Residential Ground-Source Heat Pumps: In-Field System Performance and Energy Modeling

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ABSTRACT

Ground-source heat pumps (GSHPs) are often touted as one of the most efficient, sustainable system choices for heating and cooling of homes. While there is much anecdotal evidence, both supporting and detracting from GSHPs, there is little data documenting the long-term installed performance of GSHPs in homes.

To establish a deeper understanding of installed GSHP system performance and the associated energy savings potential, the authors worked with contractors and homeowners in Connecticut, Virginia, and Wisconsin to monitor the in-situ performance of three residential ground source heat pump systems. As market penetration for GSHPs continues to increase, partially due to greater availability of federal, state, and utility incentives that help offset the higher installation costs associated with these systems, the findings of these field evaluations are presented to assist manufacturers in identifying specific areas of opportunity for improving the technology and to support the development of more accurate methods and modeling tools to predict the energy consumption of heat pump systems.

Four key objectives were identified for this research:

- Develop a better understanding of the in-field performance of residential ground-source heat pump systems by measuring real-world conditions, including ancillary components.

- Identify optional system components and installation methods that have an impact on the total system energy consumption, have the potential to improve system performance, and/or result in increased system reliability.

- Compare measured conditions to the ground-source heat pump unit rating provided by the Air-Conditioning, Heating, and Refrigeration Institute (AHRI) for use by others in developing a more accurate accounting method to assess system performance.

- Contrast the predicted energy performance with the actual energy performance to determine the accuracy of current modeling methods.

All three monitored systems have two-stage compressors to provide additional heating and cooling capacity during periods of peak demand and each system is served by a horizontal ground loop. After a minimum of one heating season of monitoring for each system, all three systems are operating at efficiency levels within the range of anticipated performance. Measured heating Coefficients of Performance (COP) typically vary from 3.0 to 4.3. Although these measured COPs fall below the rated efficiency levels for these units, the rated efficiency does not account for pressure drop in the ground loop or the duct system. It is interesting to not that the results do not show increased efficiency when the units operate at part-load capacity. The authors address the potential cause of this finding in this report, as well as some common errors observed in these GSHP installations and possible methods to avoid these issues.

Introduction

The Department of Energy's (DOE) Building America Program is a partnership between researchers and the various facets of the residential building industry with the intent to improve the quality and energy efficiency of homes. The goal is to develop cost effective solutions that reduce the average source energy use of housing by 40% to 100%. The authors are team members of the Consortium for Advanced Residential Buildings (CARB), one of the six Building America research teams, which is led by Steven Winter Associates, Inc.

Ground-source heat pump technology has been around since the 1940s and has been growing in acceptance since the 1970s. ASHRAE/ISO Standard 13256-1 for Water-Loop Heat Pump, Ground-Water Heat Pump, and Ground-Loop Heat Pump Applications is the current standard for certifying the performance of GSHP units.

Table 1. Summary of homes and monitored heat pumps.

