U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

BUILDING TECHNOLOGIES PROGRAM

# Residential Ground Source Heat Pumps with Integrated Domestic Hot Water Generation: Performance Results from Long-Term Monitoring

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*IBACOS, Inc.*

November 2012

Building AMERICA SM
U.S. Department of Energy

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# Residential Ground Source Heat Pumps with Integrated Domestic Hot Water Generation: Performance Results from Long-Term Monitoring

Prepared for:

The National Renewable Energy Laboratory

On behalf of the U.S. Department of Energy's Building America Program

Office of Energy Efficiency and Renewable Energy

15013 Denver West Parkway

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NREL Contract No. DE-AC36-08GO28308


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Prepared under Subcontract No. KNDJ-0-40341-02

November 2012

## Acknowledgments

The authors thank the U.S. Department of Energy's Building America Program for support to conduct this research. They also thank Pine Mountain Builders, especially David Barnes and Marc Hoefert, for their assistance on site. Thanks also go to Bill Rittelmann and Chris Imm, who were instrumental to the test procedure development and the instrumentation installation, respectively.

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## Definitions

| | |
|---|---|
| COP | Coefficient of performance |
| DHW | Domestic hot water |
| EER | Energy efficiency ratio |
| EF | Energy factor |
| EWT | Entering water temperature |
| ft | Foot |
| gal | Gallon |
| gpm | Gallons per minute |
| GSHP | Ground source heat pump |
| Hz | Hertz |
| kW | Kilowatt |
| L | Liter |
| LED | Light-emitting diode |
| SHGC | Solar heat gain coefficient |
| XPS | Extruded polystyrene |

# Executive Summary

Ground source heat pumps (GSHPs) show great promise as a means to substantially reduce energy consumption in houses. Laboratory test data from manufacturers of these units indicate that using the soil between 6 and 600 ft below the surface of the earth as the thermal energy source or sink gives GSHPs the potential to obtain coefficients of performance (COPs) ranging from 4 to 6 for heating and cooling.

In addition, generating domestic hot water (DHW) consumes substantial amounts of energy in a house. As energy for space heating and cooling decreases, reducing energy for hot water generation becomes the next target. Using a desuperheater to generate DHW is a potential strategy for reducing this energy consumption. In this strategy, the heat pump from the space conditioning system is used to create hot water instead of electric resistance or fossil fuel. Before widespread implementation can be recommended, however, it is necessary to understand the magnitude of the impact of the factors that affect the thermal energy output of the desuperheater, such as heat pump runtime.

In this study, the IBACOS team instrumented two unoccupied houses built by Pine Mountain Builders in Pine Mountain, Georgia. The project was designed to document the installed operational space conditioning and water heating efficiency of the houses' GSHP systems. The monitoring period began in January 2010 and continued through April 2011. During this period, interior thermostat set points were maintained at constant values for heating and cooling, and hot water was consumed according to the occupancy profile schedule used in the U.S. Department of Energy's Building America Program.[1]

This report discusses the instrumentation methods and field operation characteristics of the two GSHPs in the test houses, including a comparison between the manufacturer's listed COP values and the COPs calculated from field data. Note that both GSHPs are made by the same manufacturer. The measured efficiency of the desuperheater-assisted DHW system is compared to efficiencies of other DHW systems available on the market.

[1] See http://www1.eere.energy.gov/buildings/residential/ba_index.html for more information.

# 1 Introduction

Ground source heat pumps (GSHPs) show great promise as a way to substantially reduce energy consumption in houses. GSHPs use the soil at depths ranging from 6 to 600 ft below the earth's surface as the thermal energy source or sink. In the years preceding this study, observers noted an annual increase of 12% in the number of GSHP installations in the United States, primarily in the northern Midwest and along the East Coast. Most of these installations were closed-loop systems with vertical ground wells (Lund et al. 2004).

As part of its work under the U.S. Department of Energy's Building America Program (see footnote 1), IBACOS collaborated with Pine Mountain Builders in 2008 to build two houses in Pine Mountain, Georgia. As part of the upgrades necessary to meet the 50% source energy reduction level with respect to the 2008 Building America benchmark definition (Hendron 2008), each house uses a GSHP for its heating and cooling needs. As energy used for heating and cooling decreases, the amount of energy used for potable hot water can become the largest single point of household energy consumption. As a result, reducing energy for hot water production becomes a priority. Options are limited, though, in all-electric houses such as these. A potential strategy for reducing the energy required to generate hot water is using a desuperheater (or supplemental heat exchanger) on the GSHP. This strategy, which was incorporated into the test houses, creates hot water in conjunction with an electric resistance tank water heater. Research performed by Merrigan and Parker (1990) indicates measured efficiency levels of 110% (thermal energy output divided by site electrical energy input as a percentage) for desuperheaters installed on air source heat pumps in Florida during the 1980s.

