Case Study of a Heating Only Central GSHP System Using a Shallow Aquifer for a Warehouse

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ABSTRACT

High initial cost and lack of public awareness of ground source heat pump (GSHP) technology are the two major barriers preventing rapid deployment of this energy saving technology in the United States. Under the American Recovery and Reinvestment Act (ARRA), 26 GSHP projects have been competitively selected and carried out to demonstrate the benefits of GSHP systems and innovative technologies for cost reduction and/or performance improvement. This paper highlights findings of a case study of one of the ARRA-funded GSHP demonstration projects, which is a heating only central GSHP system using shallow aquifer as heat source and installed at a warehouse and truck bay at Kalispell, MT. This case study is based on the analysis of measured performance data, utility bills, and calculations of energy consumptions of conventional central heating systems for providing the same heat outputs as the central GSHP system did. The evaluated performance metrics include energy efficiency of the heat pump equipment and the overall GSHP system, pumping performance, energy savings, carbon emission reductions, and cost-effectiveness of GSHP system compared with conventional heating systems. This case study also identified areas for reducing uncertainties in performance evaluation, improving operational efficiency, and reducing installed cost of similar GSHP systems in the future.

INTRODUCTION

High initial cost and lack of public awareness of ground source heat pump (GSHP) technology are the two major barriers preventing rapid deployment of this energy saving technology in the United States (Hughes 2008). To tackle these barriers, 26 GSHP projects were competitively selected by the US Department of Energy (DOE) in 2009 and provided with grant under the American Recovery and Reinvestment Act (ARRA) to demonstrate the benefits of GSHP systems and innovative technologies for cost reduction and/or performance improvement.

One of the selected GSHP demonstration projects is in Kalispell, Montana. The demonstrated GSHP system uses an abundant and clean local natural resource—a shallow aquifer—as the heat source, and a central modular water-to-water heat pump (WWHP) to provide space heating to an existing 22,000 ft^2 (2,044 m^2) warehouse and truck bay, and a newly added 9,300 ft^2 (864 m^2) truck bay of a local cooperative utility company. The existing warehouse and truck bay was heated by electric unit heaters and it is retrofitted with the new GSHP system in 2010. All the electric unit heaters are converted to hydronic unit heaters, to which hot water generated by the GSHP system is supplied. The new truck bay is heated by a radiant floor with hot water from the GSHP system.

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Figure 1 shows the schematic of the new GSHP system. It consists of a 80 ton WWHP unit to provide hot water to: i) 14 hydronic unit heaters in the existing ware house and truck bay, ii) radiant floor system in the truck bay addition, and iii) fan coils in a 5,000 cfm heat recovery ventilator (HRV). The WWHP unit has four identical refrigeration modules and each containing two independently circuited hermetic scroll compressors. The four modules can stage heat output in response to fluctuating heating demands. The refrigerant used in the WWHP unit is R410A. The set point of the supply temperature of the hot water generated by the WWHP unit is automatically adjusted based on outdoor air (OA) temperature—140°F (60°C) when the OA is cooler than 0°F (-17.8°C), 100°F (37.8°C) when the OA is warmer than 55°F (12.8°C), and linearly decreases from 140°F (60°C) to 100°F (37.8°C) when OA temperature increases from 0°F (-17.8°C) to 55°F (12.8°C). The groundwater at the demonstration site has good quality and it transfers heat directly with the WWHP unit without any intermediate heat exchanger, which results in both cost and energy savings.

