COLD CLIMATE HOUSING RESEARCH CENTER

CCHRC

Ground Source Heat Pump Demonstration in Fairbanks, Alaska

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ABSTRACT

Alaskans are continually searching for safe and affordable options to heat their homes and in recent years residential ground source heat pumps (GSHPs) have been gaining in popularity. This has occurred despite a lack of research on their long-term performance or 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. For instance, Fairbanks, located in Alaska's Interior region, has 7,509°C heating degree-days$_{18}$ (13,517°F HDD$_{65}$) and only 40°C cooling degree-days$_{18}$ (72°F CDD$_{65}$). This large and unbalanced heating load creates a challenging environment for GSHPs. Additionally, soil temperatures average near freezing (0°C/32°F); the soil may be frozen year-round, just above freezing, or in an annual freeze-thaw cycle.

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 a 464 m^2 (5,000 ft^2) office space via an in-floor hydronic radiant heating system. The ground heat exchanger (GHE) was installed in moisture-rich silty soils underlain with permafrost near 0°C (32°F). The heat extraction coils are horizontal slinky loops buried at a depth of 2.7 m (9 ft.). The intent of the installation was to observe and monitor the system over a 10-year period in order 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 4 heating seasons. The system operated for two seasons with better-than-expected performance, with an annual coefficient of performance (COP) of 3.69 the first winter and 3.34 the second winter. In the third winter, the annual COP dropped to 3.01 and the ground started to freeze in the area around the heat extraction coils. The annual COP during the 4th winter was 2.82. The ground temperatures around the heat extraction coils measured approximately 1.1°C (34°F) in November 2013 and have declined steadily over four years of service. Thus far, no ice around the heat extraction tubes has lasted for a full year, but permafrost is expected to develop in the next few years based on modelling. CCHRC's intent is to continue to monitor the system's performance and effect on ground temperatures to determine if and when those metrics stabilize.

The depth of the GHE was designed to be below the seasonal active layer but above the permafrost table, however the installation depth is not backed by much underlying research. Determining the optimal depth for future GSHP installations in the Fairbanks area was assessed via finite element modeling. In addition to the model and demonstration project, a life cycle assessment indicated that the human health and environmental impacts of the GSHP heating are relatively similar to common combustion fuel heating scenarios used in Interior Alaska.

Keywords: Ground Source Heat Pump, Permafrost, Soil Thermal Degradation

Ground Source Heat Pump Demonstration in Fairbanks, Alaska

A ground source heat pump (GSHP) uses a refrigeration cycle to extract energy from the ground and transfer it to a building for space heating. The cost of this heat is in the form of electricity to run the pumps and the compressor in the refrigeration cycle. The efficiency of a GSHP depends on many aspects of the system design and configuration, the most fundamental determined by the site's climate, the subsurface characteristics in the vicinity of the ground heat exchanger (GHE), and the building-side fluid delivery temperature. Higher ground temperatures require less electricity to deliver heat; however, the annual thermal balance in the ground can be a more significant factor since it can determine success or failure of a system. A GSHP that only supplies heat to a building (due to a long heating season) can extract more heat from the ground than is returned to the ground in the summer on an annual basis. Over time, this unbalanced extraction can lead to lower soil temperatures and lower efficiency.

In an effort to address the lack of studies into the long-term performance of GSHPs in cold climates, CCHRC began a ten-year study of a GSHP system at their Research and Testing Facility (RTF) in Fairbanks, Alaska in 2013. The study is designed to use models and a demonstration heat pump to evaluate the long-term performance of a GSHP. Data from the demonstration project are used to inform the finite element analysis which was used to aid in system design and to determine the optimal depth for ground heat exchanger placement in locations with similar soil conditions. The efficiency information from the demonstration is used to create a Life Cycle Assessment (LCA) of the environmental impact of a GSHP system compared with typical fossil fuel heating systems. Additionally, the conditions of the soils around the slinky coils (GHE) are monitored to evaluate the thermal degradation as well as the significance of practical and affordable ground surface treatments to maximize energy capture in the ground.

This is an interim report based on the first 4 years of the heat pump operation. The report will discuss:

- The cost and maintenance of the GSHP
- The efficiency of the GHSP
- The effects of various ground surface treatments on soil temperature
- The results of the Life Cycle Assessment
- The model used to determine the optimum depth of the GHE
- The modeled long-term efficiency of the GSHP

GSHPs in Cold Climates

CCHRC and the Alaska Center for Energy and Power (ACEP) completed a study on ground source heat pump technology in cold climates in 2011 (Meyer, Pride, O'Toole, Craven, and Spencer). They found that, depending on the system performance, the price of oil, and available rebates, GSHPs can be cost effective in many areas in Alaska even with high capital costs. The study also found that the use of GSHPs is increasing in colder climates as the technology improves, but there is a lack of information on long-term performance in cold climates. Of particular interest is the effect of unbalanced heat extraction on the soil surrounding the GHE and the potential degradation in the efficiency of the heat pump system. Heat extraction from the ground that does not have equal heat recharge by solar radiation in the summer months has the potential to increase permafrost, especially in areas with existing discontinuous permafrost.

A few studies have looked at ways to achieve better GSHP performance in heating dominated climates. Wu, Wang, You, Shi, and Li (2013) note that the soil temperatures around a GHE in a heating dominated climate can degrade over time, which reduces the efficiency of the GSHP. There are several approaches to overcoming this problem: increasing the GHE size, installing a secondary heating source, and using thermal storage (Wu et al., 2013). You, Wu, Shi, Wang, and Li (2016) also suggest several ways to improve GHE performance. Increasing the size of the GHE or changing the layout of boreholes can mitigate thermal imbalance slightly, but is not effective for a larger thermal imbalance. Modifying the heat pump system itself to include auxiliary heating sources or restricting use to certain times of the day when other heating options are not available is a practical and effective way to help the GHE maintain higher temperatures and improves efficiency (You et al., 2016). Eslami-nejad and Bernier (2012) found that by saturating soils around the GHE boreholes, latent energy from freezing the soil was added to the heat pump system. Yang, Kong, and Chen (2015) also looked at phase change process in the GHE. They found that freezing in the GHE area can enhance the heat transfer performance and can help in downsizing the heat exchanger. The higher thermal diffusivity of the soil has the largest effect on the improvement of heat transfer with phase change in the heat exchanger (Yang, et al. 2015). Rezaei, Kolahdouz, Dargush, and Weber (2012) studied the effects of surface treatments on soil temperatures in a GHE. A layer of tire-derived aggregate (shredded tires) affects soil temperatures down to 4 m (13 ft.) with a layer of material that is 0.2 m (0.6 ft.) thick (Rezaei, et al., 2012). The surface layer of aggregate had the potential to increase the energy absorbed from the "GHE by 17% over no surface treatment" and the aggregate performed better in cold climates (Rezaei, et al., 2012).

