MEASURED SPACE CONDITIONING AND WATER HEATING PERFORMANCE OF A GROUND-SOURCE INTEGRATED HEAT PUMP IN A RESIDENTIAL APPLICATION

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Abstract: In an effort to reduce residential building energy consumption, a ground-source integrated heat pump was developed to meet a home's entire space conditioning and water heating needs, while providing 50% energy savings relative to a baseline suite of minimum efficiency equipment. A prototype 7.0 kW system was installed in a 344 m^2 research house with simulated occupancy in Oak Ridge, TN. The equipment was monitored from June 2012 through January 2013.

Key Words: integrated heat pump, ground-source, geothermal, variable-speed, field measurement

1 INTRODUCTION

In support of the United States Department of Energy's (DOE's) effort to reduce heating, cooling, and water heating energy use, Oak Ridge National Laboratory partnered with a leading geothermal heat pump manufacturer to develop a ground-source integrated heat pump (GSIHP) that would be capable of providing all of the required heating, cooling, and water heating to a residential home. Variable-speed components (pumps, fan, and compressor) allow the unit to operate over a wide range of capacities and modulate to meet the desired load. Efficiency is greatly increased at part-load conditions due to the benefit of unloading the heat exchangers. The condenser waste heat from space cooling is utilized to heat water when there is a simultaneous requirement for space cooling and water heating that provides additional efficiency improvement. The initial development and modeling of this system are detailed in a prior report (Rice, et al., 2013), and the field test results will be outlined in this paper.

2 EQUIPMENT DESCRIPTION

The ground-source integrated heat pump (GSIHP) design includes all variable-speed components, compressor, ground loop pump, domestic hot water (DHW) pump, and indoor blower motor. The GSIHP was coupled with a 303 L hot water storage tank, and the DHW pump was used to circulate the water between the GSIHP and the tank. The heat exchangers (HXs) consist of a micro-channel air-to-refrigerant HX, a double wall brazed plate HX for the DHW HX, and a single wall brazed plate HX for the ground loop-to-refrigerant HX. The unit operated in four distinct modes, space cooling (SC), space heating (SH), space cooling plus water heating (SC+WH), and dedicated water heating (DWH) with the heat source/sink in each mode shown in Table 1. The SC+WH mode is unique because the heat transfer at both the heat source and heat sink are desirable outputs of the process.

Table 1: GSIHP Operating Modes

Mode	Heat Source	Heat Sink
Space Cooling	Indoor Air	Ground Loop
Space Heating	Ground Loop	Indoor Air

Space Cooling plus Water Heating	Indoor Air	Domestic Hot Water
Dedicated Water Heating	Ground Loop	Domestic Hot Water

3 HOUSE DESCRIPTION

The GSIHP was installed in a 344 m^2 research house with simulated occupancy in Oak Ridge, Tennessee. The home was 2-stories tall with an unfinished walkout basement where the GSIHP was installed. The home was split into four zones, upstairs, downstairs living space, master bedroom, and basement, which were all controlled to same set points of 21.7°C for heating and 24.4°C for cooling. The envelope of the home utilized an optimum value framing (OVF) technique, fully insulated foundation, and triple pane windows (Ally, Munk, & Baxter, 2011). The 796 m of ground loop heat exchanger were placed around the foundation of two of the basement walls in addition to the utility trench and a rain garden in the backyard (Im, Hughes, & Liu, 2012).

4 MEASURED PERFORMANCE

The following sections will detail the measured equipment performance in the four modes of operation for the time period from June 1st, 2012 to January 31st, 2013. During the cooling season, the unit can operate in three of the four modes: SC, SC+WH, or DWH. If there are coincident space cooling and water heating demands, the unit will run in the SC+WH mode. If there is only a demand for water heating, the unit will run in DWH mode. During the heating season, the unit only operates in two of the four modes: SH and DWH. There is no combined space heating and water heating mode, so the unit gives water heating priority unless the indoor space temperature falls a preset number of degrees below the heating set point.

Since the unit was installed in the conditioned basement of the home, all heat rejected by the compressor, pumps, fans, and electronics was assumed to be delivered to the living space. For the purpose of calculating equipment capacities, either the ground loop measurements or DHW loop measurements were used in conjunction with the total system power to calculate the resulting net capacities.