CONNECTICUT SYSTEM		Climate Information	
City, State	Glastonbury, CT (near Hartford, CT)	**Climate Region**	Cold (Climate Zone 5A)
House Style	Craftsman	**Cooling Degree Days**	338 (70°F base)
# of Stories / Bedrooms	2 stories with conditioned basement / 5 bedrooms	**Heating Degree Days**	6,104 (65°F base)
Floor Area	2,966 ft^2 (includes actively conditioned basement area)		
HERS Index	33		
GSHP cost	$30,800 for system (including backup heating)		
Specifications			
Building Envelope	R-38 cathedral ceiling, R-23 exterior wall assembly, R-13 on interior of foundation walls, R-8 under basement slab, R-30 for exposed floors, and double pane, low-e windows (U-0.32 / SHGC-0.31)		
GSHP	A horizontal closed loop, pressurized system consisting of two 225-ft six-pipe heat exchangers buried approximately 6 feet below grade (a total of 2,700 feet of pipe). A 10% propylene glycol solution is circulated between the ground coils and a 3-ton dual capacity Water Furnace Envision heat pump (NDV038A111NTR: rated EER 30 and COP 5.1 for low stage and EER 20.1 and COP 4.2 for high stage) located in the unconditioned portion of the basement. The heating capacity was sized to 80% of the building load to save on first cost and auxiliary heating is provided by a Polaris water heater (90+ thermal efficiency). A desuperheater is also installed to a buffer tank prior to the Polaris water heater. An ERV is connected to the central duct system.		
Performance Testing	Building infiltration of 1,091 cfm$_{50}$ (2.32 ACH$_{50}$ or 0.11 ACH$_{natural}$) Duct leakage to outside of 24 cfm$_{25}$ (0.71 cfm$_{25}$/100 ft^2)		
VIRGINIA SYSTEM		Climate Information	
City, State	Aldie, VA (near Dulles International Airport)	**Climate Region**	Mixed, Humid (Climate Zone 4A)
House Style	Neocolonial	**Cooling Degree Days**	538 (70°F base)
# of Stories / Bedrooms	2 stories with conditioned basement / 5 bedrooms	**Heating Degree Days**	4,925 (65°F base)
Floor Area	6,919 ft^2 (includes finished walk-out basement area)		
HERS Index	42		
GSHP cost	$39,000 for system and $2,500 for excavation		
Specifications			
Building Envelope	R-50 ceiling, Icynene in wall cavities of 2x6 studs @ 16" o.c. (R-20), R-13 on interior of foundation walls, Icynene sprayed on rim/band joists, and double pane, low-e windows (U-0.32 / SHGC-0.27)		
GSHP	A horizontal closed loop, pressurized system consisting of four trenches with 240-ft four-pipe heat exchangers buried approximately 5 feet below grade and spaced 10 feet apart. Environol 1000 solution (21.4% ethanol) is circulated between the ground coils and 2 GSHPs. The basement and 1st floor are serviced by a 4-ton dual capacity Water Furnace Envision heat pump (NDV049A111CTL: rated EER 25.1 and COP 4.6 for low stage and EER 18.3 and COP 4.1 for high stage) located in the unconditioned portion of the basement. The 2nd floor is serviced by a 2-ton dual capacity WaterFurnace Envision split heat pump (not monitoring this system). Auxiliary heating is electric resistance and whole-house ventilation is supply-only ducted to the ductwork of the lower zone heat pump.		
Performance Testing	Building infiltration of 1,990 cfm$_{50}$ (1.67 ACH$_{50}$ or 0.094 ACH$_{natural}$) Duct leakage to outside of 86 cfm$_{25}$ (1.24 cfm$_{25}$/100 ft^2)		
WISCONSIN SYSTEM		Climate Information	
City, State	Black River Falls, WI (near Eau Claire, WI)	**Climate Region**	Cold (Climate Zone 6A)
House Style	Contemporary	**Cooling Degree Days**	234 (70°F base)
# of Stories / Bedrooms	1 story with conditioned basement / 3 bedrooms	**Heating Degree Days**	8,196 (65°F base)
Floor Area	3,100 ft^2 of conditioned space, of which, 1,800 ft^2 is finished space (includes basement area)		
HERS Index	21		
GSHP cost	Approximately $28,000		
Specifications			
Building Envelope	R-50 flat ceiling, R-27 2x8 stud walls + R-5 rigid insulation on exterior, R-10 on exterior of foundation walls and under slab, and double pane, low-e windows.		
GSHP	A horizontal closed loop, pressurized slinky system consisting of 2-300 foot trenches at a depth of 8 feet and separated by 8 feet. Environol 1000 solution (21.4% ethanol) is circulated between the ground coils and a 3-ton dual capacity Water Furnace Synergy 3-D heat pump (SDV038A121CTL: rated EER 23.7 and COP 4.5 for low stage and EER 18.5 and COP 4.0 for high stage) located in the unfinished portion of the basement. This unit also has a third mode of hot water heating that goes to a 50 gal buffer tank prior to the 80 gal electric water heater. A desuperheater runs directly to the electric water heater. A HRV is connected to the central duct system.		
Performance Testing	Building infiltration of 383 cfm$_{50}$ (1.25 ACH$_{50}$ or 0.08 ACH$_{natural}$)Duct leakage to outside was negligible		

It is the authors' belief that evaluation and documentation of "real-world" ground-source heat pump installations will provide a more accurate understanding of the current technology's performance. It is critically important to know how systems are actually performing and for modeling tools to accurately predict the performance these advanced systems. Results from field evaluations of GSHP's will identify specific areas of opportunities for improvements in the technology and may allow more accurate modeling of heat pump systems.

Monitoring Procedures

The authors have been monitoring performance of three ground-source heat pump (GSHP) systems in very energy-efficient, new homes in different regions: Connecticut, Virginia, and Wisconsin. The primary focus of the study has been on heating season GSHP performance – especially in the colder climates. All of the systems were water-to-air heat pumps, ground loops were horizontal, and heat (and cooling) was distributed by air handlers and duct systems.

Homes and Systems

An overview of the parameters of each home and installed GSHP system is below.

Instrumentation

Because of inherent uncertainties in air flow measurements – and because in these residential systems it was challenging to find straight sections of duct with laminar flow – the authors used flow and temperature measurements on the ground loop for most thermal calculations. Typical instrumentation consisted of:

- Turbine meter in the ground loop to measure total fluid flow to the heat pump;
- Temperature sensors (thermistors) in the ground loop at the inlet and outlet of the heat pump;
- Air temperature and relative humidity sensors in the return and supply air plenums;
- Energy transducers measuring electrical consumption of each of the following separately:
  - Ground loop circulator(s)
  - Air handler fan
  - Compressor
  - Total heat pump unit

At some sites, the authors were also able to monitor desuperheater and/or domestic hot water (DHW) circulator power, flow, and water temperatures. Sensors were connected to Campbell Scientific CR10X dataloggers and data were collected bi-monthly via cellular modems.