As Meyer et al. found there are very few long-term studies of heat pumps in cold climates. Prior to this CCHRC study, the longest study of the GSHP as a heating source in Alaska lasted 1.5 years and concluded that the soil temperatures with the GHE at 1.2 m (4 ft.) of depth recovered early in the summer season (Nielsen and Zarling, 1983). A one-year study in Southcentral Alaska found that deeper heat extraction coils (2.7 m, 9 ft.) did not recover temperature completely in the summer months, whereas the shallower coils (1.5 m, 5ft) recovered well (Mueller and Zarling, 1996). The longest cold climate heat pump studies use heat pumps to cool building foundations to protect the permafrost. Svalbard, Norway has several buildings that use heat pump cooling to maintain the permafrost (Instanes and Instanes, 2008). A 1993 home retrofit in Fairbanks installed a GSHP under the foundation to re-cool the permafrost and maintained the foundation for more than 20 years (McFadden, 2007). Neither of these studies looked into the performance of the heat pump as a space heating device.

The CCHRC Heat Pump

CCHRC's Research and Testing Facility (RTF) is located on the campus of the University of Alaska Fairbanks (UAF) (Figure 1). Fairbanks has 7,509°C heating degree-days$_{18}$ (13,517 °F HDD$_{65}$) and 40°C cooling degree-days$_{18}$ (72°F CDD$_{65}$); the 99.6% design temperature is -41.9°C (-43.5°F) (ASHRAE, 2013). Fairbanks is in a zone of discontinuous and warm permafrost (0°C, 32°F). The area surrounding the RTF is an open field cleared of native vegetation more than 60 years ago and is made up of moist silt (Shannon & Wilson, Inc., 2002). The permafrost in the area underlying and around the RTF has been degrading since the land was first cleared (Shannon & Wilson, Inc., 2002).

The RTF is 2,044 m^2 (22,000 ft^2) with 3 distinct heating sections. The heat pump was sized to heat the 464 m^2 (5,000 ft^2) office space on the east side of the building with a design heat load of 17.6 KW (60,000 BTU/hr.). Heat is distributed to the area via an in-floor hydronic tubing system embedded in concrete. The office space has 9 thermostatically controlled zone valves. The heat pump system replaced a 22.3 KW (76,000 BTU/hr.) oil fired condensing boiler as the main source of heat for this portion of the building; a masonry stove is still used for supplemental space heating and ambiance.

Figure 1. CCHRC's Research and Testing Facility. The original building (the right side of the photo) was built in 2006; the addition on the left was completed in 2012. The heat pump heats the section on the far right end of the photo.

Design and Installation

The soils around the RTF have been extensively surveyed in the past 20 years for road and building construction projects. Borehole logs from these surveys were used to inform the design of the heat pump GHE. Boreholes drilled on the site in 2006 prior to the construction of the RTF found the site underlain with a sloping layer of permafrost. The top of the layer started at 3 m (10 ft.) on the south side of the building near the undisturbed vegetation and sloped down to 9.1 m (30 ft.) on the north side where the native vegetation had been cleared. Data collected under the east end of the RTF since 2006 shows that the permafrost table has further degraded by an additional 0.6 m (2 ft.). A test borehole northwest of the RTF in 2012, prior to installing the GHE, did not find permafrost within 9.1 m (30 ft.) of the surface. All the soils were found to be moist silt.

A soil thermal conductivity (TC) test was conducted in October 2012, one year prior to the installation of the heat pump. A 34 m (112 ft.) long horizontal loop at 2.7 m (9 ft.) of depth was installed 12 days prior to the testing. The test lasted 48 hours. A 20% methanol solution was run through the piping. Energy was added to the fluid via an electric heating coil. The temperature change in fluid and the energy input into the system was recorded. Geothermal Resource Technologies, Inc. evaluated the data and determined the soil thermal conductivity was 1.42 W/m·K (0.82 Btu/hr·ft·°F). The thermal diffusivity was estimated to be 0.055 m^2/day (0.59 ft^2/day).

CCHRC originally wanted to demonstrate both deep wells and horizontally trenched GHEs. However, test bores for Thompson Drive (about 183 m, 200 yards from the GHE) construction in 2001 discovered frozen schist bedrock from 19.5 m (64 ft.) down to 45.7 m (150 ft.) (the bottom of the boreholes). The frozen schist was -6.7 °C (20°F), which was deemed too cold for this demonstration. A horizontal GHE was designed based on the technology available in Fairbanks at the time. Since directionally drilling was not an option, horizontal “slinky” coils were developed. Six 30.5 m (100 ft.) long by 1 m (3 ft.) wide slinky coils with an 0.5 m (18 in.) pitch were installed 1.8 m (6 ft.) apart (see Figure 2). Overall, 1,463 lineal m (4,800 ft.) of 1.9 cm (3/4 in.) HDPE was installed at 2.7 m (9 ft.) depth to create the in-ground heat exchanger. The GHE size and depth were determined by knowledge of past installations in the area, in conjunction with ground thermal conductivity test data, and information from a finite element model. Additionally, IGSHPA (International Ground Source Heat Pump Association) guidelines for flow path (one 30 m (100 ft.) slinky coil per ton of capacity) and turbulent flow were used to further guide the design of the ground heat exchanger (IGSHPA, 2009).

The depth of the GHE is more than was recommended by the Mueller and Zarling (1996) and Nielsen and Zarling’s (1983) Alaskan studies. However, the depth was chosen to be below the line of seasonal frost (about 1.2 m (4 ft.)) and above the top of the permafrost (near 9.1 m (30 ft.)). In addition, the 2.7 m (9 ft.) depth is the typical installation depth for residential horizontal GHE in the Fairbanks area. Part of the finite element analysis portion of this study is to determine an optimum depth for the ground heat exchanger.