4.1 Space Cooling Performance

The space cooling capacity is calculated based on measurements of the entering water temperature (EWT), leaving water temperature (LWT), ground loop flow rate, and the system power use as seen in equation 1. Table 2 shows the space cooling performance of the GSIHP on a monthly basis.

$$\dot{Q}_{Cooling} = \dot{V}_{Loop}\rho_{loop}c_{loop}(LWT - EWT) - \dot{W}_{Total} \tag{1}$$

Table 2: GSIHP Space Cooling Performance

	June	July	August	September	October
Average Outdoor Temp (°C)	24.0	26.3	23.6	20.5	13.6
Average Entering Water Temperature (°C)	22.8	27.7	27.7	26.1	22.3
Average Cooling Capacity (kW)	3.75	4.74	3.41	3.03	2.12
Average Total Power (kW)	0.71	1.08	0.73	0.61	0.49
Average COP (W/W)	5.3	4.4	4.7	5.0	4.3
Runtime (h)	357.2	483.0	478.3	295.7	50.5

Since the indoor conditions were held relatively constant by the GSIHP, the two major contributors to variations in SC efficiency are the ground loop EWT and the compressor speed (represented by cooling capacity). Figure 1 is a plot that illustrates how the efficiency varied with respect to these two factors. As expected, efficiency shows a strong dependency on the EWT, as seen by comparing the different lines. The lower the EWT for any given compressor speed, the higher the cooling efficiency. Likewise, it can be seen that efficiency increases as the compressor speed is reduced and the heat exchangers are unloaded. The majority of the data points fall in the lower capacity ranges indicating that the unit spent the majority of the time running in the lower compressor speed ranges. This is reinforced by the long runtimes seen in Table 2, with the unit operating in the space cooling mode for 65% of the total time in the month.

