of the SC energy delivered during the combined SC+WH mode. The GS-IHP SC COP reported in Table 4 (7.75) does include that impact, accounting for the slight difference in the COP values. The table also includes estimated RTU SC COPs for comparison. Note that the WH mode COPs are based on the WH delivered at the exit of the Trilogy WSHP to the WH tank and connecting lines. Thus they are comparable to the WH COP excluding tank/line losses in Table 4. Figure 13 provides a graphical comparison of the SC-only COPs for the GS-IHP and Baseline RTU/heat pump.

Table 5. GS-IHP monthly average COPs by operation mode

Month	GS-IHP SC-only mode	GS-IHP SC+WH mode[a]	GS-IHP demand WH mode[a]	Baseline RTU SC-only COP
August 18-31	8.06	5.51	2.83	3.95
September 1-30	7.94	5.42	2.80	4.05
October 1-31	7.89	5.44	2.77	4.48
November 1-30	8.10	5.45	2.74	4.61
December 1-14	8.28	5.37	2.87	4.75
Total period	8.00	5.42	2.79	4.30

[a]Based on WH delivered from WSHP to WH tank (excludes tank & connecting line losses)

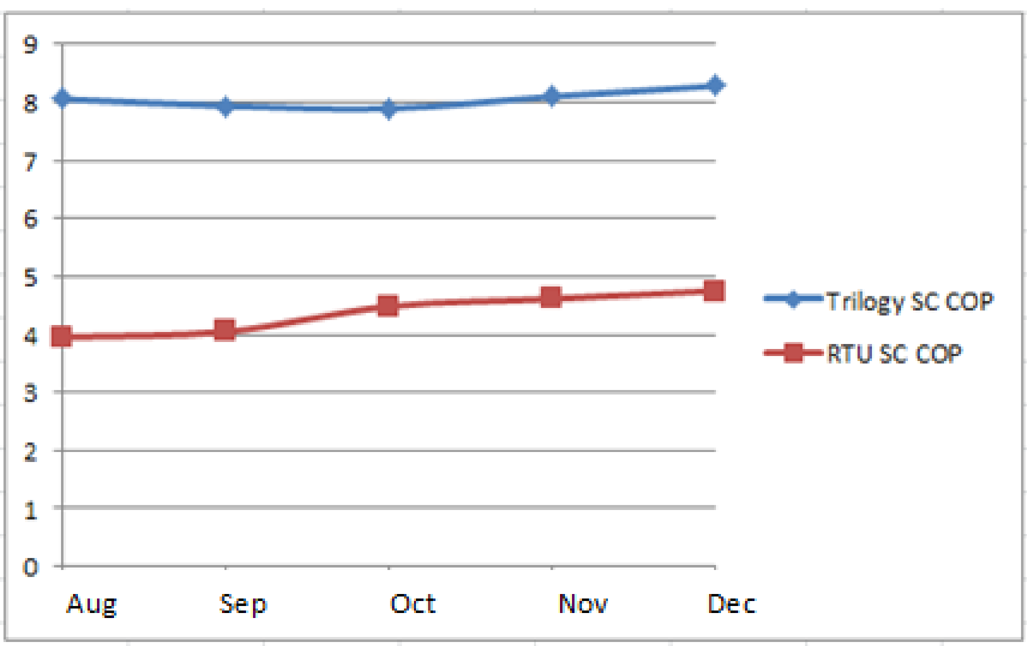

Figure 13. Trilogy WSHP vs. Baseline RTU/heat pump SC-only monthly average COPs

The primary reason the GS-IHP performs so much better than the baseline in SC is that the entering water temperature (EWT) to the WSHP from the GHX loop is generally significantly cooler than the outdoor air temperature (OAT) during hours when space cooling was required at the site. Figure 14 compares the hourly OAT and EWT of the Trilogy in SC mode. The loop appears to have plenty of capacity and likely will show even better savings during more extreme summer weather.

