Performance Considerations for Ground Source Heat Pumps in Cold Climates

Preprint

Robbin Garber-Slaght

National Renewable Energy Laboratory

Presented at the 15th International Conference on Energy Sustainability (ES2021)
June 16-18, 2021

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

Contract No. DE-AC36-08GO28308

Conference Paper
NREL/CP-5600-79479
June 2021

Performance Considerations for Ground Source Heat Pumps in Cold Climates

Preprint

Robbin Garber-Slaght

National Renewable Energy Laboratory

Suggested Citation
Garber-Slaght, Robbin. 2021. *Performance Considerations for Ground Source Heat Pumps in Cold Climates: Preprint*. Golden, CO: National Renewable Energy Laboratory. NREL/CP-5600-79479. https://www.nrel.gov/docs/fy21osti/79479.pdf.

Contract No. DE-AC36-08GO28308

Conference Paper
NREL/CP-5600-79479
June 2021

National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

NOTICE

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding is also provided by the Alaska Energy Authority, the Alaska Housing Finance Corporation, and the Denali Commission. The views expressed herein do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

Cover Photos by Dennis Schroeder: (clockwise, left to right) NREL 51934, NREL 45897, NREL 42160, NREL 45891, NREL 48097, NREL 46526.

PERFORMANCE CONSIDERATIONS FOR GROUND SOURCE HEAT PUMPS IN COLD CLIMATES

Robbin Garber-Slaght

Cold Climate Housing Research Center-National Renewable Energy Lab, Fairbanks, AK

ABSTRACT

Remote, cold climates present challenges to finding safe and affordable space heating options. In Alaska, residential ground source heat pumps (GSHPs) have been gaining in popularity, even though there is little research on their long-term performance or their effect on soil temperatures. The extended heating season and cold soils of Alaska provide a harsh testing ground for GSHPs, even those designed and marketed for colder climates. The large and unbalanced heating load in cold climates creates a challenging environment for GSHPs. In 2013 the Cold Climate Housing Research Center (CCHRC) installed a GSHP at its Research and Testing Facility (RTF) in Fairbanks, Alaska. The heat pump replaced an oil-fired condensing boiler heating an office space via in-floor hydronic radiant piping. The ground heat exchanger (GHE) was installed in moisture-rich silty soils underlain with 0°C permafrost. The intent of the project was to observe and monitor the system over a 10-year period to develop a better understanding of the performance of GSHPs in sites with permafrost and to help inform future design. As of this writing, the heat pump system has been running for eight heating seasons. The efficiency in those eight heating seasons has been variable with ups and downs that have been difficult to explain. This paper seeks to understand the variability in performance as well as make recommendations for GSHP use in other cold climates.

Keywords: cold climates, ground source heat pump, permafrost

1. INTRODUCTION

In the United States, space heating is the single greatest energy demand in residential structures accounting for 56% of residential site energy consumption in cold and very cold climate zones [1]. Alaska, which encompasses 3 cold zones, uses 69% of its residential site energy in space heating [2]. Ground source heat pumps (GSHP) are often touted as a highly efficient space heating system and they are proven technology in moderate-to-cold climates; however their performance in extreme cold climates (areas with near 0°C soil temperatures) is not well evaluated [3].

GSHPs rely on a large reservoir of low-temperature mass to provide the energy to drive a refrigerant cycle. This reservoir is generally soil or a large body of water. The efficiency of the GHSP system is dependent on the local climate and the building heating load [4]. Systems in heating-dominated climates can suffer from a thermal imbalance in the energy reservoir, where more energy is extracted in the heating season than is returned to the reservoir in the cooling season [5]. A large thermal imbalance can lead to degradation in system efficiency and potential system failure over time [6]. Wu et al. developed a thermal imbalance ratio (TIR) to quantify degree of imbalance in the ground heat exchanger (GHE); it is the difference of the removed heat and the injected heat divided by the maximum values of removed and injected heat [7]. The larger the result, the greater the imbalance.

GSHP systems with soil temperatures near the point of water's phase change have the potential to extract the energy of phase change from the GHE. By saturating the soil around the GHE boreholes, the latent energy from soil freezing can be added to the heat pump system [8]. Freezing within the GHE enhances the heat transfer performance and helps in downsizing the heat exchanger [9]. The higher the thermal diffusivity of the soil, the larger the effect on the improvement of heat transfer with phase change [9]. A computational model on the effects of latent heat on a borehole heat pump installation determined that low-moisture soils will create a larger freeze radius around the boreholes than high-moisture soils [10]. An analysis of phase change is critical for any models of heat pumps in heating-dominated climates [10].