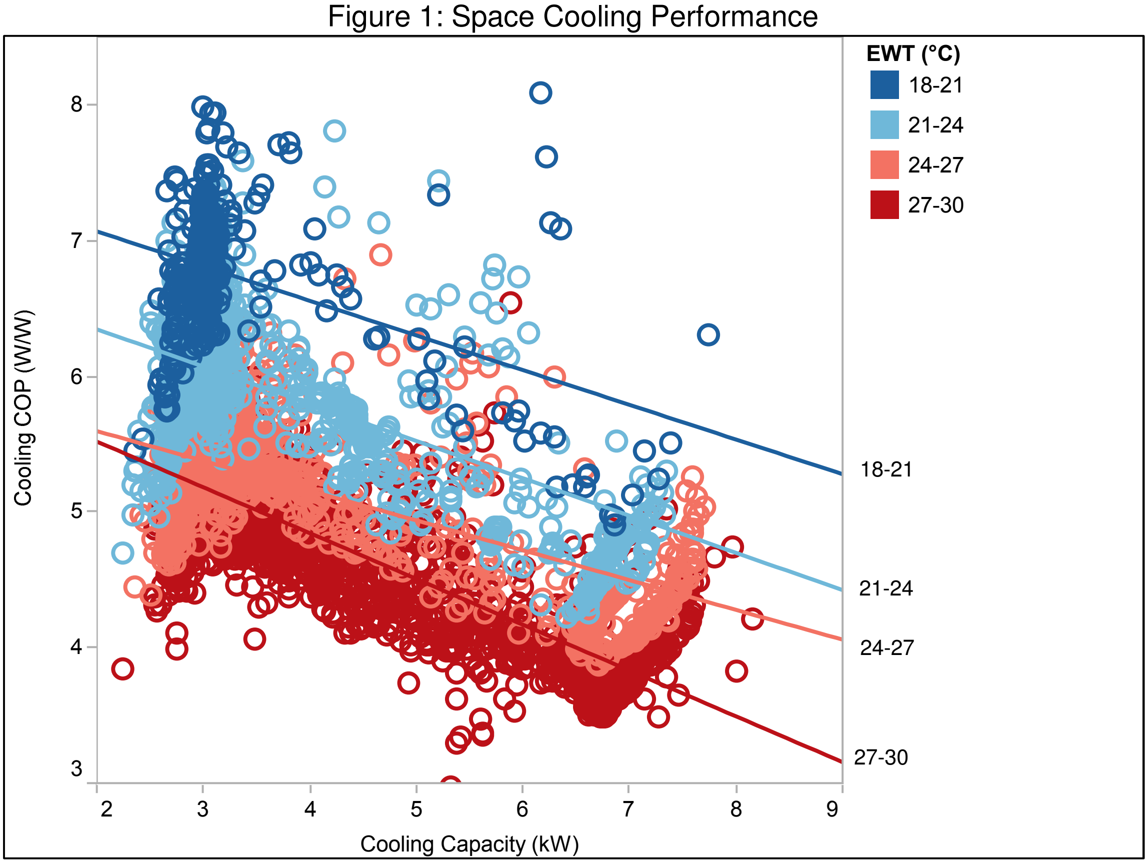

Figure 1: Space Cooling Performance

4.2 Space Cooling Plus Water Heating Performance

The SC+WH mode provides simultaneous space cooling and water heating and operates only when there are simultaneous cooling and water heating demands. In the SC+WH mode, the water heating capacity was measured directly from the DHW flow and entering and leaving DHW temperatures from the unit as seen in equation 2.

$$\dot{Q}_{WH} = \dot{V}_{DHW}\rho_{DHW}c_{DHW}(LDHWT - EDHWT) \quad (2)$$

Since the DHW is the heat sink in the SC+WH mode, the net space cooling capacity is calculated by subtracting the total power input to the system from the water heating capacity as seen in equation (3).

$$\dot{Q}_{Cooling} = \dot{Q}_{WH} - \dot{W}_{Total} \quad (3)$$

The efficiency in the SC+WH mode is calculated in two different ways, the combined COP and the WH only COP. The combined COP is calculated by summing the two useful outputs of SC and WH and dividing by the total power use. However, this number is difficult to compare to conventional setups where one piece of equipment provides the SC and another provides the WH. In order to estimate a WH only COP for the SC+WH mode, the energy that would have been used in the SC mode is subtracted from the total power, and the WH capacity is divided by the resulting power as shown in equation 4. For simplicity, the average monthly SC COP from Table 2 was used in the WH only COP calculations for the SC+WH performance shown in Table 3. It should be noted that the WH capacity and COP calculations do not account for any storage tank or interconnecting piping losses and only represent the performance of the equipment itself.

$$COP_{WH} = \frac{\dot{Q}_{WH}}{\dot{W}_{Total} - \frac{\dot{Q}_{WH}}{COP_{SC}}} \quad (4)$$

Table 3: GSIHP Space Cooling Plus Water Heating Performance

	June	July	August	September	October