Because the test houses in Georgia were intended to be unoccupied through the course of the study, there was the potential to eliminate variability resulting from user behavior. The two goals of the project were to document the space conditioning efficiency and the water heating efficiency of the GSHP systems installed in the test houses.

# 2 Specifications

The two test homes, which are located next door to one another, share the same solar orientation. Both have four bedrooms, four and a half baths, and roughly the same usable interior area. House 1 has one story; House 2 has two stories and slightly more usable interior floor space because of a loft on the second floor (see Figure 1 and Table 1).

**Figure 1. Test House 1 (left) and House 2 (right)**

**Table 1. Building Specifications**

| Building Envelope | |
|---|---|
| **Geometry** | 2,024 $ft^2$, 1-story, or 2,946 $ft^2$, 2-story (both have 4 bedrooms and 4.5 bathrooms) |
| **Roof** | Unvented attic, spray foam on underside of roof sheathing, R-30 |
| **Walls** | 2 x 6 wood framing @ 16-in. on center open cell spray foam R-22 cavity |
| **Foundation** | 12- to 18-in. tall monolithic slab with 1-in. XPS (R-5) slab edge insulation |
| **Windows** | U-value = 0.38, SHGC = 0.35, wood frame |
| **Mechanical Systems** | |
| **Heating** | 4.2 COP GSHP |
| **Cooling** | 20.1 EER GSHP: House 1, 2.6 tons; House 2, 3.8 tons |
| **DHW** | 40- or 85-gal (151.4- or 322-L) electric tank, 0.94 or 0.92 nominal EF, two 4.5-kW (1.28-ton) nonsimultaneous operation electric resistance elements in each tank, desuperheater |
| **Ducts** | In conditioned space |
| **Leakage** | 2% to outside |
| **Ventilation** | Passive into return with ventilation controller |
| **Appliances** | All-electric ENERGY STAR appliances |
| **Lighting** | 100% energy efficient fixtures—fluorescent and light-emitting diode (LED) |

Source: See IBACOS (2010).
Notes: XPS, extruded polystyrene; SHGC, solar heat gain coefficient; COP, coefficient of performance; EER, energy efficiency ratio; DHW, domestic hot water; EF, energy factor; LED, light-emitting diode

As part of the upgrades necessary to achieve 50% energy savings with respect to the 2008 Building America benchmark definition (Hendron 2008), both houses use dual-capacity GSHPs for space heating and cooling. Although made by the same manufacturer, the units have different output capacities. The GSHP used in House 1 is rated at 9.1 kW (2.6 tons), and the GSHP in House 2 is rated at 13.4 kW (3.8 tons). The ground heat exchanger consists of a closed loop in two (House 1) or three (House 2) vertical bores, each approximately 180 ft deep, using two 1-in.-diameter polyethylene pipes with a U-bend at the bottom end of each bore hole circulating a 15% methanol and 85% water mixture (IBACOS 2008).

In addition, each house features a desuperheater connected to an electric tank type water heater rated at 0.94 nominal EF and 151-L (40-gal) capacity in House 1 and 0.92 nominal EF and 322-L (85-gal) capacity in House 2. The desuperheater transfers excess heat from the GSHP refrigerant loop before the condenser into water in the water heater tank, improving the efficiency of the DHW system. This process occurs only when the thermostat is calling for space heating or cooling; desuperheater operation is not controlled based on hot water needs. Desuperheater operations in heating and cooling modes are shown in Figure 2 and Figure 3, respectively. If the DHW tank temperature falls below its set point, the electric resistance elements come online. Preliminary analysis indicated that the desuperheater could offset up to 80% of the DHW electrical demand in the summer.