Permafrost is soil that has been below 0°C for 2 consecutive years. In the Sub-Arctic permafrost is discontinuous and is often very close to 0°C, the thaw point. Low soil temperatures and frozen soil are an important consideration in the development of GHEs in the Sub-Arctic. In fact, GSHPs have a long track record of helping maintain structurally frozen soil beneath buildings [11–13]. Outside of using GHEs to maintain permafrost there has been little study of GHSPs in the Sub-Arctic [3].

This study evaluates the 8-year performance of a horizontal GHE heat pump system installed in a discontinuous permafrost area of the sub-Arctic. The system is a heating-only system and therefore has a TIR of 100% with no cooling demand returning energy to the GHE in the summer.

2. FIELD TESTING

The Cold Climate Housing Research Center's (CCHRC) Research and Testing Facility (RTF) located in Fairbanks, Alaska is at the cold end of the very cold climate zone with 7,509°C heating degree days and a design temperature of -41.9°C [14]. The RTF is a LEED Platinum building with a relatively low space heating demand for the Sub-Arctic. The 2,044 m^2 building has 3 heating zones; each heated by a separate appliance. The GSHP heats a 464m^2 office space with a design heating load of 17.6kW. Heated water is delivered to 9 thermostatically controlled zones via in-floor radiant hydronic tubing. The heat pump itself is a residential 21kW water-to-water cold climate unit. It is rated to have a coefficient of performance (COP) of 3.4 at 0°C entering fluid temperature.

The RTF sits in a field of thawing permafrost. The depth to the top of the permafrost is approximately 12m below the surface (1.2m lower than initial surveys in 2006). The thermal conductivity of thawed soil was measured to be 1.42W/mK prior to the GHE installation. The GHE is 2.7m below an unplowed field adjacent to the RTF. At 2.7m it is below the active layer (the layer that seasonally freezes and thaws) of 1.2m and above the top of the existing permafrost. Finite element models put the optimum depth of a horizontal GHE for this climate between 2.4 and 2.7m [15]. The GHE consists of six 30m long by 1m wide slinky coils with a 0.5m pitch, spaced 1.8m apart. Overall, there are 1,463 lineal meters of 1.9cm HDPE pipe in the GHE. The circulating fluid is 20:80 methanol water.

2.1 Methodology

The field test was developed to evaluate the long-term performance of the GHE and GSHP in a heating-dominated climate. The GHE and the GSHP have been continually monitored since coming online in November 2013. Table 1 lists the components of automated data collection system

Figure 1 shows a conceptual drawing of the GSHP system and includes sensor locations. There are five sets of temperature strings that drop into the GHE from the surface to below the