Average Water Heating Capacity (kW)	3.59	4.63	3.99	3.76	3.28
Average Cooling Capacity (kW)	2.31	3.23	2.74	2.56	2.19
Average Total Power (kW)	1.28	1.40	1.25	1.20	1.09
Average Combined COP (W/W)	4.6	5.6	5.4	5.3	5.0
Runtime (h)	49.2	37.4	50.1	45.3	29.9
Average WH COP if Cooling @ Average SC COP (W/W)	4.3	7.0	6.0	5.5	5.6

The water heating capacity in the SC+WH mode averaged between 3.3 and 4.6 kW for the months of June to October. This is very close to the typical 4.5 kW capacity of a standard electric water heater and therefore should be able to meet similar hot water loads. The estimated WH only COP is greater than 4.3 for all months and shows the efficiency benefit available when taking advantage of both the heating and cooling effects of a vapor compression cycle.

4.3 Dedicated Water Heating Performance

The dedicated water heating mode operates whenever there is not a simultaneous cooling demand during water heating. The water heating capacity is calculated in the same way as it was in the SC+WH mode, equation 2. Table 4 shows the average monthly performance for the DWH mode for the entire test period. It should be noted that in during the summer months, there was very little or no use of the DWH mode. This is due to the fact that the unit was running at low capacity in the SC mode for extended periods of time, which increases the likelihood of the unit being able to run in the SC+WH mode to satisfy the water heating demand.

In the DWH mode, the two factors that have the largest influence on water heating performance are the EWT and entering domestic hot water temperature (EDHWT). Figure 2 shows the water heating efficiency plotted against these two factors. As expected, the efficiency increases as the ground loop EWT increases thereby reducing the compression pressure lift. Likewise, the compression pressure lift is decreased with lower EDHWTs, which also increases water heating efficiency.