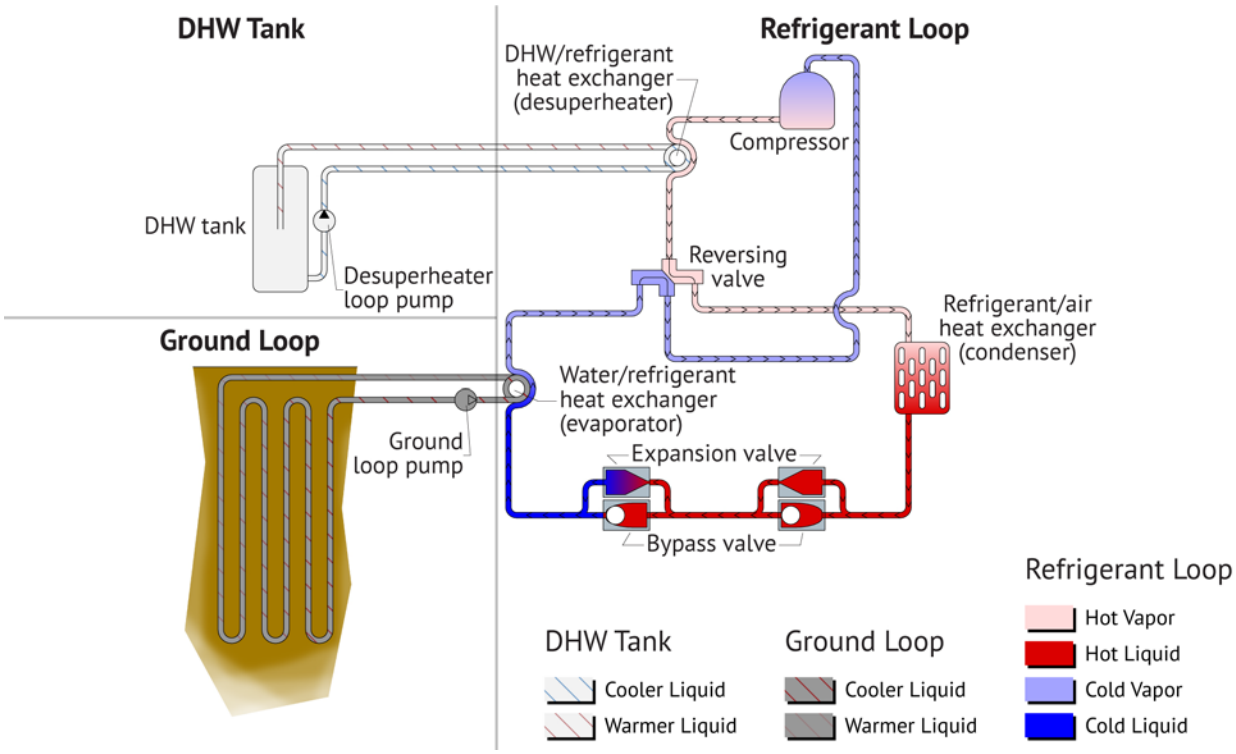


**Figure 2. Diagram of the GSHP and desuperheater operation in heating mode**

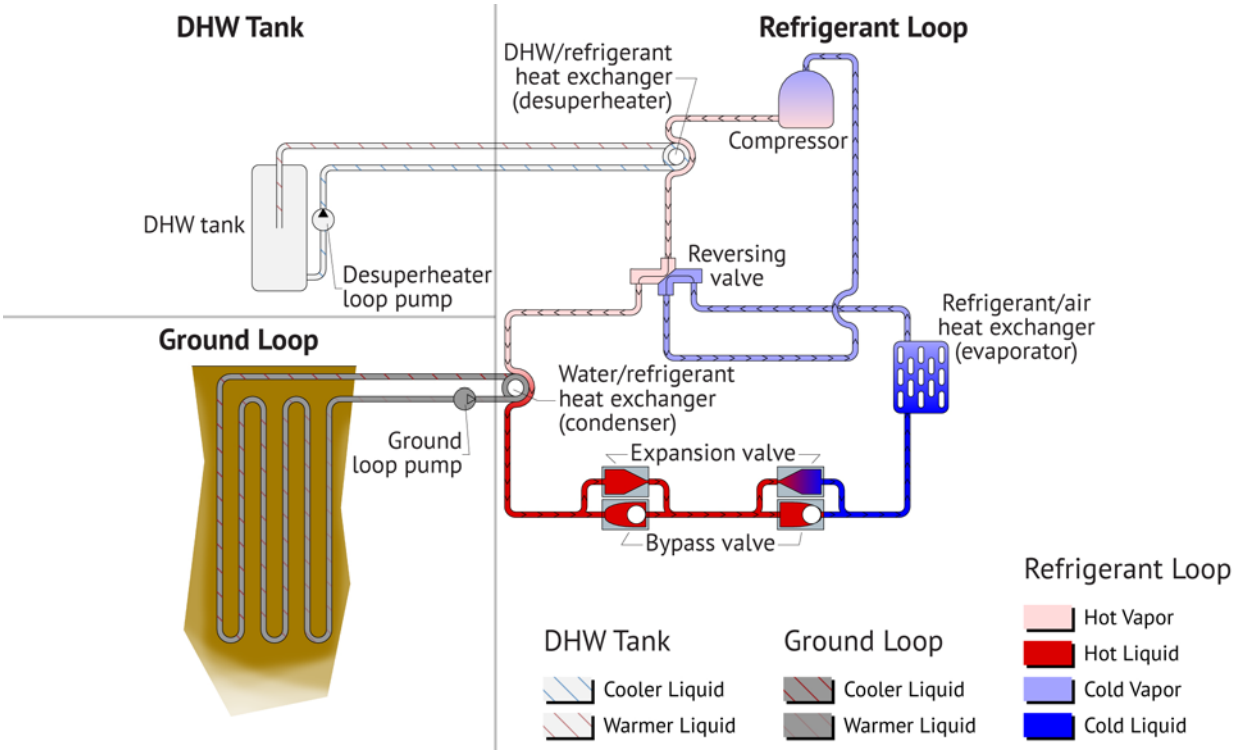


**Figure 3. Diagram of the GSHP and desuperheater operation in cooling mode**

# 3 Technical Approach

The first goal of this study was to compare the field-measured COPs with the manufacturer's listed values for the two GSHPs. The second goal was to compare the measured efficiency of the desuperheater-assisted DHW system to other market-available DHW systems.

Using equations 1, 2, and 3, the study team determined the COP of each GSHP by calculating thermal energy ($TE_{GroundLoop}$). To do so, the team used temperature measurements and the volumetric flow rate of the fluid in the ground loop and measured the electric energy of the compressor ($EE_{Compressor}$), the ground loop pump ($EE_{GroundLoopPump}$), and the air handler unit fan ($EE_{AirHandlerFan}$). The COP values calculated based on Equation 1 are negative for heating and positive for cooling.

$$COP_{GSHP} = \frac{TE_{GroundLoop} - TE_{Compressor}}{EE_{Compressor} + EE_{GroundLoopPump} + EE_{AirHandlerFan}}, \quad (1)$$

$$TE_{Compressor} = 0.3 * EE_{Compressor}, \quad (2)$$

$$TE_{GroundLoop} = \left(T_{GroundLoopOut} - T_{GroundLoopIn}\right) \times Q_{GroundLoop} \times \rho_{Water} \times C_P, \quad (3)$$

where

$TE_{GroundLoop}$ is the thermal energy sent to (positive value) or extracted from (negative value) the ground loop wells.