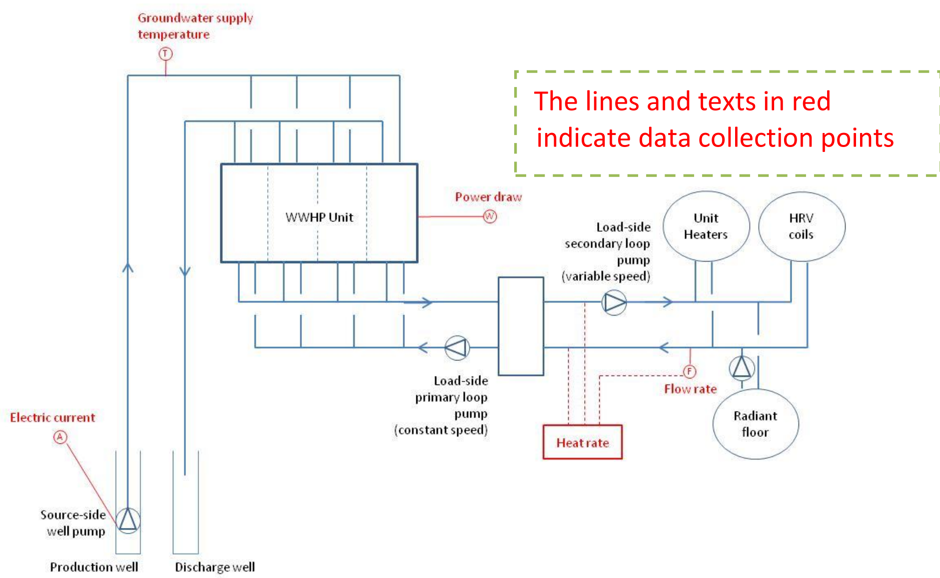


Figure 1. *GSHP system schematic with monitoring data collection points.*

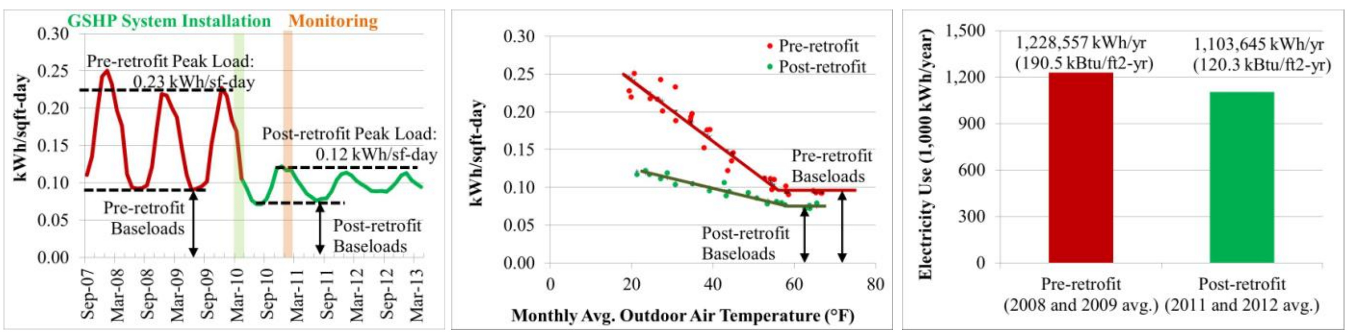
On the source-side of the GSHP system, groundwater is extracted from a 35 ft. (10.67m) deep well by a 7.5 hp, 230 gpm (871 L/m), variable-speed submersible pump, and returned to the ground through another water well 84 ft. (25.6m) away. The submersible pump (referred as "well pump") is modulated to maintain a constant differential pressure (35 psi or 241.3 kPa) across the source side (groundwater) loop. The design supply and return temperature of the groundwater are 48°F (8.9°C) and 40°F (4.4°C), respectively. On the load-side of GSHP system, two identical pumps are installed, one circulates water through a primary loop whenever the WWHP unit is in operation, and the other is modulated by a variable-speed drive to maintain a constant differential pressure across the supply and return pipes of a secondary loop. In addition, there is another circulation pump dedicated for the radiant floor.