Calculations

Useful heat removed from the ground loop was calculated every fifteen seconds with the following equation:

$$Q_h = (\Delta T_{T_{in}-T_{out}} \times \dot{V} \times C_p \times \rho)$$

where:

Q_h = heat removed from ground stream [Btu]

$\Delta T_{T_{in}-T_{out}}$ = T_{in} minus T_{out} (°F)

$\dot{V}$ = volumetric flow in ground loop [gal]

C_p = heat capacity of ground loop fluid [Btu/lbm ·°F]

ρ = density of ground loop fluid [lbm/gal]

Total thermal and electric energy values, total volume values, and average temperature and relative humidity values were collected every 15 minutes.

Coefficient of Performance (COP): The coefficient of performance of a heat pump is the ratio of the useful heating energy outputted by the system to the net energy inputted to the system.

According to ASHRAE/ISO 13256-1, the "effective power input" used in the calculation of COP/EER should include the compressor, the water pump, the air-handler fan, and all associated controls. However, fan power used in the calculation of manufacturer's COP/EER does not include flow resistance from ducts nor does pump power include the resistance of the ground loop; the design of the duct system and ground loop is unknown to the manufacturer. As a result, literature COP values are substantially higher than coefficients of performance in installed systems. Installed system COP values were calculated as:

$$COP = \frac{\text{useful heating energy}}{\text{electric energy input}}$$

$$COP = \frac{Q_h + (W_{fan} + W_{comp} + W_{DHW,pump}) \times 3.413\,{}^{Btu}\!/\!_{Wh}}{(W_{pump} + W_{fan} + W_{comp} + W_{DHW,pump}) \times 3.413\,{}^{Btu}\!/\!_{Wh}}$$

where:

COP = coefficient of performance of the system [dimensionless]

Q_h = useful heat extracted from ground loop [Btu]

W_{comp} = energy consumed by the compressor [Wh]

W_{fan} = energy consumed by the fan [Wh]

W_{pump} = energy consumed by the ground-loop pump [Wh]

$W_{DHW,pump}$ = energy consumed by water heater or desuperheater pump, if appropriate [Wh]

The thermal energy from the ground (Q_h) in this equation primarily represents space heat, but depending on configuration it may also include some water heating. For example, if a desuperheater pump remains active during heating season, this pump energy is included in the numerator and denominator of the COP equation, as shown above.

The COP equation above assumes that 100% of the electric energy consumed by the fan and compressor is transferred into the air-stream. Performance data provided by the heat pumps monitored support this assumption (the difference between the air heating capacity and the total heat of extraction is almost identical to the total power of the fan and compressor). In addition, 100% of electric energy consumed by desuperheater or domestic hot water circulation pumps is assumed to be transferred into the water stream.

Monitoring Results

In the discussion below the term "COP when ON" includes only values when the GSHP was operating for the full logging

interval (15 minutes) at steady state. This does not include ramp up/down performance and standby electricity use. The "COP when ON" is split into two columns to separate the performance of the system in low stage and high stage operation. To determine if the GSHP was in low stage or high stage operation, the measured fan and compressor energy draws were compared to the manufacturer's data.

Connecticut System

The website advertising for WaterFurnace's Envision ground-source heat pump states the following performance: "30 EER / 5 COP (ARI 13256-1 GLHP)"[1]. Though specific to a particular tonnage unit and at one set of conditions, this is often perceived by consumers as the anticipated performance of the unit. A closer look at this particular ground-source heat pump unit comes up with an ISO/ARI rating of COP 5.1 for low stage and COP 4.2 for high stage. Again this is at one set of conditions (entering water of 32°F at full load and 41°F at part load, entering air at 68°F, and ground loop flow rates of 9 gpm at full load and 8 gpm at part load).

When looking at the complete system and the full range of conditions, the authors calculated an overall COP of 3.59; looking at energy use only when the heat pump was operating in steady state (when system is operating for the full 15-minute logging period, so this discounts part-load intervals and standby loads), the average COP was 3.76 for high stage and 3.60 for low stage. This averaged out to an overall COP when ON of 3.70. One noteworthy finding is the relatively large standby load of the heat pump system. When the heat pump is not operating, the system still consumes approximately 45 Watts (likely attributed to standby load and zoning controls).

Though 10-30% lower than the unit's rated efficiency, the heating performance of the overall ground-source heat pump system

Table 2. Monthly System Performance for Connecticut Site.