$TE_{Compressor}$ is the thermal energy given off by the compressor.

$EE_{Compressor}$ is the site electrical consumption of the GSHP compressor.

0.3 is the assumed fraction of electrical energy input to the compressor that is lost to the surroundings as heat.

$EE_{GroundLoopPump}$ is the site electrical consumption of the ground loop pump.

$EE_{AirHandlerFan}$ is the site electrical consumption of the air handler unit fan.

$T_{GroundLoopOut}$ is the temperature of fluid leaving the GSHP and traveling toward the ground loop well.

$T_{GroundLoopIn}$ is the temperature of fluid entering the GSHP (known in manufacturers' literature as entering water temperature, or EWT) returning from the ground loop well.

$Q_{GroundLoop}$ is the volume of water flowing through the ground loop.

$\rho_{Water}$ is the density of water.

$C_P$ is the specific heat of water.

To conduct thermal energy metering on the ground loop, the team mounted a high-temperature, chemical-resistant flow meter on the loop line returning to the GSHP unit from the ground loop. Type T immersion thermocouple probes (Figure 4) measured the temperature of both the outgoing and incoming fluids. Thermal energy metering was performed in the same manner to determine the energy output from the DHW system to the fixtures in the house and on the circulation loop connecting the desuperheater in the GSHP to the DHW system.