Table 4: GSIHP Dedicated Water Heating Performance

	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan

Average EWT (℃)	21.6	26.9	N/A	24.9	21.6	15.2	11.4	6.7
Average Water Heating Capacity (kW)	3.39	2.77	N/A	3.00	3.72	4.41	4.58	4.77
Average Total Power (kW)	1.44	0.68	N/A	0.76	0.92	1.22	1.39	1.60
Average COP (W/W)	4.0	4.1	N/A	3.9	4.0	3.6	3.3	3.0
Runtime (h)	5.6	2.4	N/A	14.2	35.0	59.0	53.6	62.0

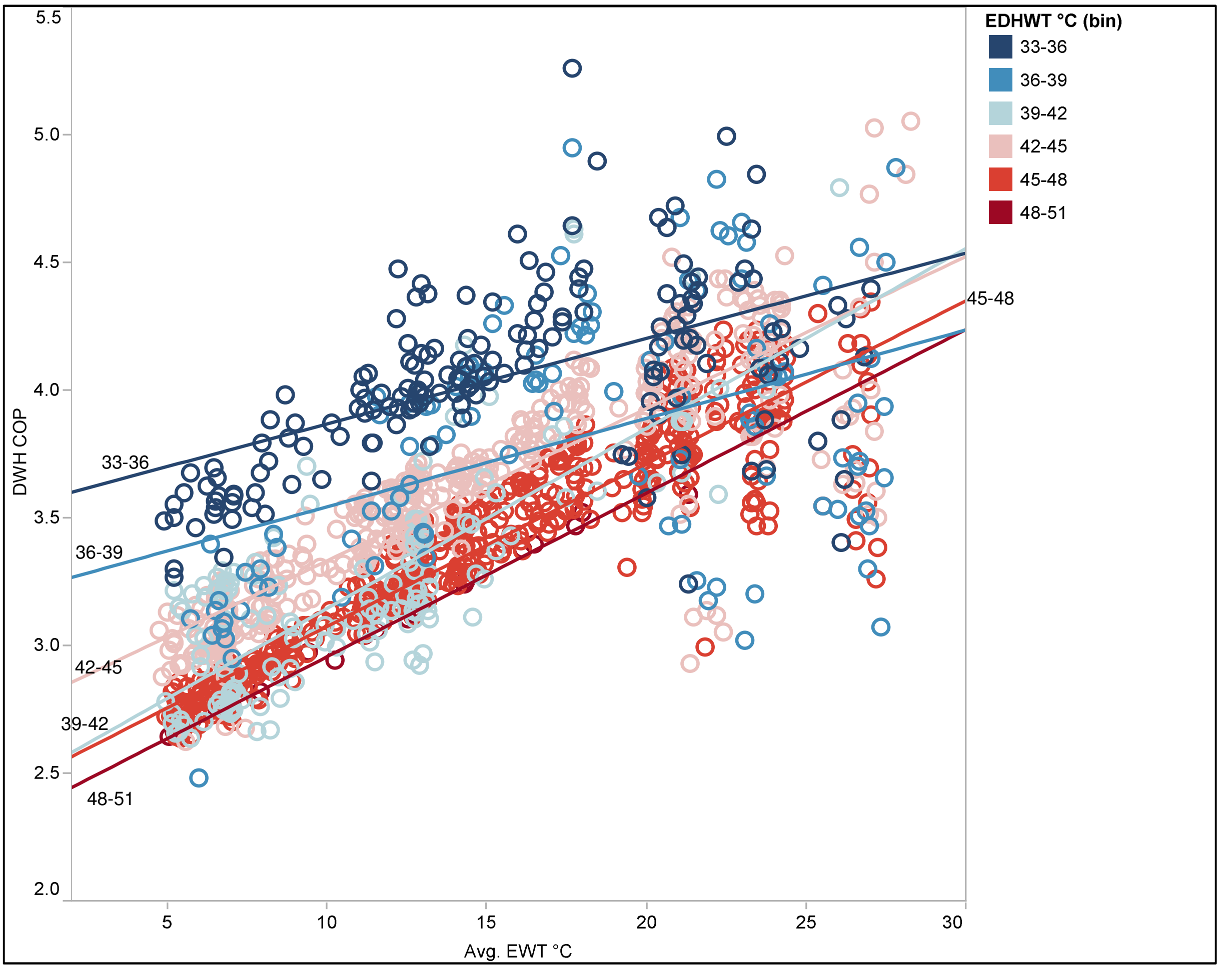

Figure 2: Dedicated Water Heating Performance

4.4 Space Heating Performance

The space heating capacity is calculated based on measurements of the EWT, LWT, ground loop flow rate, and the system power use as seen in equation 5. Table 5 shows the monthly average SH mode performance. As with the SC mode, the SH mode has very high runtime in the peak heating months of November through January with the runtime as a percentage of total time reaching approximately 80% in January. The average monthly SH mode COPs range from 3.9 to 5.3 with a strong dependence on the EWT. As with the SC mode, the major factors influencing the efficiency in the SH mode are the ground loop EWT and the compressor speed (represented by heating capacity) shown in Figure 3. As with the SC mode, efficiency increases as the compressor speed (capacity) is reduced. Efficiency also increases with an increase in the EWT as this reduces the temperature lift of the vapor compression cycle.

$$\dot{Q}_{Heating} = \dot{V}_{Loop}\rho_{loop}c_{loop}(EWT - LWT) + \dot{W}_{Total} \quad (5)$$

Table 5: GSIHP Space Heating Performance

	September	October	November	December	January
Average Outdoor Temp (℃)	20.5	13.6	8.0	7.7	5.3
Average EWT (℃)	25.2	20.3	15.1	11.2	6.8
Average Heating Capacity (kW)	1.85	2.48	3.45	4.10	4.84
Average Total Power (kW)	0.22	0.47	0.67	0.94	1.25
Average COP (W/W)	8.4	5.3	5.2	4.4	3.9
Runtime (h)	14.4	208.2	499.7	479.8	594.0