For a two-month period spanning January 12 through March 14, 2011, battery-powered, portable data loggers recorded 1-min. data of i) the heat output, power consumption and load-side water flow rate of the WWHP unit, and ii) electric current input for the well pump. Power draw of well pump and the distribution pumps were derived from the continuous measurements of the electric current or the flow rate of the pumps and correlations between these variables and the pump power derived from a few one-time measurements (Liu et al. 2014).

This case study utilized utility bills and measured performance data to evaluate the energy savings and CO_2 emission reductions from the demonstrated GSHP system over conventional heating systems. It also identified areas for further improvement in reducing uncertainties in performance evaluation, improving operational efficiency, and reducing installed cost of similar GSHP systems. A cost effectiveness analysis of the demonstrated GSHP system is also conducted.

ANALYSIS OF UTILITY BILLS

Pre- and post-retrofit utility bills were analyzed to assess the impact of the GSHP retrofit on the whole-building energy use. Utility bills since 2007 were obtained, adjusted to align with the calendar months, and normalized by floor area. A time-series plot of the normalized electricity use (Figure 2a) shows that the peak daily energy use intensity (EUI) was reduced by 50% (from 0.23 to 0.12 kWh/ft^2-day (2.48 to 1.29 kWh/m^2-day)) after the retrofit. A scatter plot (Figure 2b) shows the pre- and post-retrofit energy use intensity versus coincident ambient temperature along with the "best-fit" curves made with the three-parameter model of the Inverse Modeling Toolkit (Kissock et al. 2002). As can be seen in this figure, the post-retrofit base load decreased by 22.2% (which is thought due to possibly smaller base load in the added truck bay than the existing facility) and the slope of the post-retrofit trend line was significantly lower, which indicates increased energy efficiency of the heating system after the retrofit since there has not been any change in the overall building heat loss coefficient. As shown in Figure 2c, even with the 9,300 ft^2 (864 m^2) added floor space, the post-retrofit annual energy use of the entire building was lower than that before the retrofit. When normalized by actual floor area, the post-retrofit EUI of the whole building was reduced by 37% (from 190.5 to 120.3 kBtu/ft^2-yr [601 to 379 kWh/m^2-yr]). It should be noted that the above comparison did not account for any possible change in weather conditions, non-space-heating electricity uses, and heating loads during the pre- and post-retrofit time periods. A comparison of annual energy uses between the demonstrated GSHP system and comparable baseline heating systems, which are calculated with identical weather data and heating loads, is discussed later.



(a) *(b)* *(c)*

Figure 2. *Pre- and post-retrofit utility bill analysis presented as: (a) a time-series plot of energy use intensity, (b) a scatter plot of monthly energy use intensity versus coincident outdoor air temperature, and (c) whole-building annual energy use.*

ANALYSIS OF MEASURED DATA

Measured data collected over the two-month period (January-March 2011) was analyzed to assess energy efficiencies, identify faults and abnormalities in the system operation, and determine potential improvements of the GSHP system. The general observations include:

Ground source temperature. The temperature of the groundwater entering the heat pump was stable (ranged from 49.6°F (9.8°C) to 54.9°F (12.7°C)) with a slight decreasing trend from January to March. Contrastingly, the coincident ambient temperature varied much more widely from -12°F (-24.4°C) to 61°F (16.1°C) (Figure 3).

Energy efficiency. The average heating COPs of the WWHP unit and the GSHP system during the two-month period were calculated as 3.19 and 2.66, respectively, from the measured cumulative heat output and associated power consumptions. While only the power consumption of the WWHP unit is used to calculate the COP of the WWHP unit, all the pumping power consumptions are included when calculating the COP of the entire GSHP system. A scatter plot of instantaneous COPs of the WWHP unit and the GSHP system versus OA temperature (Figure 4a) shows that both the

COPs increased with the increase of OA temperature, which is expected given the OA reset control. However, the GSHP system's COP is always lower than that of the WWHP unit, although the difference is smaller at lower OA temperature (i.e., below 10°F or -12.2°C). It is due to the pump energy use of the GSHP system and is discussed later.