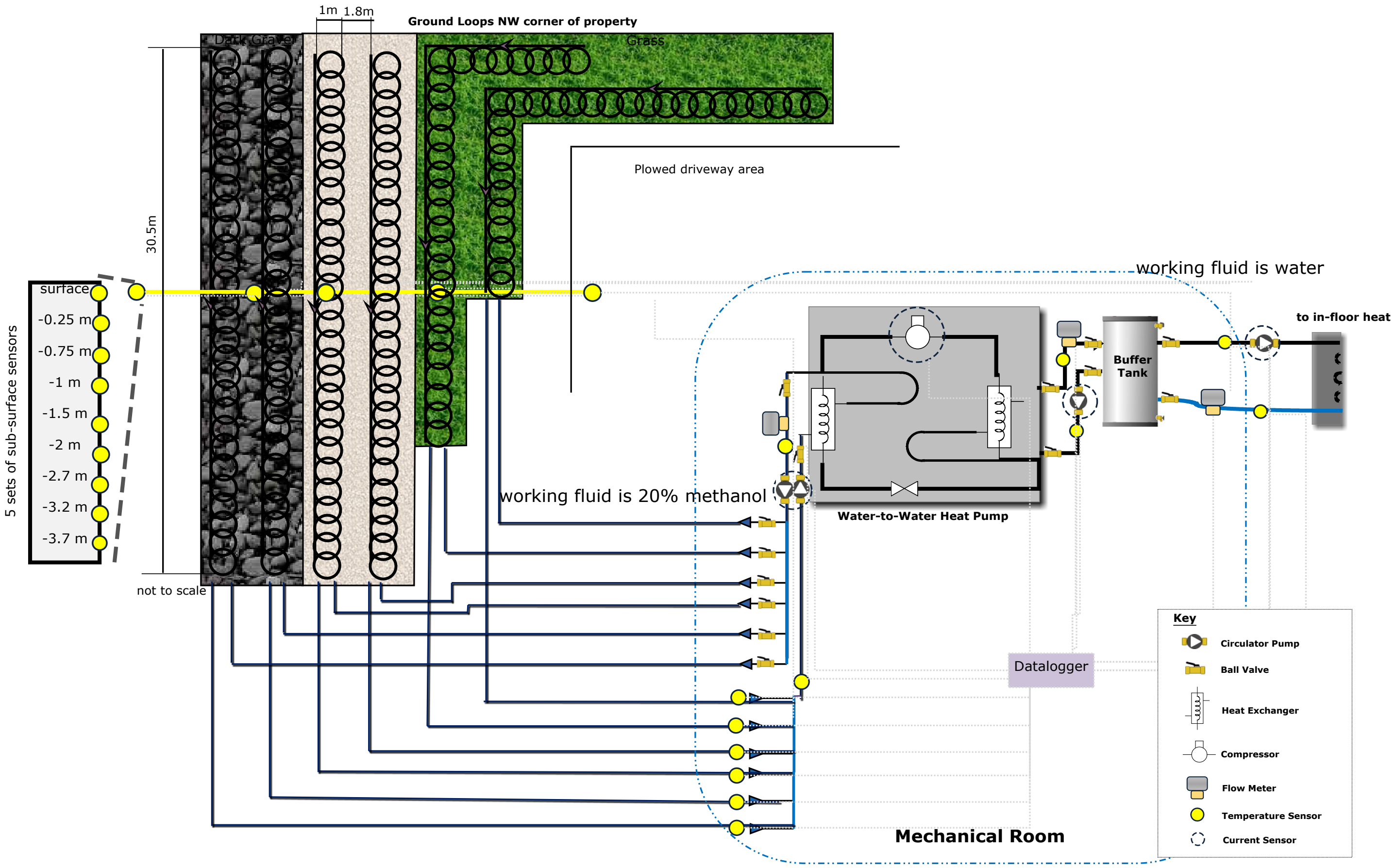


FIGURE 1: GSHP CONCEPTUAL DRAWING. SENSOR LOCATIONS ARE ROUGH APPROXIMATIONS

TABLE 1: DATA COLLECTION SYSTEM COMPONENTS

Data Point	Sensors and Location
Ground Temperatures	Thermistors within and around the GHE
Manifold Temperatures	Thermistors in the manifold returning from the GHE
Heat Energy Produced by the Heat Pump	Flow meters and temperature sensors in the piping to and from the buffer tank
Heat Pump Electrical Use	VT and CT on the wiring to the heat pump

slinky coils. The GHE was initially designed with different surface treatments, to help determine if there was enough improved efficiency to recommend a certain treatment. This aspect of the project ended in 2017; dark rocks on the surface enhanced the COP by 0.08 [15].

The heat energy delivered by the heat pump to the building is calculated both before and after the it reaches the buffer tank. Heat energy, q, is calculated using Eq (1).

$$q = Q\rho c_p \Delta t \qquad (1)$$

where Q is the water flow rate, ρ is the heating fluid density, c_p is the specific heat of the heat fluid and Δt is the change in temperature between the supply and the return.

The efficiency of the GSHP system is calculated as the monthly coefficient of performance (COP) using Eq. (2).