In addition to determining an optimum heat exchanger depth, this study also evaluates the effects of different ground coverings and which are more advantageous for energy recharge. Three different coverings are being evaluated: dark rocks, sand, and grass. Each treatment covers 2 slinky loops (see Figure 2). The soil temperatures under the coverings are monitored as are the temperatures of the fluid returning from the slinky coils.

The heat pump is a residential 21 kW (6 ton) water-to-water unit, selected based on previous experience with the model in Fairbanks. It is connected to the existing in-floor hydronic heat delivery system. The heat pump heats a 303 liter (80 gallon) buffer tank of water to a temperature determined by the outdoor set point curve. The minimum temperature set point for the buffer tank is 26.7°C (80°F) and the maximum is 42.8° C (109°F). Originally, the set point curve had a maximum of 41.7°C (107°F); however the in-floor heating tubes are configured in a way that requires a higher temperature so the set point curve was changed. This higher set point lowers the efficiency of the heat pump slightly. The GHE side of the heat pump is charged with a 20% methanol, 80% water mixture. The building hydronic side of the heat pump is charged with water.

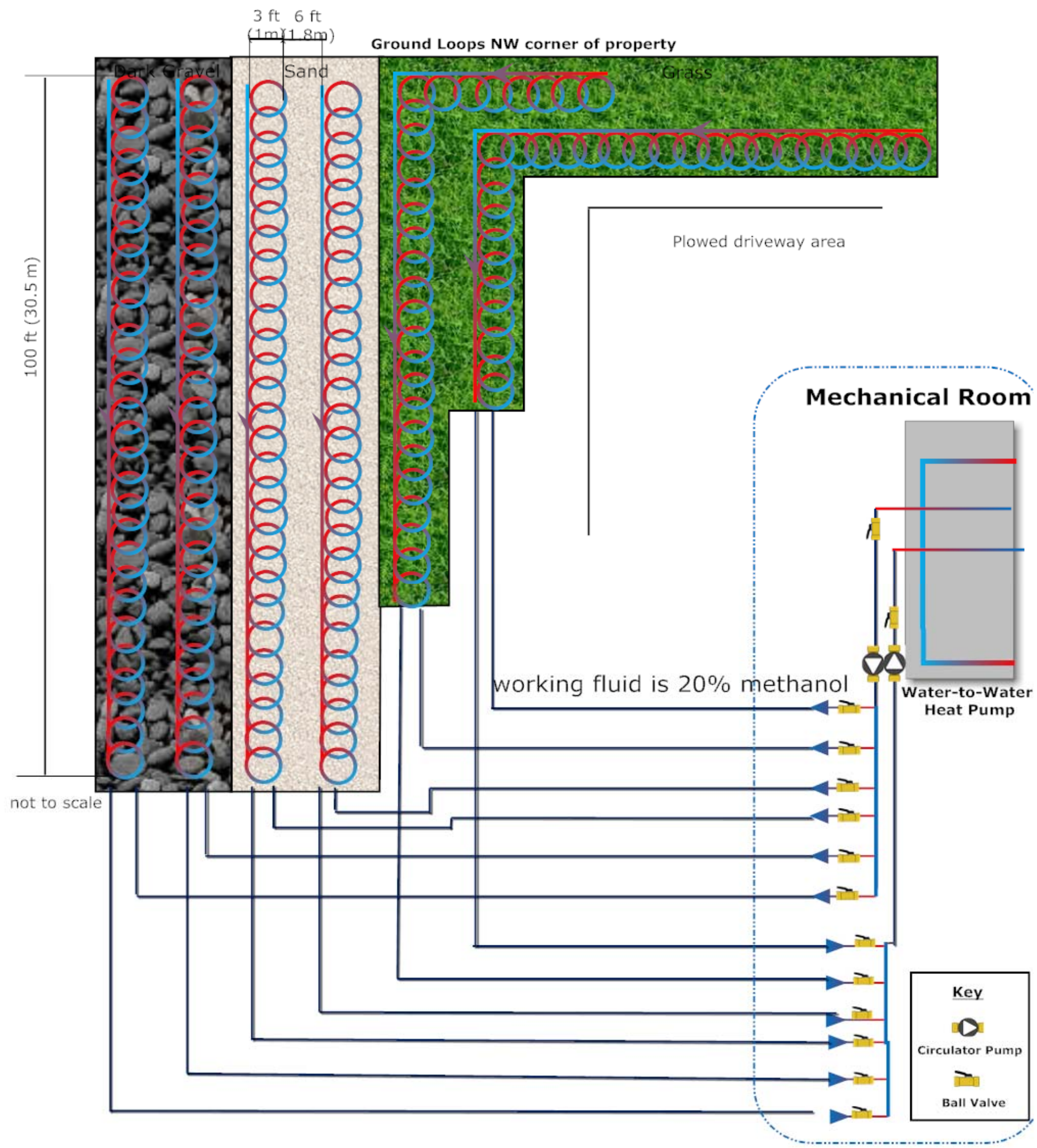

Figure 2. Schematic of the heat pump layout. The GHE is to the northwest of the RTF. (The schematic is not to scale.)

Maintenance and History

The heat pump was installed between May 2013 and October 2013. The GHE was installed in May to take advantage of the stability of the frozen ground (Figure 3). Six 2.7 m (9 ft.) deep trenches were dug, while the first 0.6 to 1.2m (2 to 4 ft.) of soil was frozen making certain that the soils did not slump into the trenches. In October 2013 the plumbing for the heat pump was completed (Figure 4) and the unit was started and commissioned. The data collection system came online in November 2013.

The heat pump itself has had two warranty callbacks, both related to faulty electrical parts. In November 2013 a contact and the control board were replaced, and in February 2016 a contactor was replaced. The GHE and all the circulation pumps have not required any maintenance.

Figure 3. GHE slinky coil installation. The installation of the GHE required a large excavation that took nine days.

Figure 4. Heat pump and plumbing installation. The heat pump plumbing involved setting the heat pump and the buffer tanks and connecting lots of copper pipe.

Data Collection

The automated data collection system is composed of several components listed in Table 1 and shown in Figure 5 on the system diagram.