Figure 4b compares the measured COPs of the WWHP unit with the COP data given in heat pump manufacturer's catalog for the same source-side (groundwater) supply temperatures and the load-side hot water supply temperatures, which are determined by the OA reset control described previously. It shows that the measured COPs were lower than the catalog data, which represents heat pump efficiencies at steady state conditions. This discrepancy is thought due to the transient operation of the WWHP unit when it staged its output to match the fluctuating heating demands. The operational efficiency of the WWHP unit can potentially be improved by refining the OA reset control. Based on heat pump manufacturer's catalog data, it is found that the operational efficiency of the WWHP unit can be increased by about 28% if the hot water supply temperature is lowered down by 10°F (5.6°C) (see the black dashed line in Figure 4b). However, it should be noted that the hot water supply temperature will affect the heat transfer performance of the terminal units, such as the radiant floor and hydronic unit heaters used in this project. Therefore, a holistic design approach is needed to optimize the OA reset schedule to improve the operational efficiency of the WWHP unit while delivering sufficient heat to the building.

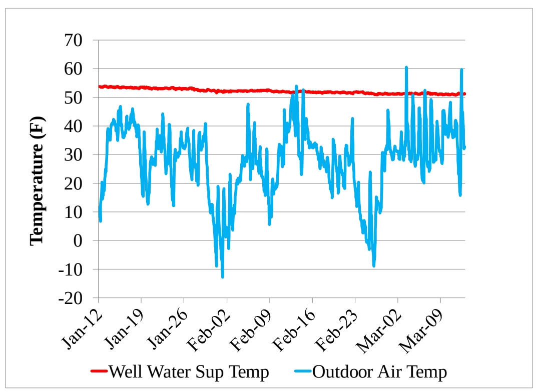


Figure 3. *Groundwater supply temperature vs. coincident outdoor air temperature.*

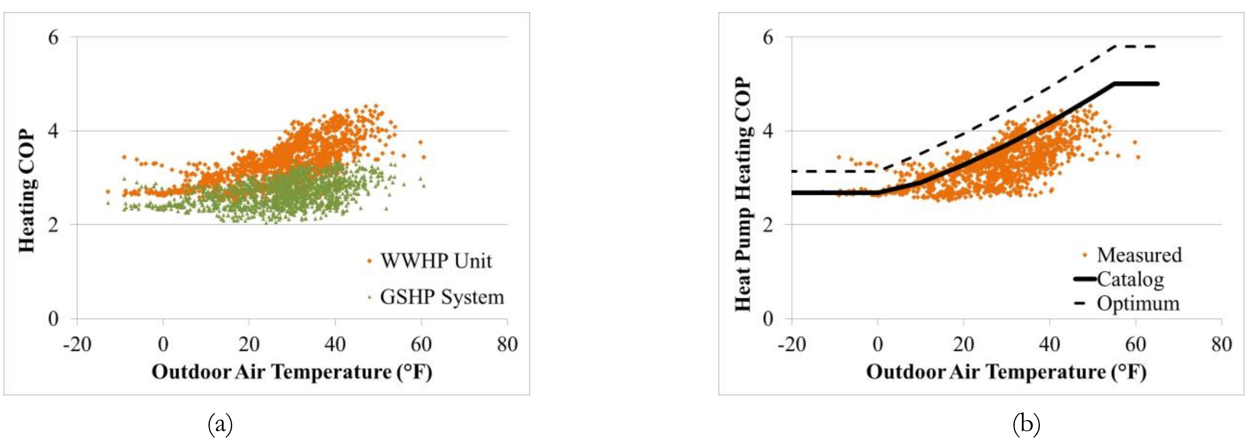
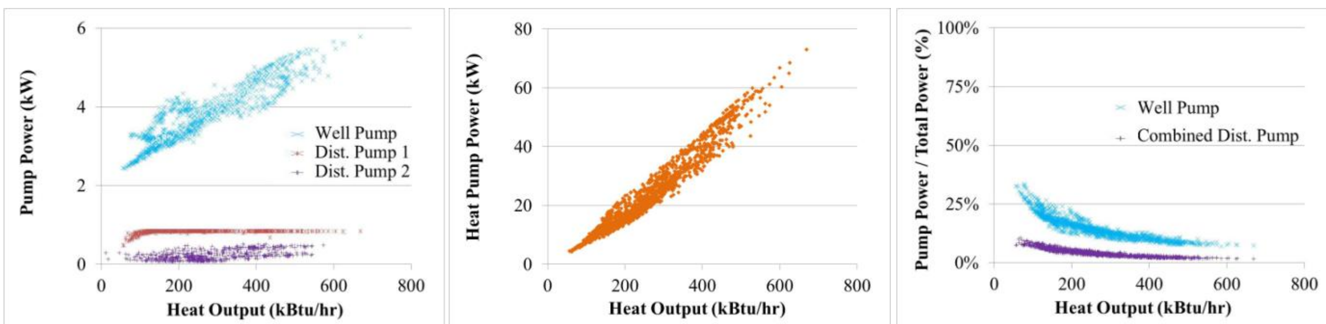