$$COP = \frac{q}{e} \qquad (2)$$

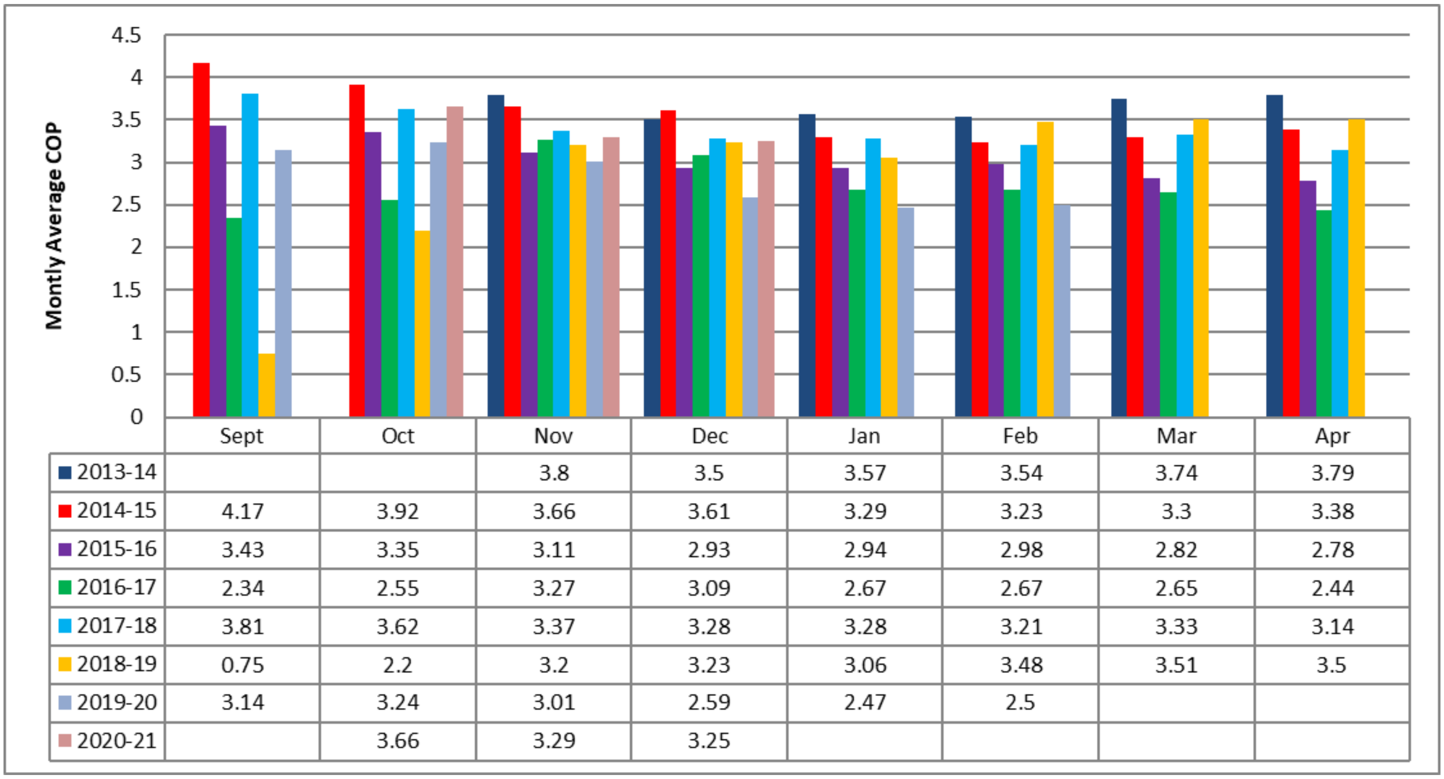
where e is the electrical energy consumed by the heat pump and circulating pumps per month. This calculation includes the electrical use of the 3 circulation pumps (2 for the GHE and one to the buffer tank). The COP of the full system is evaluated because the heat pump does not operate without the circulating pumps; however, the COP of the heat pump by itself could be calculated if necessary.

3. ENERGY PERFORMANCE RESULTS

The heat pump was expected to lose efficiency over time as continual energy extraction from the ground without full summer recharge lowered the GHE temperature. Preliminary models showed a leveling out of efficiency in 5 to 7 years [15]. The system is in its eighth year of service and has seen degradation of efficiency, albeit not linear degradation. The COP for years 5 through the first half of year 8 has averaged 3.18, slightly lower than the 3.40 average COP in the first 3 years of service. Figure 2 shows the monthly average COPs by month and year.

The heat pump efficiency trends down over the course of a heating season but has not shown significant annual average change since the third year of service (except for the fall of 2018). Incoming GHE fluid temperatures drop every season from September to March and tend to rebound a little in the late spring. The COP tracks with these temperature changes (see Figure 3).

The incoming GHE fluid temperatures have not varied much from year to year, while the COPs have been more varied. Some of the year-to-year variation can be due to electrical and



	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr
■ 2013-14			3.8	3.5	3.57	3.54	3.74	3.79
■ 2014-15	4.17	3.92	3.66	3.61	3.29	3.23	3.3	3.38
■ 2015-16	3.43	3.35	3.11	2.93	2.94	2.98	2.82	2.78
■ 2016-17	2.34	2.55	3.27	3.09	2.67	2.67	2.65	2.44
■ 2017-18	3.81	3.62	3.37	3.28	3.28	3.21	3.33	3.14
■ 2018-19	0.75	2.2	3.2	3.23	3.06	3.48	3.51	3.5
■ 2019-20	3.14	3.24	3.01	2.59	2.47	2.5		
■ 2020-21		3.66	3.29	3.25				