Table 1. Data Collection System Components

Data Point	Sensors and Location	Range and Accuracy
Ground Temperatures	Thermistors within and around the GHE	-20°C to 80°C ±0.1°C (-4°F to 176°F)
Manifold Temperatures	Thermistors in the manifold returning from the GHE (see Figure 5)	-20°C to 80°C ±0.1°C (-4°F to 176°F)
Ground Loop Energy	BTU meters in the piping to and from the GHE	0 to 20 gpm ±2%(0 to 75.6 l/min) 10 to 70°F ± 0.15°F (-12°C to 21.1)
Heat Pump Energy	In the piping to and from the buffer tank and to and from the building	0 to 15 gpm ±2% (0 to 56.8 l/min) 40 to 140°F ± 0.15°F (4.4°C to 60°C)
Heat Pump Electrical Use	Heat pump and the circulating pumps	0 to 100 amp ±1% 115 to 230 VAC ±1%

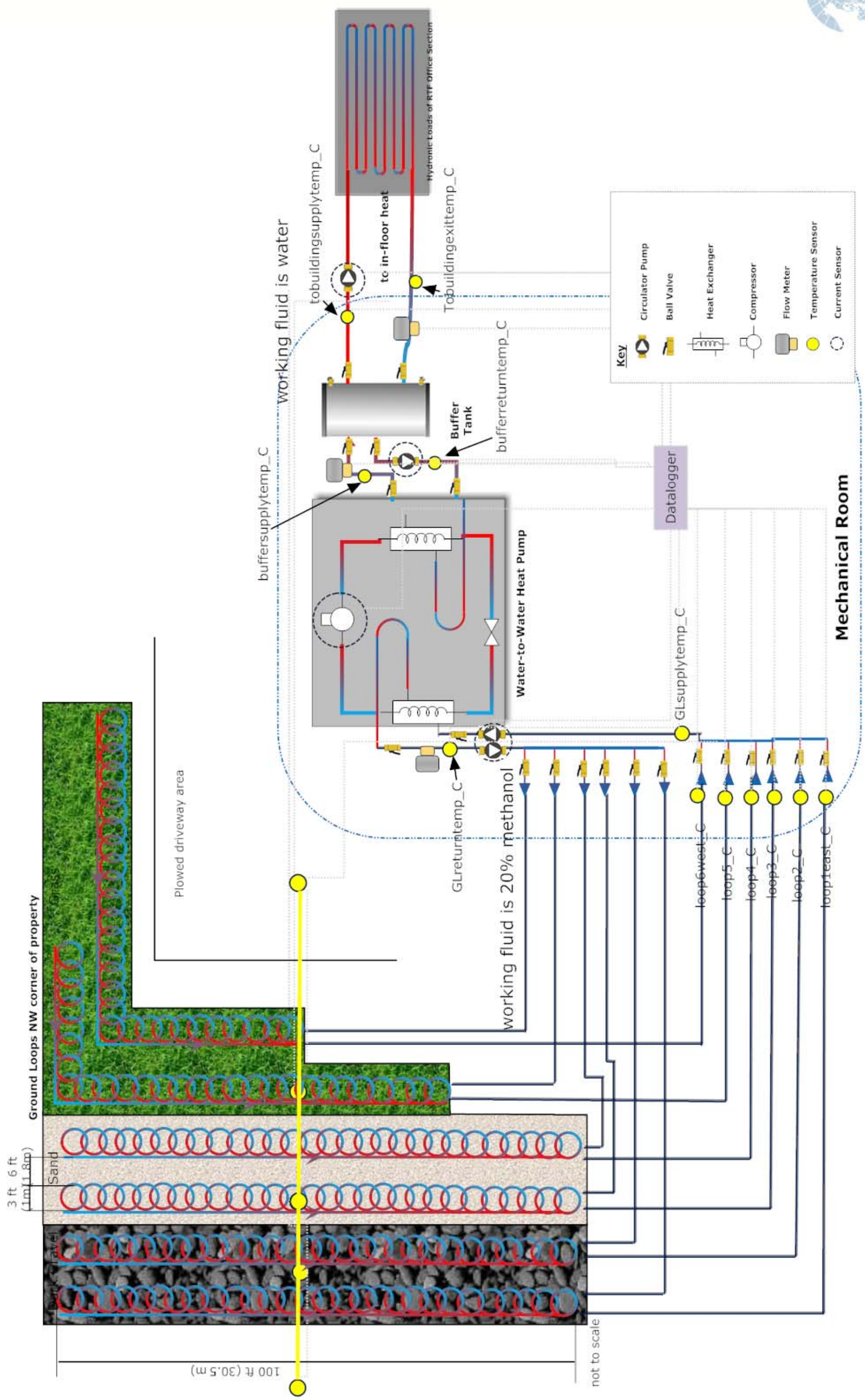

Figure 5. Data collection system. Each temperature data point in the GHE has multiple temperature sensors going to depth under it. (The schematic is not to scale.)

Ground Heat Exchanger

Temperatures and soil freezing front data is being collected in the GHE. The automatic data collection system is collecting temperature data from 7 temperature strings in and around the GHE (Figure 6) as well as the temperatures of the fluid entering the building at the manifold from each heat extraction slinky coil.