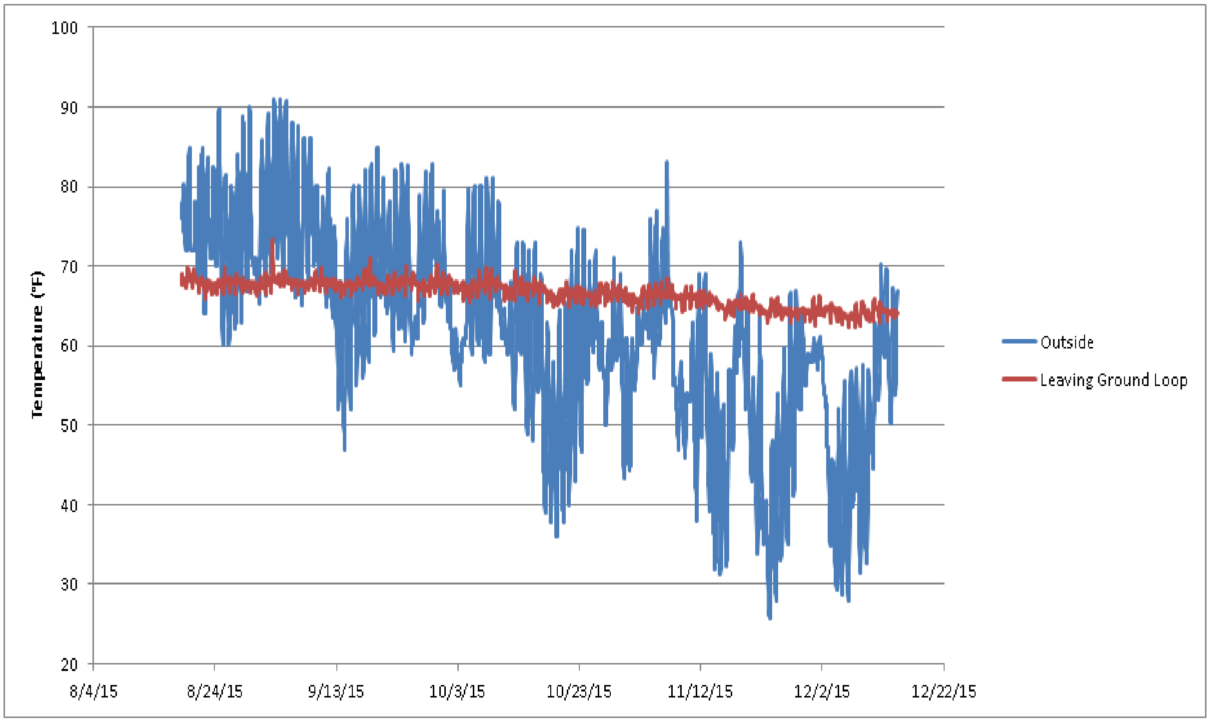

Figure 14. Trilogy WSHP EWT vs. OAT during Aug-Dec test period

Also, as a side note, the kitchen staff keep the SC set point fairly low as evidenced by the space temperature history during the test period, shown in Figure 15, below. During the occupied periods (week days) ranged as low as ~66°F.