FIGURE 2: GSHP MONTHLY AVERAGE COPS

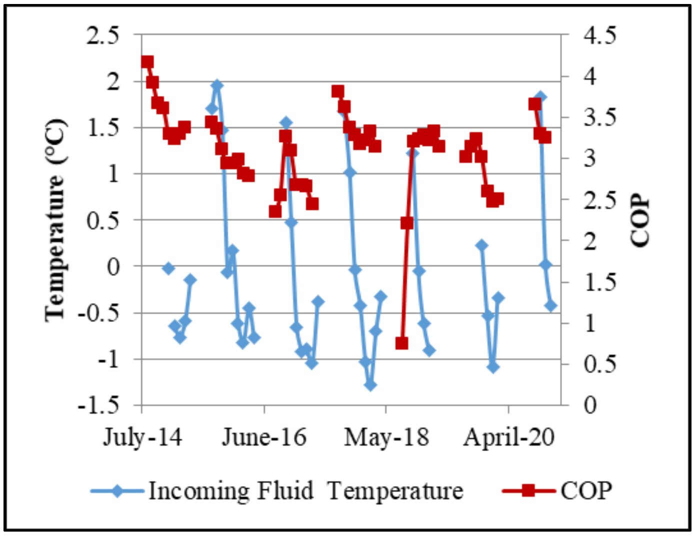


FIGURE 3: GHE FLUID TEMPERATURE VS. COP.

mechanical failures in the heat pump components. For example, the very low COPs in September and October 2018 were the direct result of a failing thermostatic expansion valve (TXV) within the heat pump. As the TXV failed it came apart, fouled the refrigerant in the system, and put metal bits in the compressor. The TXV was replaced and the refrigerant flushed but the compressor was not replaced. Not replacing the compressor could lead to lower efficiencies over time, it may eventually need to be replaced.

September and October 2016 (the fourth season) efficiency data do not follow the trend of high COPs in the early season. The soil temperature was high but the temperature differential between incoming GHE and return to GHE temperature was a full degree C lower for this period than other fall data; the to-building temperature difference was also about 1C° lower. This lower COP is unexplained, but likely due to mechanical problem within the refrigerant cycle.

In late January 2020, the heat delivery system to the building failed and stopped calling the heat pump for heat. The building diesel back-up heating system stepped in and the problem was not found for 7 days; in those 7 days the outdoor ambient temperature was approximately -40°C and the GHE piping froze where it enters the building. The system was offline until late September 2020 when the pin leak in the GHE pipe was finally repaired (repairs were hampered by difficulty in locating the leak and Covid-19 access issues). The 20% methanol solution in the GHE has a freeze point of -15°C, the extended exposure to extreme low temperature, and the lack of flow allowed for the fluid to freeze in this case.

4. GHE EFFECTS ON THE SOIL

The GHE is in an area of discontinuous and degrading permafrost, soil that has been below 0°C for two or more years. A GHE has the potential to aggrade the permafrost as it extracts energy [12], this installation was set up to determine how that aggradation would affect the efficiency of the system.

TABLE 2: ENERGY EXTRACTED FROM THE GROUND ANNUALLLY

Year 1* (winter 2013-14)	9,459 kWh
Year 2 (winter 2014-15)	14,086 kWh
Year 3 (winter 2015-16)	13,931 kWh
Year 4 (winter 2016-17)	17,897 kWh
Year 5 (winter 2017- 18)	17,229 kWh
Year 6 (winter 2018-19)	15,750 kWh
Year 7*(winter 2019-20)	11,481 kWh

*Incomplete years

4.1 Soil Thermal Imbalance

The GHE extracted almost 100,000kWh of energy from the ground in seven years. Table 2 shows the energy extraction of GHE by year. The only energy recharge to the GHE during this period was via passive solar radiation (and potentially flowing ground water, discussed below). The GHE is roughly 30 by 15m or 450 m^2. The average annual solar radiation on the surface of