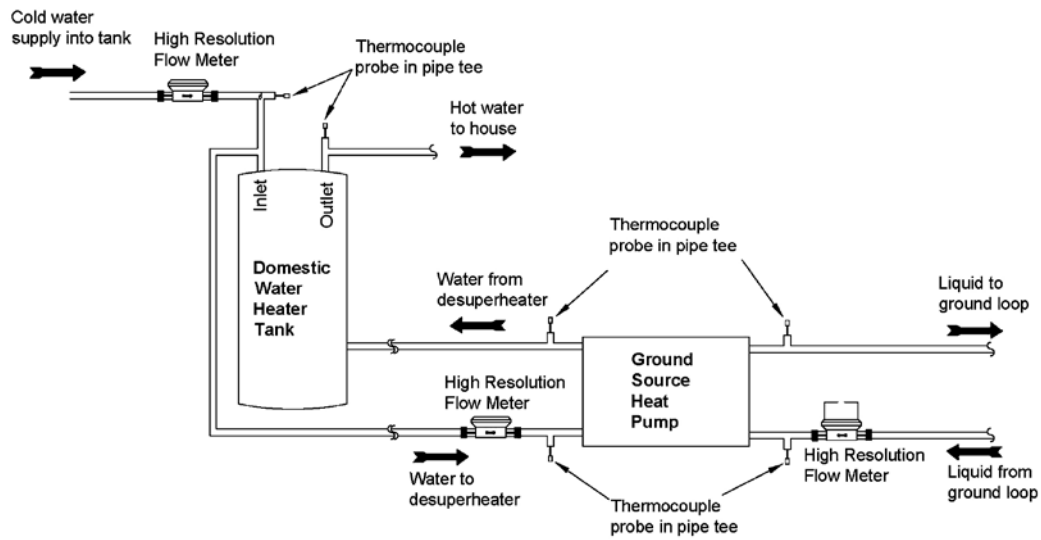


**Figure 4. Diagram showing temperature and flow measurement locations on the GSHP and DHW systems**

Electricity consumption of the ground loop pump, compressor, air handler unit fan, and desuperheater loop pump was measured individually for each device using pulse output Watt-hour meters (4-Hz full-scale output frequency). These meters were installed with appropriately sized current transducers rated at no more than a factor of 2 greater than the anticipated maximum load. For circuits with only resistive loads (the electric resistance heating elements in the DHW system), voltage output current transducers were installed, and Watt-hours were calculated using Equation 4:

$$\text{Watt-hours} = amps_{measured} \times 244 \times \text{hour}, \quad (4)$$

where $amps_{measured}$ is the measured amperage from the current transducer and 244 is the typical line voltage.

The team took electrical measurements for the DHW system in the main circuit panel. Measurements related to the performance of the GSHP were taken at the unit. Type T thermocouples were used for the indoor air temperature measurement in each thermostatically controlled zone; the reference temperature was taken at the data logger using a thermistor. Investigators also measured outdoor temperature and relative humidity.

All sensors were connected to a central data logger using low-voltage shielded wire, and 60-Hz noise-cancelling integration was used to mitigate any noise caused by electrical power lines. The team sampled the sensors every 10 s and averaged the data on a minute and hourly basis. A cellular data modem was used to allow daily remote collection.

During the monitoring period from January 2010 to April 2011, the houses were unoccupied, and the interior thermostat set points were maintained at constant values of 20.6°C (69°F) heating and 23.3°C (74°F) cooling. To determine the efficiency of the desuperheater, DHW needed to be used. To facilitate this, the study team installed a solenoid valve controlled by the central data logger on the hot water spigot in the washing machine box in each house. This allowed water flow on a regular basis according to a slightly modified version of the schedule used in the Building America House Simulation Protocols (Hendron and Engebrecht 2010). In this case, however, the protocols had to be simplified because only one flow rate was available from the fixed orifice opening used in the field test. The flow rate through the solenoid valve was fixed at 0.095 L/s (1.5 gpm), and the solenoid valve opening duration was varied to simulate different volumes. To more accurately simulate the usage patterns of real people, three daily water consumption volumes were used during the weekly schedule:

- Days 1 through 3 used 177 L (46.8 gal) each day.
- Days 4 and 5 used an additional 99.5 L (26.3 gal) for a total of 277 L (73.1 gal) per day.
- Days 6 and 7 used an additional 78.0 L (20.6 gal) for a total of 355 L (93.7 gal) per day.