Figure 4. *Energy efficiency presented as: (a) instantaneous COPs of the WWHP unit and the GSHP system versus OA temperature, and (b) a comparison between the measured COP and the catalog data at same hot water supply temperatures (determined by the OA reset control).*

Pumping performance. Figure 5a shows the power draw of all three circulation pumps with respect to the heat output of the GSHP system. It can be seen that the well pump consumed much higher power than the two load-side pumps. It is the result of the static pressure and the friction resistances that must be overcome to lift up ground water from the well, push it through the WWHP unit, and return back to the aquifer. If the 35 psi (241.3 kPa) differential pressure maintained by the well pump can be lowered without sacrificing system performance, the well pump energy use can be reduced. The load-side primary loop pump ("Dist. Pump 1") ran constantly and consumed about three times more power than the secondary loop pump ("Dist. Pump 2"), which is a pressure-controlled variable speed pump.

Different from the linear relationship between the power draw of the WWHP unit and its heat output as shown in Figure 5b, the power draws of the well pump and the load-side primary loop pump did not decrease proportionally with the heat output[1]. As a result, faction of the pumping power (sum of the well pump and the combined load-side pumps) in the total GSHP system power increased from less than 10% to 40% when the heat output decreased from 600 to 50 kBtu/h (175.8 to 14.7 kW) as can be seen in Figure 5c. During the two-month period, the cumulative power consumptions of the well pump and the load-side pumps accounted for 13% and 4% of the total energy use of the GSHP system, respectively.



(a) (b) (c)

Figure 5. *(a) power draw of circulation pumps, (b) power draw of WWHP unit, and (c) fraction of pumping power in the total power consumption of the GSHP system.*

ANNUAL ENERGY AND COST ANALYSIS

To capture the full spectrum of the GSHP system performance in response to fluctuating heating loads of the building throughout a year, the full-year heating loads and power consumption of the GSHP system are calculated. It is based on the correlations among the OA temperatures, heating loads, and the power consumption of each component of the GSHP system, which is derived from the measured data in the two-month period. Detailed information of the correlations is given in a technical report of the case study (Liu et al. 2014). OA temperatures measured at a nearby airport (9.7 miles (15.6km) southwest of the site) during the entire year of 2011 were used to calculate the heating loads. Energy consumptions of comparable baseline heating systems were calculated with the heating loads and typical performance data of conventional heating equipment. The energy savings and emission reductions from the GSHP system, as well as its cost effectiveness, were determined by comparing the performance and cost of the GSHP system with the baseline systems.