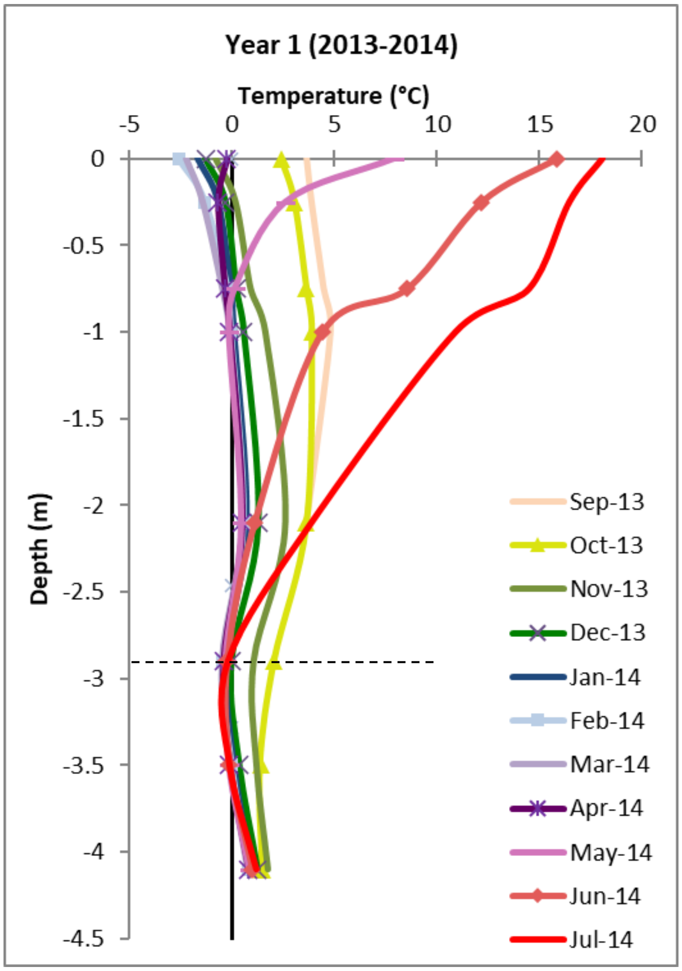


FIGURE 4: CENTER OF GHE TEMPERATURES IN THE FIRST SEASON OF OPERATION. (THE DOTTED LINE IS THE LEVEL OF THE GHE PIPING)

the GHE is 13,763kWh. In some years, the surface radiation matches or exceeds the energy extraction by the heat pump. However, much of the annual energy at the surface is absorbed in thawing the first 1m of soil. Only a small faction of solar energy reaches the GHE at 2.7m of depth; this is observed in the soil temperature. Figure 4 shows the soil temperatures during the first year of operation. The cold depth from -2.5 to -3.5m is the area around the GHE. October is usually the warmest month at the level of the GHE.

4.2 Development of Frozen Soil

The temperature around and below the GHE (-2.7m) reaches 0°C quickly each fall. The original GHE soil temperature when the system was commissioned in 2013 was 1.8°C, by December 2013 the GHE soil temperature was 0°C. Energy from phase change is the majority of the heat energy used by the pump. From December 2013 until August 2014 the middle of the GHE remained between 0.5°C and -0.14°C.

Each year the heat pump has started in the fall with a slightly lower soil temperature. In the fall of 2017 (Year 5) the soil temperature below the GHE was -0.099°C at the start of the heating season (see Figure 5). From December 2016 until October 2018 the GHE was below 0°C; the GHE was just 2 months shy of meeting the 2-year criteria for permafrost.

A comparison of Figures 4 and 5 shows the lowering of temperatures around the GHE over five years. The year-long below-freezing temperatures just below the GHE slinky loops are visible in Figure 5. The location and temperature of the frozen soil agrees with early simulations [15]. The temperatures within the GHE have risen slightly since the low temperatures in years 5 and 6 (see Figures 6 and 7). The rise is the result of moving groundwater that has risen across the site to within one meter of the surface. The flowing groundwater stays above 0°C and has a higher heat capacity than the soil, this has led a higher COP.

Figure 7 shows the temperature below the GHE (at -3.5m) compared to the same depth that is outside the influence of the GHE (baseline). This data begins in October 2014, one year after the commissioning of the heat pump. The soil in the GHE is noticeably colder than the undistributed area and has less seasonal recovery.

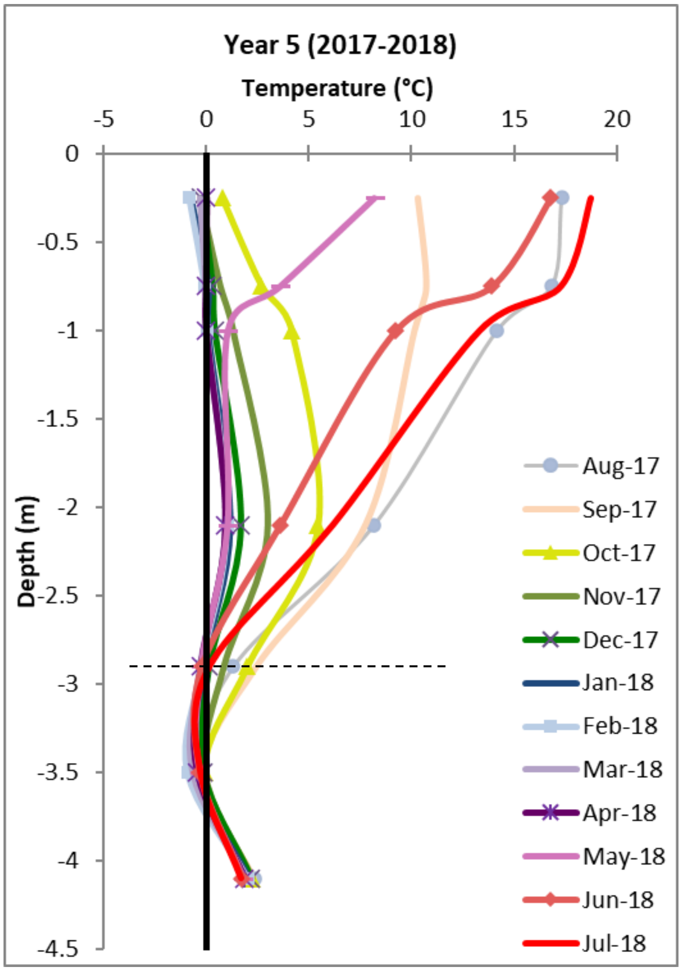


FIGURE 5: CENTER OF GHE TEMPERATURES IN THE FIFTH SEASON OF OPERATION. (THE DOTTED LINE IS THE LEVEL OF THE GHE PIPING)