Typical flow events simulated the water used for showering, hand washing at a sink, and operating the dishwasher and the clothes washer. Individual flow events ranged from 1.9 to 57 L (0.5 to 15 gal). Hot water was consumed according to this schedule for the duration of the monitoring period.

# 4 Analysis

## 4.1 Space Conditioning Coefficient of Performance

The study team calculated the COP values every 10 s and averaged the data (weighted with respect to GSHP runtime) on a minute and hourly basis. Investigators assumed that during a given hour, the system operated in only one mode: heating or cooling. Based on hourly data outputs, monthly average COPs were created, weighted by runtime in each mode. The manufacturer's rated performance might have been met at various times throughout the monitoring period; however, over the course of the year, the values were lower. Table 2 shows seasonal average COPs and system runtime for heating or cooling. The results plotted in Figure 5 are the COPs for the mode in which most of the runtime occurred. Measured COPs while the system was in cooling mode were closer to the range of the manufacturer's values shown in Table 3 (Waterfurnace 2007) than measured COPs while the system was in heating mode. Note that the wide range in the manufacturer's values results from two stages of system operating capacity and two fan speeds for each stage.

**Table 2. Seasonal Average COP**

| | House 1 COP | House 2 COP |
|---|---|---|
| Winter early 2010 (heating) | 4.86 | 2.65 |
| Summer 2010 (cooling) | 5.24 | 4.26 |
| Winter 2010 to 2011 (heating) | 3.44 | 2.36 |

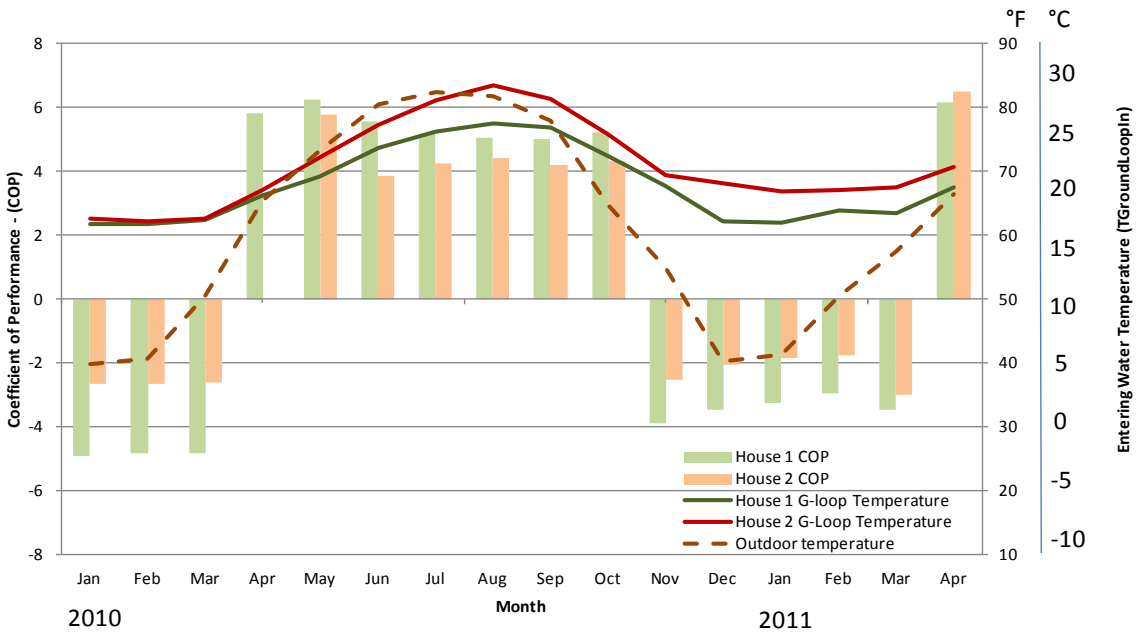


**Figure 5. EWT and monthly average COP for both houses; heating COPs are shown as negative values, and cooling COPs are shown as positive values. (Data for House 2 in April 2010 are unavailable because a data logger malfunctioned.)**