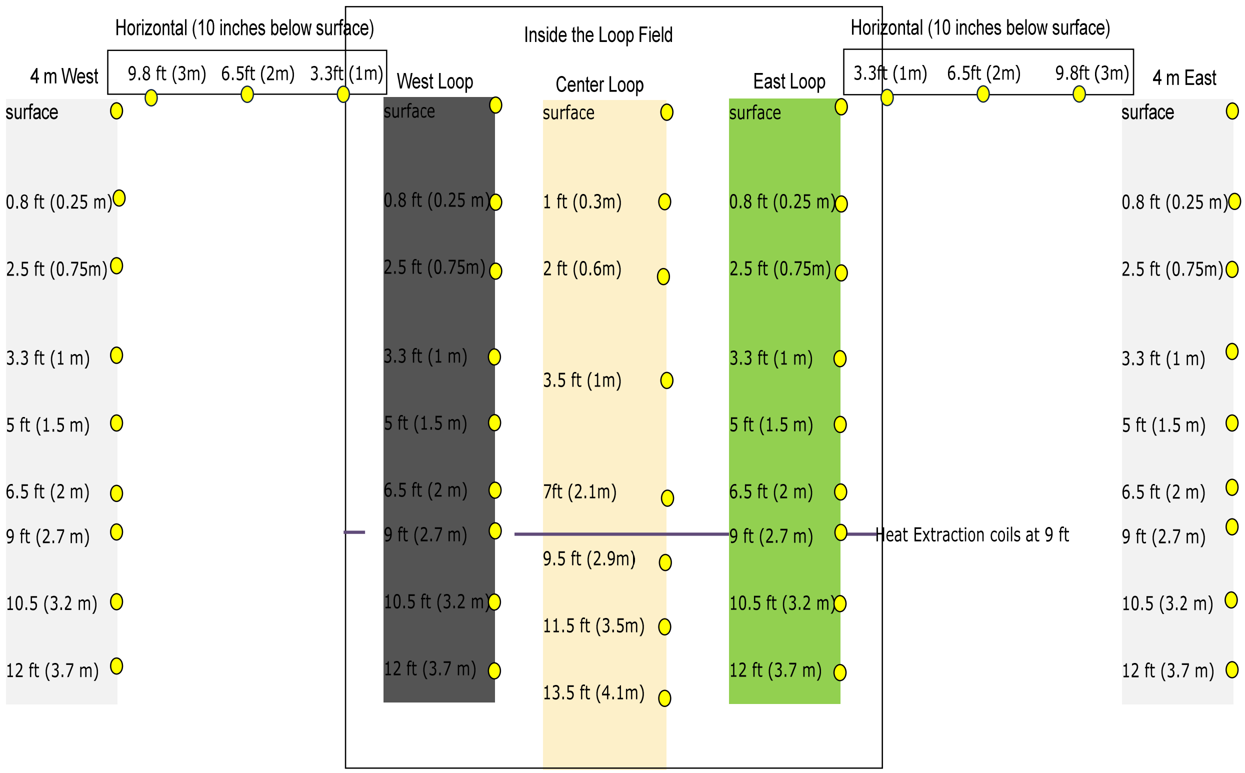

Figure 6. In-ground temperature strings. Some of the sensors in this configuration have failed in four years. Some have been replaced but most are not accessible.

The GHE temperatures are used to determine if the ground heat extraction coils are cooling the soil more than the solar recharge in the summer can recover. The temperatures are taken across the surface of the loop field, as shown by the yellow line across the loop field in Figure 5. They are also taken down into the GHE field, as far down as 4.1 m (13.5 ft.) in the center of the GHE field. Two of the vertical temperature strings are located in the middle of the slinky coils, while the third is between two sets of coils. The ground heat extraction coils cross the vertical temperature strings at approximately 2.7 m (9 ft.) from the surface. Two other vertical temperature strings are 4 m (13.1 ft.) to the west and east sides of the GHE field.

The sensors in the manifold record the temperature of the fluid as it comes back from the GHE field (Figure 7). These temperatures were intended to verify whether or not the surface treatments were creating any differences in temperature in each slinky coil loop.

In addition to recording ground temperatures, permafrost tubes are installed in three locations in and around the GHE. A permafrost tube consists of a thin column of dyed water within a pipe in the ground (Figure 8). Once a month the tubes are pulled out of the ground and the depth and extent of the ice within the water column is recorded. There are 2 permafrost tubes within the GHE (one in the center of a sand loop and one between the two gravel loops) and one in the field to the west of the GHE.

Figure 7. GSHP manifold. The manifold is located in the mechanical room. Temperature sensors are in thermowells on the return loop from the ground side of the GHE (the bottom in this photo).

The temperatures from the GHE are used to chart the change in soil temperature over time at certain depths. Additionally, the temperatures are used to create whiplash curves for the GHE. Whiplash curves are configured to show the temperature on the x-axis and the depth of the soil on the y-axis. This configuration creates a visual analysis of the changes in ground temperature over time. Since below-freezing temperature in the ground loop does not necessarily indicate frozen soil, the permafrost tubes are used to verify if the water in the soil is frozen. As energy is extracted from the GHE the temperature drops to 32°F (0°C) quickly, and once the freezing temperature is reached the energy that is extracted changes the phase of the water in the soil to a solid. This phase change takes much longer than the temperature changes and the soil is not necessarily frozen at the freezing temperature. Locations that stay frozen for more than 2 years are then considered permafrost.

Figure 8. Checking permafrost tubes. The separated lines of blue in the right hand photo indicate areas of frozen ground.

Mechanical System

The automated data collection system is also collecting data on the mechanical side of the heat pump. The heat pump uses two circulation pumps to pump fluid through the GHE and an additional one to pump hot water to the buffer tank. The electrical use of the heat pump is monitored as is the electrical use of each pump individually. A fourth circulation pump, which delivers hot water from the buffer tank to the in-floor distribution coils in the building, is also monitored for electrical use.

The heat energy in the fluid is monitored using flow and temperature sensors: the energy delivered to the heat pump from the GHE, the energy from the heat pump to the buffer tank, and the energy from the buffer tank to the building.

The oil-fired condensing boiler replaced by the heat pump is still on site and can be used as a backup system should the heat pump ever fail. The energy output of the condensing boiler is monitored to verify if the boiler is augmenting the heat pump. The masonry stove is still used to heat the same area as the heat pump. The amount of wood added to the stove is recorded to verify how much the heat pump is offset by the stove.

The efficiency of a heat pump is also called the Coefficient of Performance (COP). It is calculated using Equation 1.

$$COP = \frac{Heat\ Energy\ to\ the\ Building}{Electricity\ for\ the\ Heat\ Pump} \qquad (1)$$

"Electricity for the heat pump" includes the electricity powering the heat pump and the 3 circulation pumps (2 to the GHE and one to the buffer tank) that are controlled by the heat pump. Data is collected on an hourly basis but the COP is calculated as an average for each month.

The Economics of the CCHRC Heat Pump

Installation Costs

Prior to the design and installation of the heat pump, CCHRC performed the previously mentioned thermal conductivity (TC) test in the soil near the future GHE. A TC test is not commonly performed for residential GSHP system designs, therefore the added cost for the TC test in not included as part of normal design and heat pump installation costs (TC test costs are listed in table 2). The TC test was completed to ensure the GSHP system design would be optimized and to provide better input data for the finite element model analysis. CCHRC worked with Geothermal Resources Technologies Inc. (GRTI) and Alaska Geothermal, LLC to conduct a TC test.