Prediction of Annual Energy Use

The correlations derived from the measured data were first verified by comparing the predicted and measured values for the two-month period, and then used to calculate the heating loads and power consumptions of each component of the GSHP system for the entire year. Table 1 compares the measured and calculated data over the two-month period, indicating a good match with less than 10% difference. It also listed the calculated annual energy use of the GSHP system[2]. As shown in Table 1, the annual average COPs of the WWHP unit and the GSHP system are 3.6 and 2.87, respectively, a 12.9% and 7.9% increase over the corresponding average COPs during the two-month period. It is because of the relatively warmer

[1] The well pump has to lift the groundwater up to the surface and its power draw does not reduce proportional to the reduced groundwater flow..
[2] The annual energy use excludes the three summer months (June through August) when the GSHP system was shut down.

weather in the rest of the year and the OA reset control for the hot water supply temperature. However, the annual combined pumping energy use is 20.3% of the annual total GSHP system energy use, which is higher than that during the two-month period by 3.7 percentage points (a 22.3% increase). The warmer weather resulted in lower heating loads and heat pump energy use; however, pumping power, especially for the well pump and the constant speed primary loop pump, did not decrease proportionally. As a result, the percentage of pumping power is increased at times with warm weather as shown in Figure 6.

Table 1. Summary of measured and calculated performance

	Unit	two-month measured	two-month predicted		Full year predicted	
				% Difference		% Difference
Total heat output	MBtu (GJ)	379 (400)	379 (400)	0.0%	1,281 (1351)	
Total heat pump energy use	kWh	34,850	32,746	6.0%	104,235	
Total well pump energy use	kWh	5,425	5,301	2.3%	20,329	
Total energy use of primary loop pump	kWh	1,201	1,210	-0.7%	5,153	
Total energy use of secondary loop pump	kWh	320	309	3.6%	1,130	
Total GSHP system energy use	**kWh**	**41,797**	**39,565**	**5.3%**	**130,847**	
Average COP of heat pump	-	3.2			3.6	12.9%
Average COP of GSHP system	-	2.7			2.87	7.9%
Percentage of pumping energy use	%	16.6			20.3	22.3%

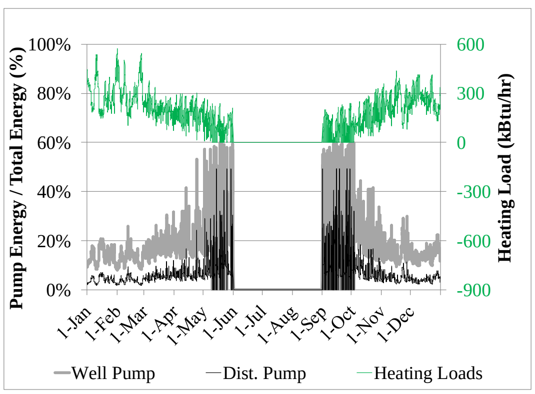


Figure 6. *Heating loads and the percentages of pumping power over the full year period.*

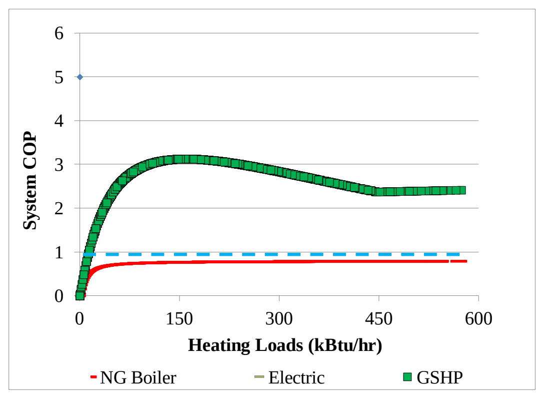


Figure 7. *COP of GSHP system compared with baseline systems.*

Comparison with Baseline Energy use

The baseline system was assumed to be a conventional boiler to provide hot water to all terminal heating devices including the radiant floor system, hydronic unit heaters, and fan coils in the HRV. Two types of conventional boiler were used: i) a 292 kW (1 MBtu/h) electric boiler, and ii) a 1 MBtu/h natural gas-fired, forced-air draft, non-condensing boiler. The boiler heating capacity was determined from the measured peak heat output of the WWHP unit and a safety factor of 1.2. The energy efficiencies of the electric and gas-fired boilers are 0.98 and 80%, respectively, which are the minimum efficiencies required by ASHRAE Standard 90.1 (ASHRAE 2010). The boiler's part load performance curve was obtained from a boiler manufacturer and available in the technical report (Liu et al. 2014).