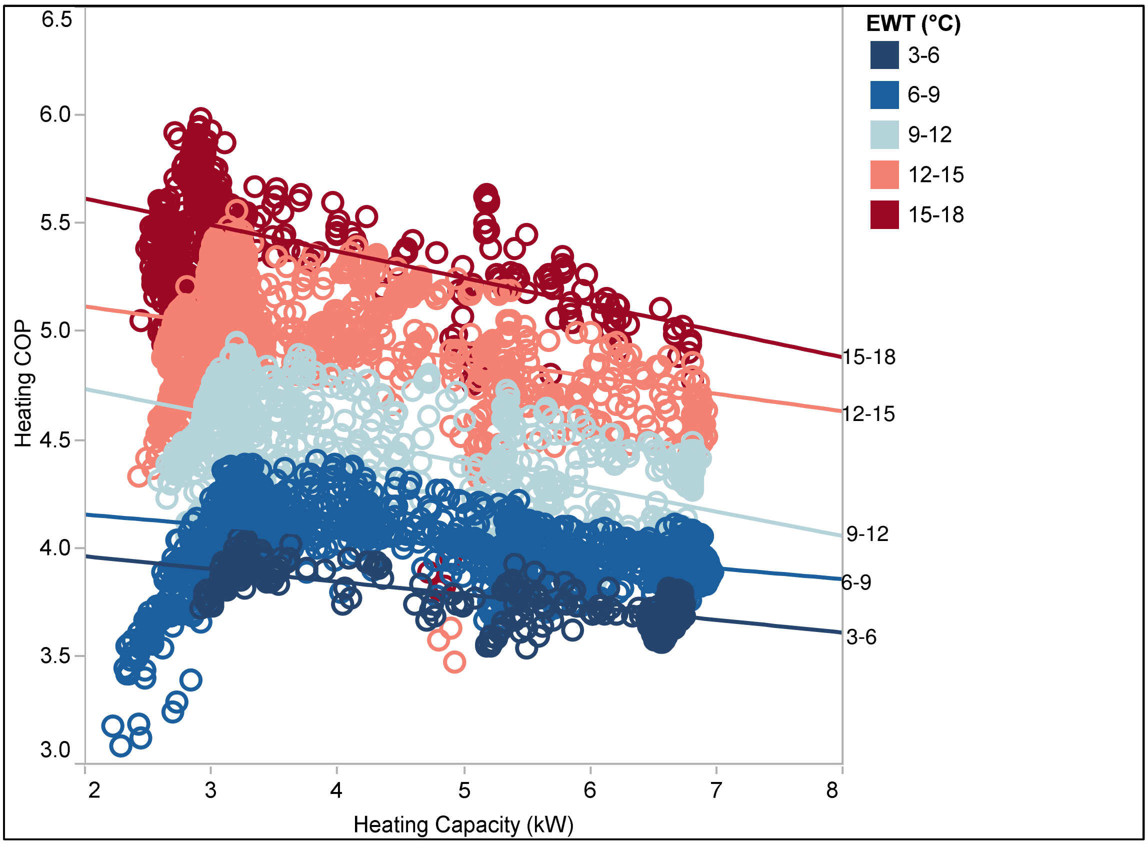

Figure 3: Space Heating Performance

5 ANNUAL PERFORMANCE

Since an entire year's worth of data was not able to be collected during the project, estimates were made for months where data was not available. The first step in this process was to fit a sinusoidal wave to the daily average OAT and daily average EWT data (the EWT data was averaged only when the GSIHP was running in order to prevent off-cycle measurements from skewing the data). These waveforms were then used to generate average monthly OATs and EWTs for the months without data, Figure 4. The load in each mode was then estimated by plotting the monthly delivered output in kWh against the average OAT for the month. A linear fit was applied and along with the estimated OAT, a delivered load was estimated for months without data. Similarly the COPs for each mode were estimated by plotting the existing data against the average EWT for each month. Results are shown in Table 6 below, with estimated data shown with gray filled cells. When the outputs of the SC+WH mode are split between cooling and water heating, the annual space cooling COP is unchanged at 4.9 since the SC mode COPs were used to determine the energy use in the SC+WH mode that should be charged to space cooling. However, the annual water heating COP is 3.8 and is 15% higher than the DWH mode annual COP. The space cooling performance is similar to the performance seen from high end air-source heat pumps that have been tested in this climate. However, the water heating COP of 3.8 and space heating COP of 4.1 are very high relative to air-source heat pumps.