Table 2. Soil Thermal Conductivity Testing

Component	Cost
Excavation	$2,875
Equipment Shipping	$632
Equipment Rental	$1,150
Data Analysis	$800
Total	$5,457

The costs for the overall heat pump installation (minus the TC test and the data collection system) are presented in Table 3. This installation was more expensive than a typical residential installation due in part to the fact that this is a research project and has some unique features (i.e. manifold inside the building). Residential GSHP installations in the Fairbanks area generally cost between $20,000 and $35,000 in total to install (Garber-Slaght & Stevens, 2014).

Table 3. Heat Pump System Installation Costs

Component	Cost
System Design	$1,162
GHE Installation	$30,305
Heat Pump Installation	$22,546
Total	$54,014

Operating Cost

The maintenance costs to operate the heat pump have been minimal. Two previously mentioned electrical problems were solved under warranty and no out-of-warranty maintenance problems have occurred to date.

Over the course of the study thus far, the system has used 26,517 kWh of electricity. This amounts to $6,361 in heating costs at a constant $0.24 per kWh. Figure 9 shows the electrical cost trends by year.

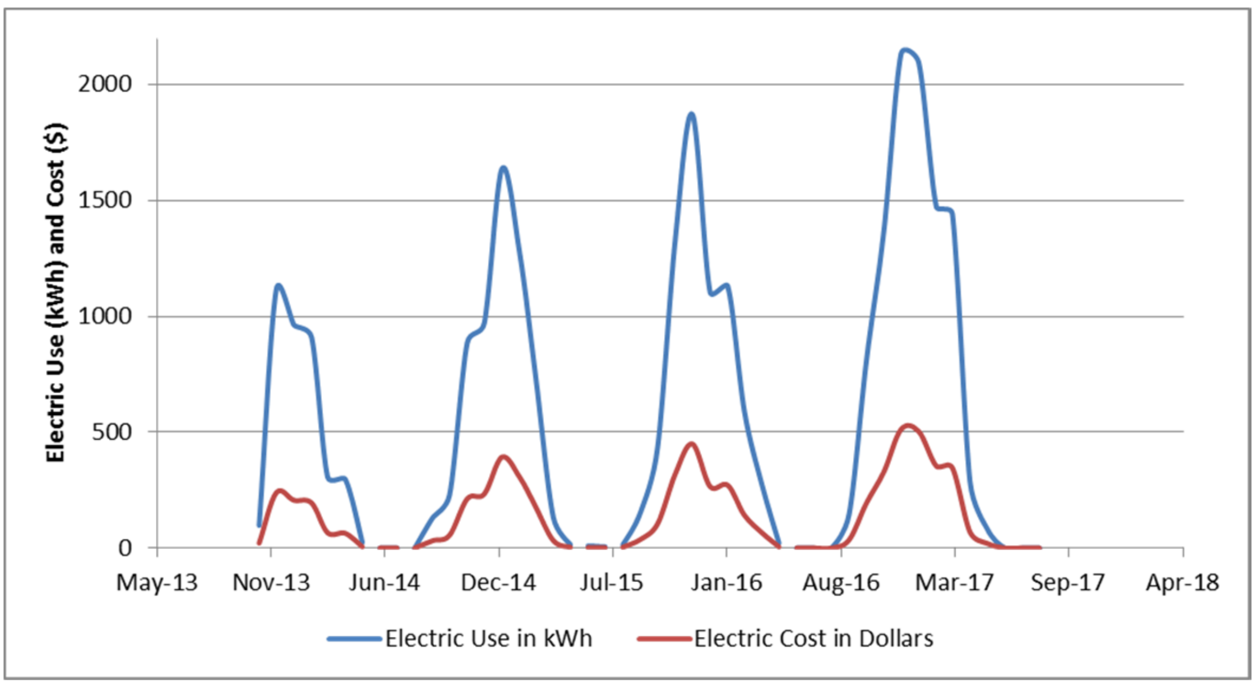

Figure 9. Electrical use of the heat pump system. Each successive winter has seen a rise in the electrical use and cost for operating the heat pump.

Table 4 breaks out electrical use and cost by month. The heat pump has a small electrical load of 13 W when it is not running. This load runs the thermostat which keeps the buffer tank at a set point based on the outdoor temperature. Each summer, except for 2015, CCHRC turned off the heat pump when the heating season was over in late May and kept it off into September. This off time is indicated by a 0 in the table. The summer of 2015 provides an example of how much the heat pump costs in idle mode, as it was not turned off that summer.

Table 4. Annual Electrical Cost of the Heat Pump System.

	Year 1 (winter 2013-14)		Year 2 (winter 2014-15)		Year 3 (winter 2015-16)		Year 4 (winter 2016-17)	
	Electric Use (kWh)	Electric Cost	Electric Use (kWh)	Electric Cost	Electric Use (kWh)	Electric Cost	Electric Use (kWh)	Electric Cost
August			0	$0.00	13	$3.12	0	$0.00
September			129	$30.96	154	$36.96	146	$35.14
October			229	$54.96	434	$104.16	803	$192.69
November	97	$23.28	885	$212.40	1332	$319.68	1370	$328.81
December	1,115	$267.60	971	$233.04	1871	$449.04	2133	$511.98
January	962	$230.88	1636	$392.64	1104	$264.96	2096	$503.13
February	908	$217.92	1272	$305.28	1129	$270.96	1471	$353.14
March	306	$73.44	740	$177.60	593	$142.32	1442	$346.12
April	297	$71.28	132	$31.68	272	$65.28	286	$68.74
May	24	$5.76	14	$3.36	39	$9.36	83	$19.94
June	0	$0.00	9	$2.16	0	$0.00	0	$0.00
July	0	$0.00	5	$1.20	0	$0.00	0	$0.00
Annual Total	3,712	$890.16	6,027	$1,445.28	6,946	$1,665.84	9,832	$2,359.70

Savings of the Heat Pump Over Using Oil

The amount of savings over using an oil-fired boiler is heavily dependent on the cost of oil per gallon and the efficiency of the oil-fired boiler. Oil prices have been variable since the start of this project; Table 5 shows the change in heating fuel costs over the first 4 years of heat pump operation. The cost of electricity has remained consistent at $0.24/kWh over the first 4 years of the project.