Month	Average Incoming Fluid Temp.	Overall COP when ON	COP when ON - High Speed	COP when ON - Low Speed
November 2007	53°F	4.1	4.1	4.2
December 2007	44°F	3.9	3.9	3.9
January 2008	40°F	4.1	4.1	4.2
February 2008	37°F	3.9	3.9	3.9
March 2008	39°F	3.9	3.9	3.9
April 2008	43°F	4.0	4.0	4.0
May 2008	49°F	3.9	3.7	3.9
October 2008	57°F	4.3	4.2	4.4
November 2008	51°F	4.1	4.1	4.2
December 2008	43°F	3.8	3.8	3.8
January 2009	38°F	3.7	3.7	3.6
February 2009	36°F	3.4	3.4	3.3
March 2009	37°F	3.2	3.3	3.2
April 2009	42°F	3.5	3.5	3.5
October 2009	56°F	4.2	4.2	4.2
November 2009	52°F	4.0	4.0	4.0
December 2009	44°F	3.7	3.7	3.7
January 2010	39°F	3.5	3.6	3.5
Winter Totals	43°F	3.7	3.8	3.6

appears to be quite good. Three years after the initial installation, the HVAC contractor for this GSHP commissioned the system to verify performance. By measuring the inlet/outlet ground loop pressure and temperature, as well as the supply/return air temperature, it was calculated that the heat of extraction was 17,460 Btu/hr. The heat of extraction, based on the manufacturer's data, should be 17,600 Btu/hr, so this system is working as intended.

Figure 1 shows the system COP when ON versus the incoming ground loop fluid temperature for each 15 minute period (system running for the entire logging period) when the system was heating. This system utilized a single speed ground loop pump that was operating at 10.8 gpm. The literature COPs in the figure below are based on 9 gpm for high stage and 8 gpm for low stage (these are the highest flow rates for which rated efficiencies are provided by the manufacturer for this heat pump).
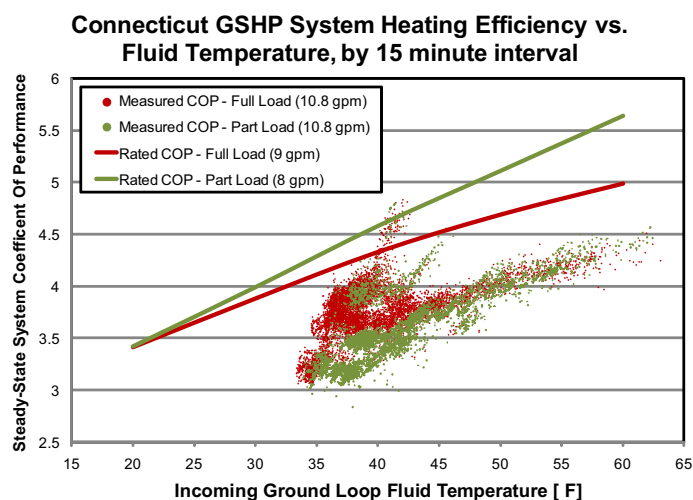

Figure 1. Steady state heating performance of Connecticut system from Nov. 2007 through Jan. 2010.

The full load system performance is actually better than the part load system performance. The authors speculate that this is due to the high single-speed ground loop flow rate and will be monitoring a similar system by the same HVAC contractor with a two speed ground loop pump to investigate this further. As this system was only designed to provide 80% of the design heating building load to save on first cost (auxiliary heating is provided by a Polaris water heater with a 90+% thermal efficiency), it tends to operate in full load for the majority of the heating season. The higher efficiency of low stage operation in literature is exaggerated in the rating process by operating the heat pump on low stage while the fan is at full speed. This increases the sensible capacity, but greatly hampers the latent capacity of the unit.[2] Installed units often use lower airflows at the lower heat pump stage.

Virginia System

This ground-source heat pump unit is ISO/ARI rated as COP 4.6 for low stage and COP 4.1 for high stage. CARB measured an overall COP of 3.25; looking at energy use only when the heat pump was operating in steady state (when system is operating for the full 15-minute logging period, referred to as "COP when ON"), the average COP was 3.48 for high stage and 3.32 for low stage. This averaged out to an overall COP when ON of 3.39. It should

Table 3. Monthly System Performance Summary for Virginia Site.

Month	Average Incoming Fluid Temp.	Overall COP when ON	COP when ON - High Speed	COP when ON - Low Speed	COP when ON - High Speed [half pump power]	COP when ON - Low Speed [half pump power]
February 2009	37°F	3.1	3.2	3.0	3.5	3.4
March 2009	40°F	3.1	3.2	3.1	3.6	3.5
October 2009	70°F	3.9	3.9	3.9	4.3	4.5
November 2009	57°F	3.7	3.8	3.7	4.2	4.2
December 2009	46°F	3.5	3.5	3.5	3.9	4.0
January 2010	38°F	3.5	3.5	3.4	3.9	3.9
February 2010	36°F	3.6	3.6	3.5	4.0	4.0
March 2010	38°F	3.0	3.3	2.8	3.7	3.2
Winter Totals	40°F	3.4	3.5	3.3		

be noted that a correction to our useful heating energy calculation was made in September 2009. The original monitoring program assumed 10% propylene glycol solution rather than the Environol 1000 solution (~21% ethanol mixture) that was actually installed. This resulted in a less than 2% error in the performance results of the initial data.