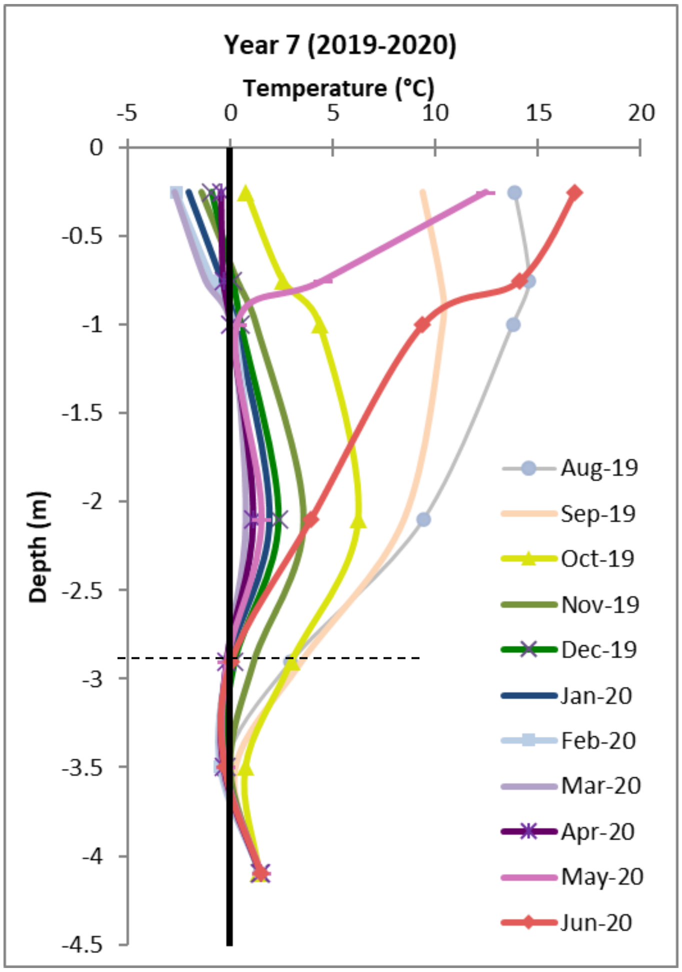


FIGURE 6: CENTER OF GHE TEMPERATURES IN THE SEVENTH SEASON OF OPERATION. (THE DOTTED LINE IS THE LEVEL OF THE GHE PIPING)

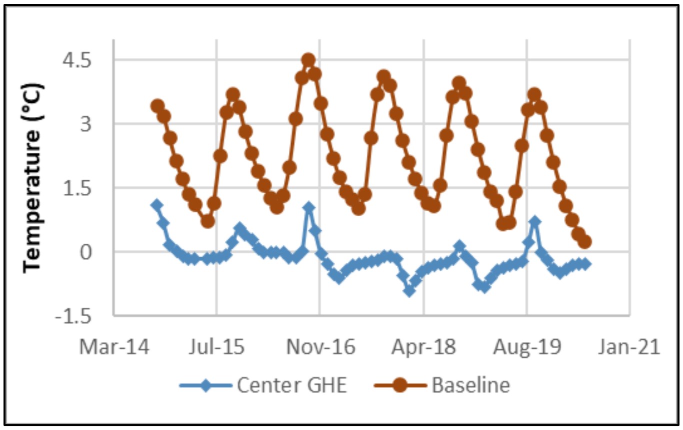


FIGURE 7: SOIL TEMPERTURE OVER 6 YEARS

5. GSHP COSTS

The capital cost of the CCHRC GSHP was significant, \$2,570/kW of heating, especially when compared to a similar sized oil-fired boiler at \$225/kW of heating. With such high capital cost, the savings from the heat pump needs to be significant in order to pay back to additional cost of the installation (there is a 26% residential tax credit through 2022).