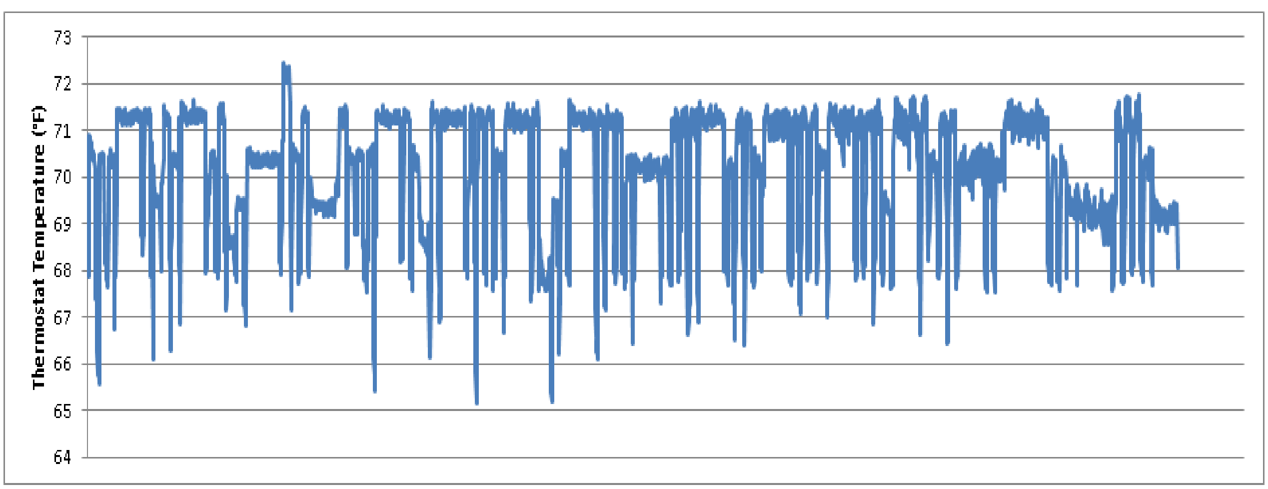

Figure 15. Kitchen space temperature measured at thermostat during Aug-Dec test period

In addition to the energy savings, the GS-IHP system achieved significant reductions in kW demand at the Knoxville site. Monthly hourly peak kW demand is shown in Table 6 for the GS-IHP and Baseline systems. The peak kW demand for the GS-IHP ranged from 33% to 59% lower than the estimated coincident demand of the RTU and electric WH of the baseline system.

Table 6. Peak hourly kW demand by month, GS-IHP vs. Baseline

Month	GS-IHP demand, kW	Date	Baseline demand, kW	Date
August 18-31	1.705	--	4.153	--
September 1-30	2.923	9/2/15, noon-1pm	4.357	9/2/15, 1-2pm
October 1-31	1.642	--	3.851	--
November 1-30	1.888	11/6/15, noon-1pm	4.609	11/10/15, 1-2pm
December 1-14	1.531	--	3.606	--
Total period	2.923	9/2/15, noon-1pm	4.609	11/10/15, 1-2pm

Energy cost savings for the Knoxville site were computed based on the energy and demand savings from Tables 4 and 6, and the commercial rate data from the Knoxville Utilities Board (KUB).[17] For the summer months of August and September, KUB charges $0.11733/kWh and $13.92/kW. For October through December the rates are $0.11692/kWh and $13.13/kW. Costs and savings for the GS-IHP vs. the Baseline are given in Table 7.

Table 7. Knoxville site GS-IHP HVAC/WH energy cost savings (8/18/15 – 12/14/15 period)

	Baseline RTU/heat pump and electric WH	**GS-IHP**
Electricity consumption	$254	$118
Electricity demand	$277	$131
Total costs	$531	$249
Energy cost savings vs. baseline	--	$282

[17] Knoxville Utilities Board, *General Power Rate – Schedule GSA*, November 2015. https://www.kub.org/wps/wcm/connect/3bfe2f80424c71338027b1d8d4cab33c/GSANOV.pdf?MOD=AJPERES&CACHEID=3bfe2f80424c71338027b1d8d4cab33c

VI. Summary Findings and Recommendations (to date)

A complete set of findings and recommendations will be provided with the project final report in September when more complete performance data are available and can be compared to installation and maintenance costs. Summary observations for the Knoxville site are provided today based on demonstrated performance for August through December 2015 along with some general observations about market potential.

A. Overall Technology Assessment at Demonstration Facility

For the August 18 through December 14 period, the Knoxville site GS-IHP provided 53.6% total source energy savings compared to a baseline electric RTU/heat pump and electric WH. Peak demand savings ranged from 33% to 59% per month. Energy cost savings of 53.1% have been achieved to date with more than half of that coming from reduced demand charges. Data on installation and maintenance costs are being collected and will be combined with total test period energy savings data for a payback analysis to be included in the project final report. The GS-IHP also saved a significant amount of carbon emissions. The total emission savings for the Knoxville site for the August-December 2015 period were ~0.8 metric tons. If trading for carbon credits ever becomes a reality, additional cost savings would be realized.

B. Market Potential and Recommendations

Based on demonstrated performance at the Knoxville site, if applied nationally to all appropriate commercial building spaces, GS-IHPs could save 0.084 quads of source energy vs. a 13 SEER RTU/heat pump and electric WH baseline. The actual utility bill savings for a building owner will depend on a number of factors, most notably the building's climate region, HVAC and DHW load profiles, and regional utility rates.

The suitability and economics of GS-IHP systems for the small commercial building application will be evaluated and the analyses reported in the final project report (due September 30).