The pump flow rate is consistent at nearly 11.8 gpm regardless of operation stage due to the single speed pumps. The literature COPs in the figure below are based on 12 gpm for high stage and 11 gpm for low stage, so they are in line with the installed system.

One noteworthy finding is the relatively large ground loop pump load of the heat pump system. Compared to a split ground loop configuration where a pump drawing closer to 265 Watts (as in the Connecticut site) could be utilized, this system shares a ground loop with the 2nd floor GSHP and the dual-pump flow station (2 Grundfos - GeoLink Type UP26-116F pumps) is drawing 713 Watts. Regardless of whether one GSHP or both GSHPs are operating, the pump power draw is the same. To simulate potential performance if the two GSHPs had separate ground loop systems, a COP utilizing half the pump power was calculated as well and shown in Figure 2.

Also, when the system was initially installed, it became evident fairly quickly that there was air in the ground loop due
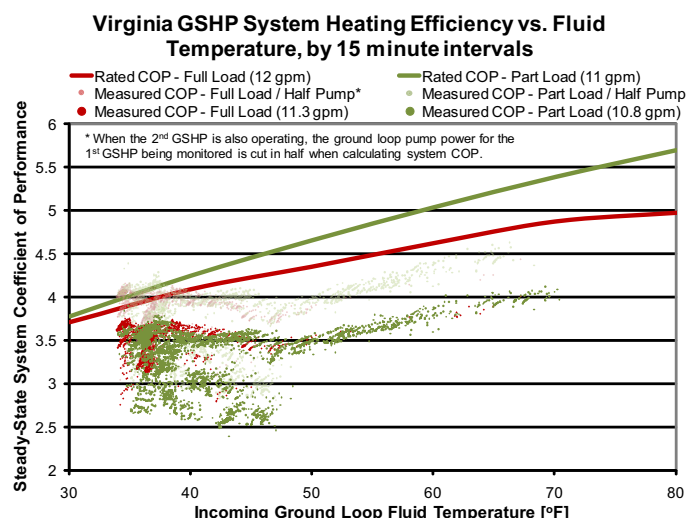
to the flow noise that was audible from the ground loop piping within the basement. The HVAC contractor had to come out to this site several times to purge the ground loop of air. The measured heating capacity for low and high stage are within the manufacturer's listed capacity ranges, so it is unlikely that air prevented flow in a loop section of the ground field, as this would cut down on the ground-coupling capacity of the heat pump unit.

It was later discovered that there was a problem with the 2nd floor heat pump unit that left it out of commission for about two-three weeks in August 2009. The air in the lines worked its way up to the top of the line and caused the upper air handler to freeze up and stop working. That issue may have skewed our initial data if the two GSHPs have a significant impact on one another. Though this does not appear to be the case after further analysis of the data.

According to the WaterFurnace's installation manual, the system needs to be flushed/purged "adequately to remove as much air as possible then pressurize the loop to a static pressure of 40-50 PSI (summer) or 50-75 PSI (winter). Pressures will be higher in the winter months than during the cooling season. This fluctuation is normal and should be considered when initially charging the system. After pressurization, be sure to turn the venting (burping) screw in the center of the pump two (2) turns open (water will drip out), wait until all air is purged from the pump, then tighten the plug. Ensure that the loop pumps provide adequate flow through the unit(s) by checking the pressure drop across the heat exchanger and comparing it to the unit capacity data in the specification catalog."[3] Typically, a 2-4 feet per second flow rate through the entire ground loop is needed to properly purge the system.[4]

Wisconsin System

This ground-source heat pump is ISO/ARI rated as EER 23.7/ COP 4.5 for low stage and EER 18.5/ COP 4.0 for high stage. In addition to space conditioning, this Synergy unit has a DHW

Virginia GSHP System Heating Efficiency vs. Fluid Temperature, by 15 minute intervals

Legend:
- Rated COP - Full Load (12 gpm)
- Measured COP - Full Load / Half Pump*
- Measured COP - Full Load (11.3 gpm)
- Rated COP - Part Load (11 gpm)
- Measured COP - Part Load / Half Pump*
- Measured COP - Part Load (10.8 gpm)

* When the 2nd GSHP is also operating, the ground loop pump power for the 1st GSHP being monitored is cut in half when calculating system COP.

Y-axis: Steady-State System Coefficient of Performance (2 to 6)
X-axis: Incoming Ground Loop Fluid Temperature [°F] (30 to 80)

Figure 2. Steady state heating performance of Virginia system from Feb 2009 through Mar. 2010.

Table 4. Monthly System Performance Summary for Wisconsin Site.

Month	Average Incoming Fluid Temp.	Heating COP when ON - High Speed	Heating COP when ON - Low Speed	DHW COP when ON
June 2009	53°F	3.7	3.6	2.5
July 2009	70°F	-	-	-
August 2009	72°F	4.1	4.2	2.8
September 2009	71°F	4.2	4.2	2.9
October 2009	55°F	4.1	4.2	-
November 2009	46°F	3.9	4.0	2.5
December 2009	38°F	3.6	3.6	2.4
January 2010	32°F	3.3	3.3	2.0
February 2010	31°F	3.2	3.1	2.1
March 2010	31°F	3.2	3.1	2.1
Avg.	41°F	3.4	3.4	2.4

mode which is ISO/ARI rated at COP 3.3 at the following conditions: 7 gpm source flow, 7 gpm load flow, 100°F entering load temperature, and 40°F entering source temperature.