The financial savings from a heat pump is tightly tied to electricity and heating fuel prices. The CCHRC heat pump was installed when diesel heating fuel prices were high, about \$4/gallon. Over 8 years heating fuel prices has ranged from \$2.30 to \$4.00/gallon, while electricity has remained constant at \$0.24/kWh. When compared to a high efficiency (96%) oil fired boiler, the GSHP is no longer cost effective when fuel prices drop below \$2.45/gallon. The CCHRC heat pump has cost \$450 more than the 96% efficient boiler it replaced would have cost in the same eight years of operation.

6. CONCLUSION

Cold climate GSHPs can function efficiently in a sub-Arctic environment like Fairbanks, Alaska. They require careful design that considers low soil temperatures and the potential energy of phase change. Creating permafrost around and under the GHE is certainly a possibility and needs to be accounted for in siting the GHE.

ACKNOWLEDGEMENTS

This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding is also provided by the Alaska Energy Authority, the Alaska Housing Finance Corporation, and the Denali Commission. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, recognizes that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

REFERENCES

[1] U.S. Energy Information Administration, 2015, “2015 Residential Energy Consumption Survey: Energy Consumption and Expenditures Tables” [Online]. Available:https://www.eia.gov/consumption/residential/data/2015/c&e/pdf/ce3.1.pdf. [Accessed: 24-Sep-2020].

[2] Alaska Housing Finance Corporation, 2018, “2018 Housing Assessment,” Alsk. Hous. Finance Corp. [Online].Available:https://www.ahfc.us/pros/energy/alaska-housing-assessment/2018-housing-assessment. [Accessed: 29-Dec-2020].

[3] Meyer, J., Pride, D., O’Toole, J., Craven, C., and Spencer, V., 2011, *Ground-Source Heat Pumps in Cold Climates*, Denali Commission, Fairbanks, AK.

[4] Liu, Z., Xu, W., Qian, C., Chen, X., and Jin, G., 2015, “Investigation on the Feasibility and Performance of Ground Source Heat Pump (GSHP) in Three Cities in Cold Climate Zone, China,” Renew. Energy, **84**, pp. 89–96.

[5] You, T., Wu, W., Shi, W., Wang, B., and Li, X., 2016, “An Overview of the Problems and Solutions of Soil Thermal Imbalance of Ground-Coupled Heat Pumps in Cold Regions,” Appl. Energy, **177**, pp. 515–536.

[6] You, T., Wang, B., Wu, W., Shi, W., and Li, X., 2014, “A New Solution for Underground Thermal Imbalance of Ground-Coupled Heat Pump Systems in Cold Regions: Heat Compensation Unit with Thermosyphon,” Appl. Therm. Eng., **64**(1–2), pp. 283–292.

[7] Wu, W., Wang, B., You, T., Shi, W., and Li, X., 2013, “A Potential Solution for Thermal Imbalance of Ground Source Heat Pump Systems in Cold Regions: Ground Source Absorption Heat Pump,” Renew. Energy, **59**, pp. 39–48.

[8] Eslami-nejad, P., and Bernier, M., 2012, “Freezing of Geothermal Borehole Surroundings: A Numerical and Experimental Assessment with Applications,” Appl. Energy, **98**, pp. 333–345.

[9] Yang, W., Kong, L., and Chen, Y., 2015, “Numerical Evaluation on the Effects of Soil Freezing on Underground Temperature Variations of Soil around Ground Heat Exchangers,” Appl. Therm. Eng., **75**, pp. 259–269.

[10] Vasil’ev, G. P., Lichman, V. A., Peskov, N. V., and Semendyaeva, N. L., 2015, “Modeling the Heat Regime of Thermal Boreholes with Pore Moisture Freezing/Melting,” Comput. Math. Model., **26**(3), pp. 336–345.

[11] Instantes, B., and Instantes, A., 2008, “Foundation Design Using a Heat Pump Cooling System,” *Ninth International Conference on Permafrost*, U.S. Permafrost Association, Fairbanks, AK.

[12] McFadden, T., 2000, *Final Report on Foundation Stabilization Using a Heat Pump Cooling System at 728 Constitution Road, Fairbanks, Alaska*, Permafrost Technology Foundation, Fairbanks, AK.

[13] McFadden, T., 2007, *Supplemental Research Report on Foundation Stabilization Using a Heat Pump Cooling System at 728 Constitution Drive, Fairbanks, Alaska, USA*, Permafrost Technology Foundation, Fairbanks, AK.

[14] ASHRAE, 2017, *2017 ASHRAE Handbook - Fundamentals*, ASHRAE, Atlanta.

[15] Garber-Slaght, R., Craven, C., Peterson, R., and Daanen, R., 2017, *Ground Source Heat Pump Demonstration in Fairbanks , Alaska*, Cold Climate Housing Research Center, Fairbanks, AK.