Figure 7 shows the COP of the GSHP system and two baseline systems at varying heating loads. The COP of the baseline systems are nearly constant and below 1. However, the COP of the GSHP system varies widely with heating load. It increases from below 1 up to above 3 when heating loads increase from 0 to around 150 kBtu/h (44 kW). At higher heating loads, the GSHP system COP decreases due to the increased hot water supply temperature resulting from the OA reset control.

The GSHP system saved 258,362 kWh/yr electricity (882 MBtu/yr or 931 GJ) and 1,202 MBtu/yr (1,268 GJ/yr) site energy compared with the electric and natural gas baselines, respectively (Figure 8a). Using the source-to-site energy conversion factors and emission factors for electricity and natural gas (Deru and Torcellini 2007), the source energy savings were 2,552MBtu/yr (2,693 GJ, 66.4%) and 546 MBtu/yr (576 GJ, 29.7%) and CO2 emission reductions were 66.4% and 30.9% compared to the electric and natural gas baselines, respectively (Figure 8b and 8c). In addition, the GSHP system reduced peak electricity demand by 103.2 kW compared to the electric baseline.

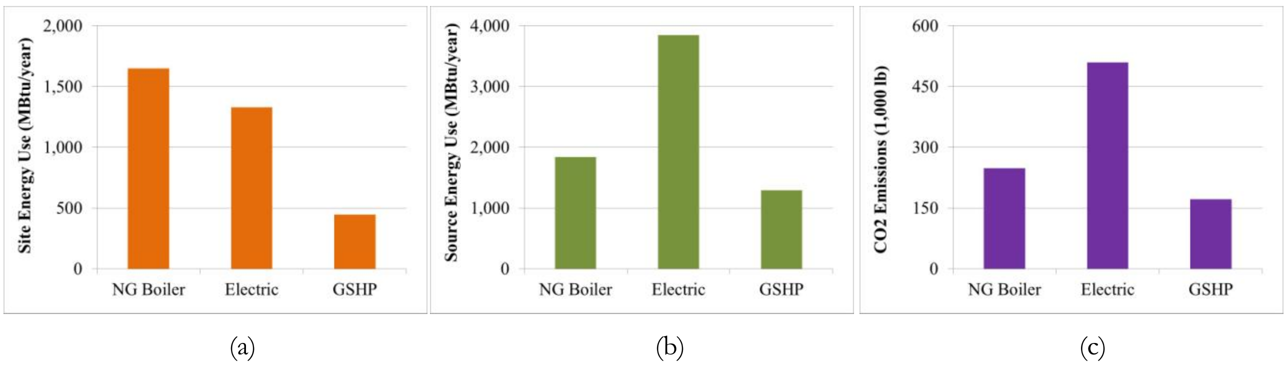


Figure 8. *(a) Site energy use, (b) source energy use, and (c) CO2 emissions for the GSHP system and baseline systems.*