The authors calculated an overall COP of 3.09; looking at energy use only when the heat pump was operating in steady state (when system is operating for the full 15-minute logging period), the average COP was 3.44 for both high stage and low stage. The DHW COP when ON was 2.43. The overall average in the table below is not an average of the monthly averages, but an average for the entire heating period (which is mostly at the lower incoming fluid temperature, <45°F).

Figure 3 shows the average monthly measured COP of the system vs. the manufacturer listed COP for the heat pump only. This system utilizes a single speed ground loop pump that is operating at roughly 7.4 gpm. The listed COPs in the figure below are based on ground loop flow rates of 7 gpm for high stage and an interpolated 7 gpm for low stage (manufacturer data provided performance ratings at 6 gpm and 8 gpm). The listed DHW COP is also based on 7 gpm ground loop flow rate, 7 gpm DHW flow rate and 100°F entering load temperature.
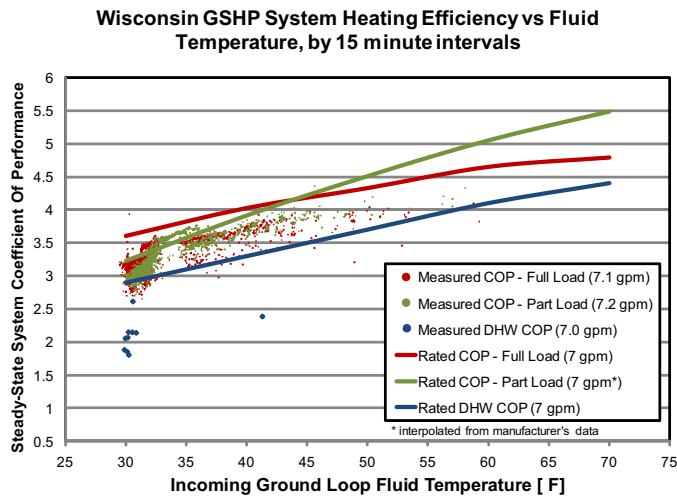
the water heater that has independent controls set to maintain heat at roughly 110°F.

In general, the desuperheater was acting as anticipated - essentially "robbing" heating capacity from the space conditioning to provide water heating during heating/DHW mode. During the coldest winter months, there was minimal operation of the electric resistance water heater.
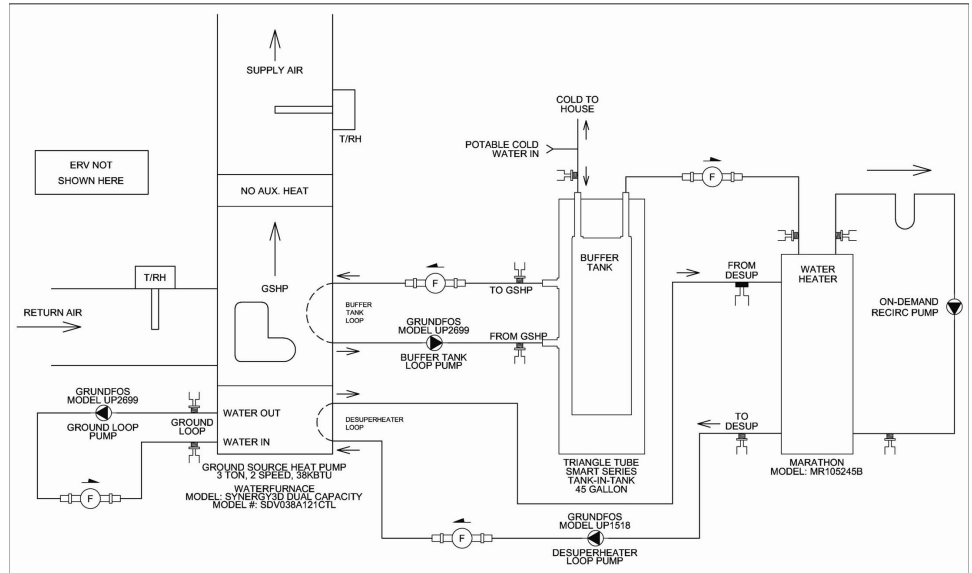

Figure 4. Schematic of the Wisconsin GSHP System.

Figure 3. Steady state heating performance of Wisconsin system from Jun 2009 through Mar. 2010.

An interesting aside for this installation was evaluation of the desuperheater. Typical operation of a desuperheater provides water pre-heating during cooling mode operation, but during heating mode, it robs heating capacity from the space conditioning to water providing pre-heating. A reversing valve or smarter control logic (available in some newer GSHP models) is needed to avoid the space heating penalty, if this is of concern.