Higher oil prices mean more savings when using the heat pump. Table 6 shows the savings in using the heat pump over the first 4 years of operation, using the real cost of fuel over that time period. In order to determine an oil-fired BTU equivalent to the amount of heat delivered by the heat pump, a 96% efficient oil-fired condensing boiler was used. This boiler was similar to the one the heat pump replaced; however the high efficiency of this model is not typical of most boilers.

When oil prices slipped below $2.45 per gallon in the third winter, the savings advantage of the heat pump ceased. In fact, using the oil condensing boiler would have saved $207 over using the heat pump in the

2015-16 heating season. In four years the heat pump has saved a combined total of $707 over using the oil fired condensing boiler that is 96% efficient. Replacing an 80% efficient boiler would have increased the savings to $1,676. Had fuel prices remained near $4 per gallon the heat pump system would have saved an estimated $3,421 over the 96% efficient boiler and $4,803 over the 80% efficient boiler in 4 years.

Table 5. Heating Fuel Prices per Gallon

	Year 1 (winter 2013-14)	Year 2 (winter 2014-15)	Year 3 (winter 2015-16)	Year 4 (winter 2016-17)
August		$3.98	$2.97	$2.29
September		$3.72	$2.97	$2.29
October		$3.67	$2.40	$2.31
November	$3.85	$3.67	$2.37	$2.31
December	$3.85	$3.47	$2.35	$2.30
January	$3.92	$3.01	$2.06	$2.40
February	$3.98	$2.76	$1.99	$2.40
March	$3.98	$2.97	$2.02	$2.38
April	$3.98	$2.97	$2.11	$2.43
May	$3.98	$2.97	$2.11	$2.43
June	$3.98	$2.97	$2.11	$2.43
July	$3.98	$2.97	$2.11	$2.43

Table 6. Savings of the Heat Pump System Compared to Equivalent Heating Oil Use.

	Year 1 (winter 2013-14)	Year 2 (winter 2014-15)	Year 3 (winter 2015-16)	Year 4 (winter 2016-17)
	Heat Pump savings over oil	Heat Pump savings over oil	Heat Pump savings over oil	Heat Pump savings over oil
August				
September		$27.78	$9.75	($10.93)
October		$113.62	($3.56)	($44.97)
November	$18.12	$146.29	($10.57)	($17.23)
December	$161.28	$135.95	($34.56)	($38.21)
January	$158.10	$93.83	($47.31)	($79.05)
February	$147.28	$42.69	($60.87)	($55.53)
March	$57.70	$53.31	($35.22)	($59.62)
April	$58.42	$21.92	($21.29)	($17.95)
May	$2.65	$3.83	($3.67)	($4.44)
June				
July				
Annual Total	$603.55	$639.22	($207.30)	($327.94)

CCHRC GSHP Results

Observed GHE Temperatures

Temperatures recorded in and around the GHE show cooling of the ground over the four years the heat pump has been in use when compared to the baseline data (Figure 10). The temperatures in the vicinity of the heat extraction coils are lower than the baseline temperatures in the adjacent field. The temperature at the depth of the coils shows 0°C (32°F) most of the winter; the baseline temperatures are 3 to 4°C (5.4°F to 7.2°F) higher. The temperature at around the coils has not dropped below 0°C (32°F) as the energy of phase change is extracted from the surrounding soils, creating ice in the soil. To date, the soil around the loops has risen above freezing each summer.