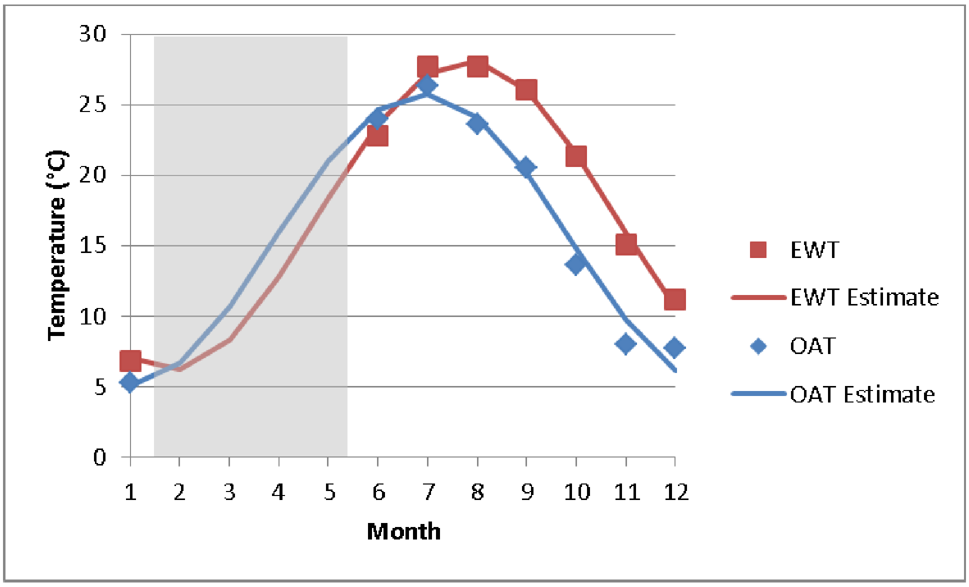

Figure 4: OAT and EWT Measured Data and Estimates

Table 6: GSIHP Annual Performance

Mode		Annual	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	OAT (°C)		5.3	6.7	10.7	15.9	21.0	24.0	26.3	23.6	20.5	13.6	8.0	7.7
	EWT (°C)		6.8	6.2	8.3	12.7	18.4	22.8	27.7	27.7	26.1	21.3	15.1	11.2
SC	COP	4.9				6.8	6.0	5.3	4.4	4.7	5.0	4.3		
	Delivered (kWh)	7807				353	1164	1339	2287	1633	895	107		
	Consumed (kWh)	1579				52	194	254	520	351	180	25		
SC + WH	Combined COP	5.2				5.2	5.2	4.6	5.6	5.4	5.3	5.0		
	Cooling COP	4.9				6.8	6.0	5.3	4.4	4.7	5.0	4.3		
	Cooling Delivered (kWh)	625				42	57	85	121	137	116	66		
	Cooling Consumed (kWh)	128				6	10	16	27	30	23	15		
	WH COP	5.4				4.4	4.3	4.3	7.0	6.0	5.5	5.6		
	WH Delivered (kWh)	922				60	88	132	173	200	170	98		
	WH Consumed (kWh)	171				13	21	31	25	33	31	17		
DWH	COP	3.3	3.0	2.9	3.1	3.5	3.8	4.0	4.1		3.9	4.0	3.6	3.3
	Delivered (kWh)	1811	330	303	216	122	53	19	7		43	158	286	275
	Consumed (kWh)	555	111	105	70	35	14	5	2		11	39	79	84
SH	COP	4.1	3.9	3.6	4.0						8.4	6.4	5.1	4.4
	Delivered (kWh)	10524	2863	2289	1200						27	495	1706	1944

	Consumed (kWh)	2539	742	636	302						3	77	333	447

The predicted annual energy use of the GSIHP can then be compared to that of the baseline equipment suite consisting of a 13 seasonal energy efficiency ratio (SEER), 8.3 Region III heating seasonal performance factor (HSPF) heat pump, as rated per AHRI 210/240 (AHRI, 2008), coupled with an electric resistance water heater. The cooling performance has been degraded by 4.7% based on manufacturer's performance data to account for return air conditions that are different from those in the AHRI 210/240 rating tests. The results for this comparison are shownTable 7. Since the tank losses from the hot water storage tank were note accounted for in the GSIHP performance, they are also omitted from the baseline equipment efficiency resulting in a WH COP of 1.0. The table shows that the largest percentage and absolute savings come from water heating, at 73.4% and 2007 kWh respectively. The energy savings in the space heating mode come in a close second at 1798 kWh due to both the high efficiency and high heating load. The total annual savings when compared to the Baseline equipment is predicted at about 47%, which is very close to the 50% targeted savings for the project.

Table 7: GSIHP Annual Performance Compared to Baseline Equipment

		GSIHP	**Baseline Equipment**	**Percent Savings Over Baseline**
Space Cooling	COP	4.9	3.7	
	Delivered (kWh)	8432	8432	
	Consumed (kWh)	1707	2298	25.7%
Space Heating	COP	4.1	2.4	
	Delivered (kWh)	10524	10524	
	Consumed (kWh)	2539	4337	41.5%
Water Heating	COP	3.8	1	
	Delivered (kWh)	2733	2733	
	Consumed (kWh)	726	2733	73.4%
Total	**Consumed (kWh)**	**4972**	**9368**	**46.9%**

6 CONCLUSION

A prototype GSIHP was installed in a high-efficiency home and monitored over the course of eight months. The unit operated in 4 different modes, SC, SC+WH, DWH, and SH with annual performance COPs estimated at 4.9, 5.2, 3.3, and 4.1 respectively. When compared to the estimated energy consumption of a baseline suite of minimum efficiency equipment, the GSIHP is estimated to save 46.9% over a year containing the 8 months of measured data. This is very close to the project target of 50% energy savings. GSIHPs are a step forward in space conditioning and water heating efficiency and are a viable option for reducing energy use.

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8 NOMENCLATURE

ρ = density (kg/m^3)
c = specific heat capacity (kJ/kg-K)
COP = coefficient of performance
DHW = domestic hot water
EDHWT = domestic hot water temperature entering equipment (℃)
EWT= ground loop water temperature entering equipment (℃)
LDHWT = domestic hot water temperature leaving equipment (℃)
LWT= ground loop water temperature leaving equipment (℃)
SC = space cooling
$\dot{V}$ = volumetric flow rate (m^3/s)
WH = water heating
$\dot{W}$ = electrical work rate (kW)

Subscripts
Cooling = cooling mode
DHW = domestic hot water
Heating = heating mode
Loop = ground loop
SC = space cooling
Total = Includes all power use including pumps, fans, and controls
WH = water heating

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