The authors recommend to all contractors to pipe the desuperheater to a pre-heat tank and not directly to the electric resistance water heater. The ideal use of a desuperheater is for pre-heating water. In this home, it is being directly plumbed to

In cooling mode, the desuperheater is having a negative impact due to it being plumbed to the primary water heater instead of the pre-heat tank. The energy taken from the water heater is dumped to the ground as waste heat. The positive contribution from the desuperheater during the June period shown in the figure below was when the GSHP was operating in the DHW mode. On a whole for the cooling months, the desuperheater is more beneficial in DHW mode compared to the negative impact in cooling mode. Therefore, the desuperheater was not shut off during the cooling mode.

Figure 5 shows the daily heating contribution of the various components (electric water heater, drain water heat recovery, desuperheater, and buffer tank, which refers to the GSHP DHW mode) that heat water for this home. Daily hot water usage is also shown on the 2nd y-axis.

When there is no demand for hot water and the GSHP is providing space heating, the desuperheater is having a negative impact to water heating, but this just means it is "robbing" heat from the water heater which increases heating capacity (the return temperature from the desuperheater loop was higher than the supply temperature during heating). Without any water demand, the primary tank is not losing heat except for standby loss. At some point, the tank temperature is hot enough that the energy provided by the desuperheater will not be useful and the desuperheater return temperature is actually returning hotter than it was leaving the GSHP. When there are draws for hot water, the tank temperature drops (from the incoming mains water temperature) and the desuperheater once again is able to provide useful energy.
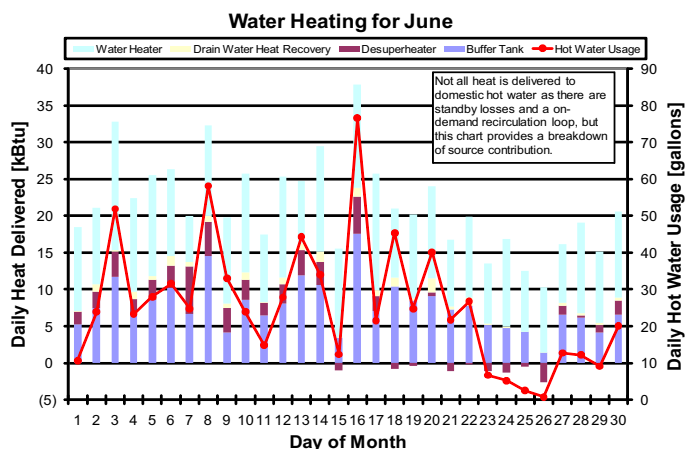
Figure 5. Domestic Water Heating Component Contributions for June 2009.

Systems Summary

As expected, the measured COP values for these heat pumps were substantially lower than the rated COPs. While the industry understands this discrepancy, the authors have seen persistent misconceptions in consumers – and even in some contractors – who expect installed performance to match rated, "advertised" performance. An overall comparison is shown in Table 5.

Table 5. Overall System Performance Summary for All Three Sites.

Project	ISO/ARI Rated Heat Pump Efficiency		Actual System Efficiency When ON		Performance Difference	
	low stage [COP]	high stage [COP]	low stage [COP]	high stage [COP]	low stage [COP%]	high stage [COP%]
Connecticut	5.1	4.2	3.6	3.8	29.4%	9.5%
Virginia	4.6	4.1	3.3	3.5	28.3%	14.6%
Wisconsin	4.5	4.0	3.4	3.4	24.4%	15.0%
Avg.	4.7	4.1	3.4	3.6	27.4%	13.1%

Energy Modeling Implications

During years of involvement in the home energy rating industry, the authors have experienced very inconsistent modeling of residential ground-source heat pumps. The two energy modeling software discussed here, REM/Rate (from Architectural Energy Corp.) and EnergyGauge USA (from the Florida Solar Energy Center), are commonly used for predicting home energy use and for generating HERS index values.

When modeling a home with a GSHP, REM/Rate software asks for the following system parameters:

- Capacity (both heating and cooling)
- Efficiency (COP and EER)
- Backup electric resistance heating capacity (if present)
- Sensible heat ratio
- Distribution type (air distribution or hydronic)
- Pump power
- Fan power
- Desuperheater included (yes/no)
- Ground field description (field type, # of wells, depth, flow rate)

The EnergyGauge USA (EGUSA) software asks users to input fewer system parameters:

- Capacity (both heating and cooling)
- Efficiency (COP and EER)
- Sensible heat ratio
- Distribution type (air distribution or hydronic)
- Tested coil air flow

Until quite recently (2008-2009), the authors found that the COP value that a modeler entered into the software was the effective, seasonal COP of the modeled system. For instance, if heat pump literature showed a rated COP of 5.0, and if 5.0 was entered into the software, the ratio of the modeled annual thermal load to modeled electricity consumed for heating would be very near 5.0. Clearly the software tools were not accurately accounting for real performance of installed systems (including pump energy, fan energy, varying field temperatures, etc.).