**Table 3. Equipment Rated COPs at Given EWTs**

| | EWT Range (°F) | Rated Heating COP Range | | Measured Heating COP Range | | Rated Cooling COP Range | | Measured Cooling COP Range | |
|---|---|---|---|---|---|---|---|---|---|
| House 1 | 60–70 | 4.86 | 6.25 | 2.4 | 5.3 | 6.21 | 9.23 | 3.4 | 6.1 |
| | 70–80 | 5.15 | 6.68 | | | 5.42 | 8.09 | 4.9 | 5.5 |
| | 80–90 | 5.28 | 7.15 | | | 4.66 | 6.71 | | |
| House 2 | 60–70 | 4.85 | 6.15 | 1.8 | 3.8 | 5.95 | 9.17 | 5.0 | 5.0 |
| | 70–80 | 5.05 | 6.58 | | | 5.25 | 8.00 | 5.4 | 6.8 |
| | 80–90 | 5.17 | 7.01 | | | 4.57 | 6.74 | 4.9 | 5.0 |

The measured COPs for the GSHP systems were lower than the manufacturer's ratings in cooling, with House 1 performing better than House 2. The measured 2010 cooling season COP was 5.24 for House 1, 3% to 35% below the manufacturer's range of 5.42 to 8.09 for the summer EWT. The measured 2010 cooling season COP was 4.26 for House 2, 16% to 47% below the manufacturer's range of 5.09 to 8.06 for the summer EWT.

The heating season COP was 4.86 for House 1 during the winter of early 2010, 4% to 22% lower than the manufacturer's range of 5.05 to 6.25 for the winter EWT. During the 2010–2011 winter season, the observed COP of 3.44 was substantially worse. Although this performance is worse than anticipated, after accounting for differences in source energy, this is comparable to the rated performance of a high-efficiency (90+% annual fuel utilization efficiency) furnace.

The heating season COP for House 2 was 2.65 in early 2010. This COP also declined during the 2010–2011 winter, averaging 2.36 for the season. This is at least 50% lower than the manufacturer's listed COP values for the winter EWT.

It is unclear why the heating season COPs varied substantially between the two houses; however, the GSHP installed in the two-story house was slightly oversized. Figure 5 shows the monthly average COPs and the corresponding EWTs for both houses. The inside temperature of House 1 was 17.2°C (63°F) in January, February, and March 2010, and in January and February 2011. The low temperature in the latter months was caused by a compressor malfunction that prevented the system from heating the house. Based on observations from adjoining data in 2011, when the inside temperature was 20.6°C (69°F), this appeared to have no impact on the measured COP.

In House 2, during January and February 2011, the air handler unit fan operated continuously at high speed, although the team excluded the extraneous runtime from COP calculations. Although the stage or fan speed at which the system was operating was not measured, knowing this information would help determine why differences occur. The substantial difference in performance between two houses with fairly similar characteristics is perplexing and highlights the need for more critical analysis of the possible differences between the houses, such as the quality of the ground loop installation.

## 4.2 Domestic Water Heating Efficiency

The "as-measured" EF of a DHW system can be approximated based on the measured thermal energy output of the water heater and the measured electrical input to the water heater (see Equation 5 and Equation 7). In this study, however, calculating the EF is somewhat more complicated because the thermal energy provided by the GSHP in heating mode is not free; it is created from electricity proportionately to the COP of the GSHP. The EF calculation is modified to account for this in Equation 6.

$$EF = \frac{TE_{output}}{E_{ER}}, \tag{5}$$

$$EF = \frac{TE_{output}}{E_{ER} + \left( \frac{TE_{desuperheater}}{COP_{GSHP}} \right)}, \tag{6}$$

where

$TE_{desuperheater}$ is the measured thermal energy provided to the DHW system from the GSHP.

$TE_{output}$ is the measured thermal energy provided from the DHW system to the house.

$E_{ER}$ is the measured electricity supplied to the heating elements in the DHW system.

$COP_{GSHP}$ is the seasonally averaged measured COP of the GSHP in heating mode.

$$TE_{output} = (T_{Out} - T_{In}) \times Q_{Tank} \times \rho_{Water} \times C_P, \tag{7}$$

where

$TE_{output}$ is the thermal energy delivered by the DHW system.

$T_{Out}$ is the temperature of water leaving the DHW system.

$T_{In}$ is the temperature of water entering the DHW system.

$Q_{Tank}$ is the volume of water flowing through the tank.

$\rho_{Water}$ is the density of water.

$C_P$ is the specific heat of water.