Cost Effectiveness

The total cost associated with the GSHP system installation was $331,232 (i.e., $4,140/ton or $10.58/ft^2 ($114/m^2)), which includes the costs for GSHP system installation ($299,037), ground water use permission ($23,435), as well as test and balance ($8,760). The installation cost of the baseline systems was estimated by replacing the costs exclusive to the GSHP system (e.g., the 80 ton WWHP unit, construction of the two water wells, and the associated hydronic piping, submersible pump, and variable speed control) with the national average installed cost of electrical or gas-fired boiler (RSMeans 2010) and keeping all other costs intact. The resulting cost premium of the GSHP system was $119,249 over the electric baseline and $117,887 over the natural gas baseline. Based on the local utility rates[3], the energy cost of the GSHP system was $7,488, which was 65% and 47% less than the electric and natural gas baselines, respectively. Cost effectiveness of the GSHP system was evaluated using simple payback period. With the above cost premium and energy cost savings of the GSHP system, the simple payback is 9 and 18 years compared with the electric and natural gas baselines, respectively[4].

CONCLUSIONS

System performance. The measured performance data during the two-month period (January 12 through March 14, 2011) indicated that the GSHP system ran as anticipated. The average COPs of the WWHP unit and the GSHP system were 3.19 and 2.66, respectively, during that time period. The annual performance prediction shows higher annual performance with average COPs of 3.6 and 2.87 for the WWHP unit and the GSHP system, respectively, because of the relatively warmer weather during the rest of the year and the OA reset control for the hot water supply temperature.

The combined pumping power annually accounts for 20.3% of the total GSHP system energy use, which is 22.3% higher than that during the January to March period when heating demands were high. Excessive pumping, especially from the well pump and the load-side primary loop pump, occurred at times when heating demands were low.

Energy, cost, and emission reduction benefits. The GSHP system achieved significant energy savings and CO_2 emission reductions over electric and natural gas baselines. Compared with the electric baseline, it resulted in a 66%

[3] A basic charge of $1.61 per kilowatt load size, a demand charge of $3.03 per kilowatt of electricity demand, and an energy charge of $0.04031 per kWh (FEC 2013). The price of natural gas in Montana for commercial customers in 2011 was $8.66 per 1000 ft3 (or $8.47 per MBtu) (EIA 2013).
[4] Given the volatile change of the natural gas price, the payback could be shorter or longer if natural gas price in other years is used in the calculation.

reduction in site and source energy use, energy cost, and CO_2 emissions and a 103 kW reduction in peak electricity demand. Compared with the natural gas baseline, the reductions were 73% site energy, 30% source energy, 47% energy cost, and 31% CO_2 emissions. The installed cost of the demonstrated GSHP system, which uses groundwater from a shallow aquifer as the heat source, is $4,140/ton ($10.58/ft^2 or $114/m^2). It is significantly lower than that of conventional GSHP systems using vertical closed-loop ground heat exchangers, which is $7,000/ton on average in 2006 dollars (DOD 2007). Given the heating only load, the vertical closed-loop ground heat exchanger may not be a good fit for this application.

Lessons Learned. Following recommendations are made for reducing uncertainties in the performance evaluation, improving operational efficiency, and reducing installed cost of the similar GSHP systems in the future:

1. Continuous direct measurement of the power draw of variable speed pumps is desirable to avoid uncertainties associated with estimating it from indirect measurements and correlations derived from a few one-time measurements.

2. Data collection period for performance evaluation should include not only the peak load months but also other time when the heating (and cooling if applicable) demands are relatively low. It will help capture the full spectrum of the GSHP system performance.

3. The operational efficiency of the GSHP system could possibly be improved by refining the OA reset control to allow lowering the hot water supply temperature. However, a holistic design approach is recommended to optimize the OA reset schedule to ensure that sufficient heat is delivered to the building.

4. Pump controls should be adjusted to avoid excessive pumping at low load conditions to improve annual operational efficiency of the GSHP system. Use of a variable-speed pump in the load-side primary loop should be implemented to reduce pumping power. Well pump energy use could possibly be reduced using a lower pressure set point.

5. Registration and permits for extracting and recharging groundwater are required in Montana. It took a great deal of time and significant effort to obtain the groundwater use permit for this project. The installed cost of the GSHP system could be reduced if the permission process becomes more efficient.

ACKNOWLEDGMENTS

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