In 2009, RESNET amended its 2006 RESNET Mortgage Industry National Home Energy Rating Systems Standards. This amendment (Section 303.5.1.7) addressed GSHP auxiliary electric consumption so that the GSHP pump and fan electric consumption are more accurately modeled. It appears that when software developers updated modeling tools based on this standard, the variance between modeled and true GSHP performance was greatly reduced (see Table 6).

Table 6. Inputted, Modeled, and Measured Coefficients of Performance. The COP entered into modeling software is the rated low-stage COP for the equipment.

System	Model Input COP	Modeled Heating COP		Measured COP
		EGUSA	REM/Rate	
CT	5.1	3.2	3.7	3.6
VA	4.6	4.1	3.0	3.3
WI	4.5	3.0	3.5	3.1

Of course, installed performance of a heat pump will vary depending on the thermal load, weather, ground field conditions, geology, duct configuration, etc. It's unreasonable to expect simple modeling tools to be tremendously accurate when so many variables contributing to performance are not known. Table 6 shows, however, that modeled COP and measured COP values are relatively close; newer models certainly provide better estimates of energy consumption than models where the rated COP is assumed to be the effective, installed COP.

The appropriate COP value to enter, however, is not necessarily clear from software instructions, especially when two-stage equipment is used. REM/Rate's help library instructs users "to use the values listed in the Air-Conditioning, Heating, and Refrigeration Institute (AHRI, formerly ARI) Directory of AHRI Certified Water-to-Air and Brine-to-Air Heat Pumps", while EnergyGauge USA instructs users that the input values are "typically available from the manufacturer." Instructions for neither software discuss how to input dual stage GSHPs. In discussions with the authors, technical support personnel from both software developers suggested using the listed, rated efficiency for the heat pump stage (i.e. part-load or full-load) that the modeler expects to be used most often. Alternately, and if available, an average COP can be used based on estimated runtime at each stage.

As it is probably unreasonable to expect a rater to accurately assess GSHP run-time in high-stage vs. low-stage, the authors recommend using the rated COP for the stage most often used. As design conditions are rare, it's expected most heat pumps sized to meet the entire residential heating load will most often run at low stage. It was rated, low-stage COPs (ASHRAE/ISO 13256-1 low-stage rating) that were used for modeling in Table 6. It is also important to find the rated COP for the exact model installed; some manufacturer literature lists the highest COP for the whole product line. Different capacities or models will usually have different rated COP values.

When modeling residential GSHPs, it's also important to properly input pump and fan power into the modeling software. Table 7 shows the effect that these inputs have on the modeled heating COP in REM/Rate (Energy Gauge USA always uses default values). While it is possible to use default fan power in REM/Rate, the default pump power is zero (though leaving it as zero does generate a warning).

Table 7. Impact of Pump and Fan Energy on Modeled COP in REM/Rate.

System	REM/Rate Modeled Heating COP				
	Model Input COP	Measured Pump + Fan Power	Measured Pump , Default Fan Power	Default (Zero) Pump, Measured Fan Power	Measured COP
CT	5.1	3.7	3.8	4.5	3.6
VA	4.6	3.0	3.2	4.4	3.3
WI	4.5	3.5	3.6	4.2	3.1

Summary and Conclusions

Ground-source heat pump systems are certainly a viable technology for providing heating and cooling in high-performance, cold-climate homes. When compared to high-efficiency fossil fuel heating equipment (such as a condensing natural gas furnace), all of the monitored systems provide energy cost savings.

If designed and installed properly, this technology is very reliable, but the growing demand for the technology has resulted in an influx of inexperienced contractors installing these systems. The authors have heard numerous anecdotal accounts of malfunctioning ground source heat pumps that result in poor performance and/or high costs. Of the three homes investigated here, one home had a malfunctioning heat pump system (Virginia) that required several visits from the installing contractor. It is unclear if these problems would have been identified without detailed long-term monitoring. As with nearly all advanced mechanical systems, commissioning is critical to ensure proper, efficient performance.

Performance ratings of ground source heat pumps are often misleading to consumers. Most advertised COP ratings are the highest achieved at various ground water temperature, air temperature, capacities, etc. Furthermore, the COP and EER ratings do not include the real-world electric energy required for ground water pumping and conditioned air distribution. As pump and fan energy can vary significantly between different installations, it's understandable that this is not included in the ratings, but this still leads to misconceptions related to performance. The overall winter system COP at the Connecticut Project, for instance, was 3.6; the advertised unit COP is 5.0.

It is encouraging, however, that the residential energy modeling tools discussed here (REM/Rate v12.83 and Energy Gauge USA v2.8.03) do account for real-world fan and pump energy. When manufacturers' GSHP data were put into these software tools, the modeled, seasonal COPs obtained were reasonably close to the authors' measured, seasonal COP values from the homes.

Acknowledgements

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