Based on monitored data (see Figure 6), the annual site EF of the DHW system in House 1 ranged from 2.8 to 3.3, depending on the volume of water consumed. By comparison, electric resistance water heaters range in EF from 0.85 to 0.95. If compared to an instantaneous gas water

heater, the difference in source energy between natural gas and electricity must be accounted for by converting the EF of each water heater to source energy weighted EF using Equation 8 and Equation 9:

$$EF_{SourceEnergyWeighted} = \frac{EF_{ElectricDHW}}{3.365}, \tag{8}$$

$$EF_{SourceEnergyWeighted} = \frac{EF_{GasDHW}}{1.092}, \tag{9}$$

where

$EF_{ElectricDHW}$ is the EF for an electric DHW system.

$EF_{GasDHW}$ is the EF for a gas DHW system.

3.365 is the site-to-source conversion factor for electricity.

1.092 is the site-to-source conversion factor for natural gas.

Figure 6 shows that, after accounting for the difference in source energy, the DHW system in House 1 is on par with or better than the rated source energy efficiency of tankless gas water heaters. The DHW system is also more efficient than other options, including tank type gas, tank type electric, and heat pump DHW systems. Rated performance is plotted as a line in Figure 6 to more clearly provide context with respect to measured results at specific flow rates; the plotted lines are not indicative of rated performance at those flow rates. In House 2, the desuperheater provided, on average, 20% of the thermal energy input to the tank, which is comparable to results obtained by Fanney and Dougherty (1992); however, there was no apparent improvement in EF over the rated performance of a conventional tank type electric water heater. Average delivered temperature of hot water from each tank was similar, with the 151.4-L (40-gal) tank in House 1 delivering at 51.1°C (124°F) and the 322-L (85-gal) tank in House 2 delivering at 46.7°C (116°F). More detailed measurements are necessary to determine if other factors, such as tank standby losses or disruption of tank stratification by the desuperheater, influenced the performance.

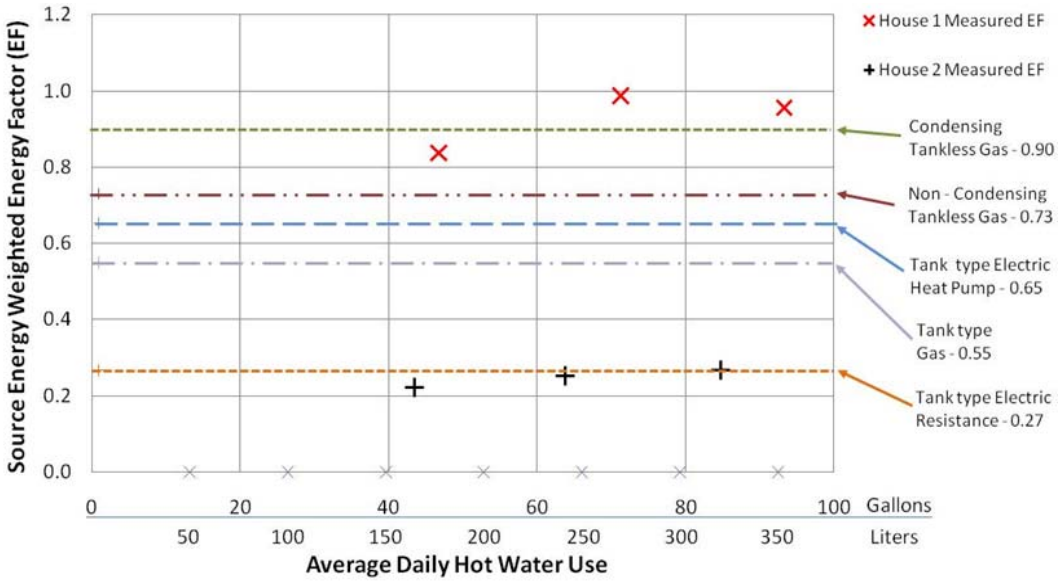


**Figure 6. As-measured EF for three different daily water consumption volumes with rated efficiencies of four other water heating systems shown; all efficiencies are weighted with respect to source energy type**

# 5 Conclusions

The study results indicate that GSHPs can be an effective means of providing space heating and cooling in warm climates. The variation in heating performance between the units in the two houses in this study, however, is a cause for concern. In general, a desuperheater is a more efficient means of providing DHW, but its efficiency varies, depending on the components to which it is connected. Based on these results, the study team recommends further research on the performance of desuperheaters in other residential applications, such as those connected to air source heat pumps.

As the desire to increase energy efficiency continues, integration of space conditioning and hot water generation systems, either directly (desuperheaters) or indirectly (heat pump water heaters), will create new challenges for calculating the *in situ* operational efficiency of both devices.

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