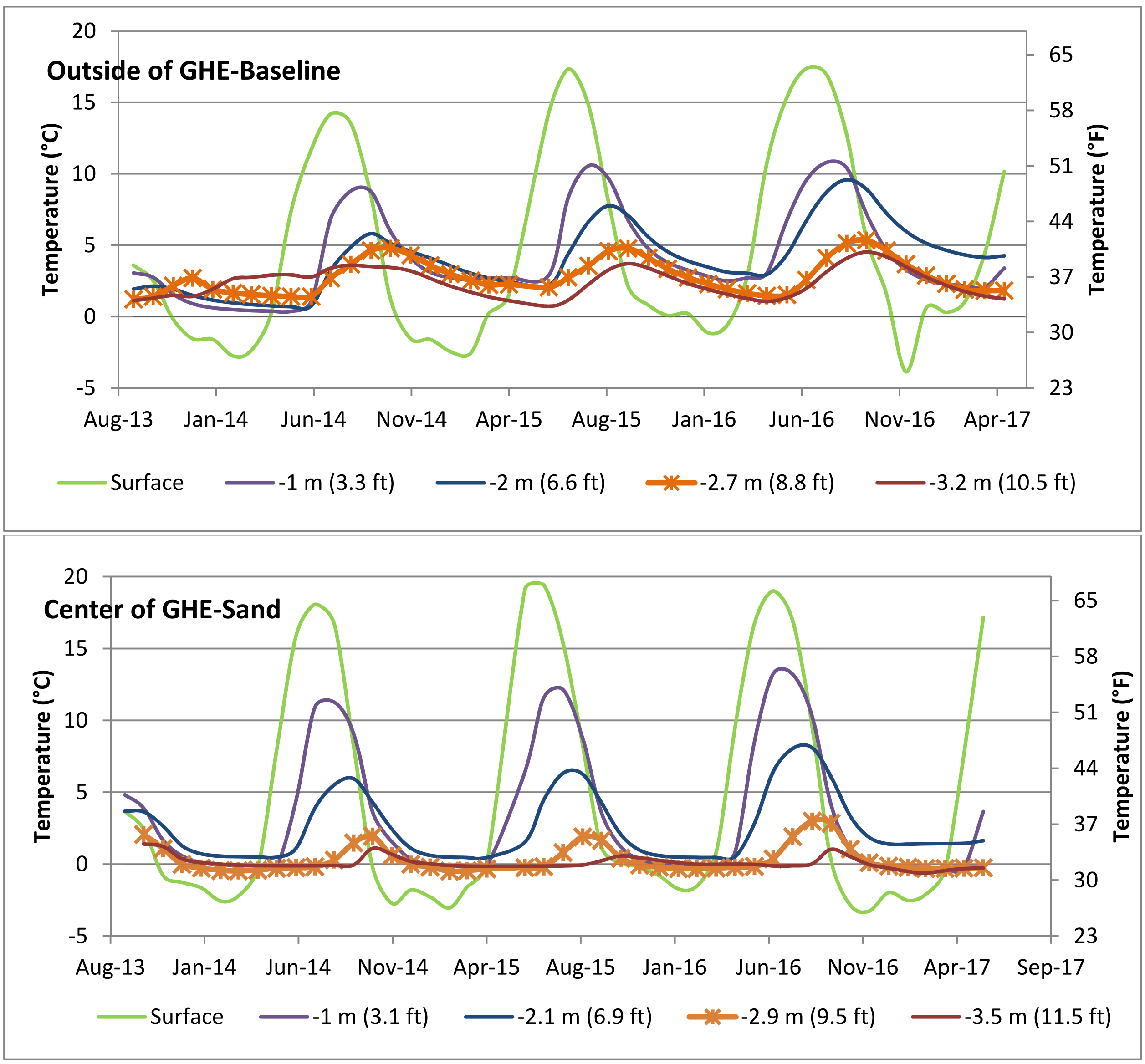

Figure 10. In-ground temperatures over time. The orange starred line is nearest to the ground heat extraction coils. Temperatures are cooler in the GHE than in the field next to the GHE. The surface temperature for the sand was warmer than the field, the field sensors are under grass.

Figure 11 shows data into the ground outside the influence of the GHE as a comparison to Figure 12, which shows the temperatures into the ground at the center of the GHE over four years. The 2.7 m (9 ft) depth of GHE line in the diagram is where the slinky coils were designed to be, however with a large excavation and backfilling and leveling, it is likely that the coils are not exactly at 9 ft. Based on the coldest temperature in this location, these coils are likely deeper than 9 ft; they appear to be around 3.4 m (11 ft). Temperatures at that depth started dropping to freezing the first winter of heat extraction and stayed near freezing throughout the 2015-2016 winter. However, they were above freezing in the fall of 2016 (rising groundwater in this area could be creating warmer conditions, which will be studied in later reports). Overall temperatures have not dropped much below 0°C (32°F) in four years, but could if permafrost develops around the GHE.

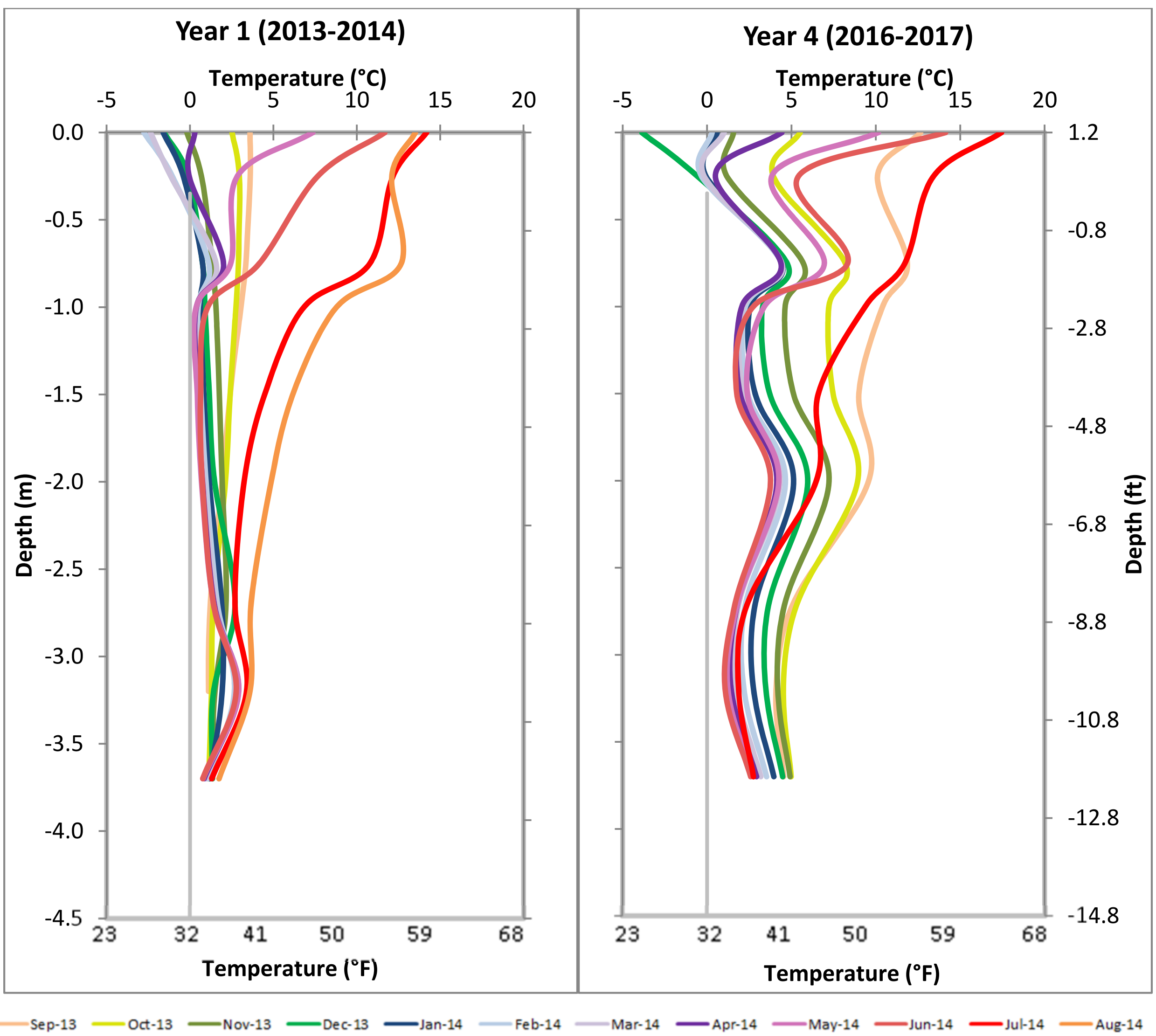

Figure 11. Whiplash curve for the baseline data. This is outside of the heat pump field and provides an example of what a typical whiplash curve looks like with no influence beyond ambient conditions. The warming of the ground at 3.7 m (12.1 ft.) is potentially the result of rising groundwater.

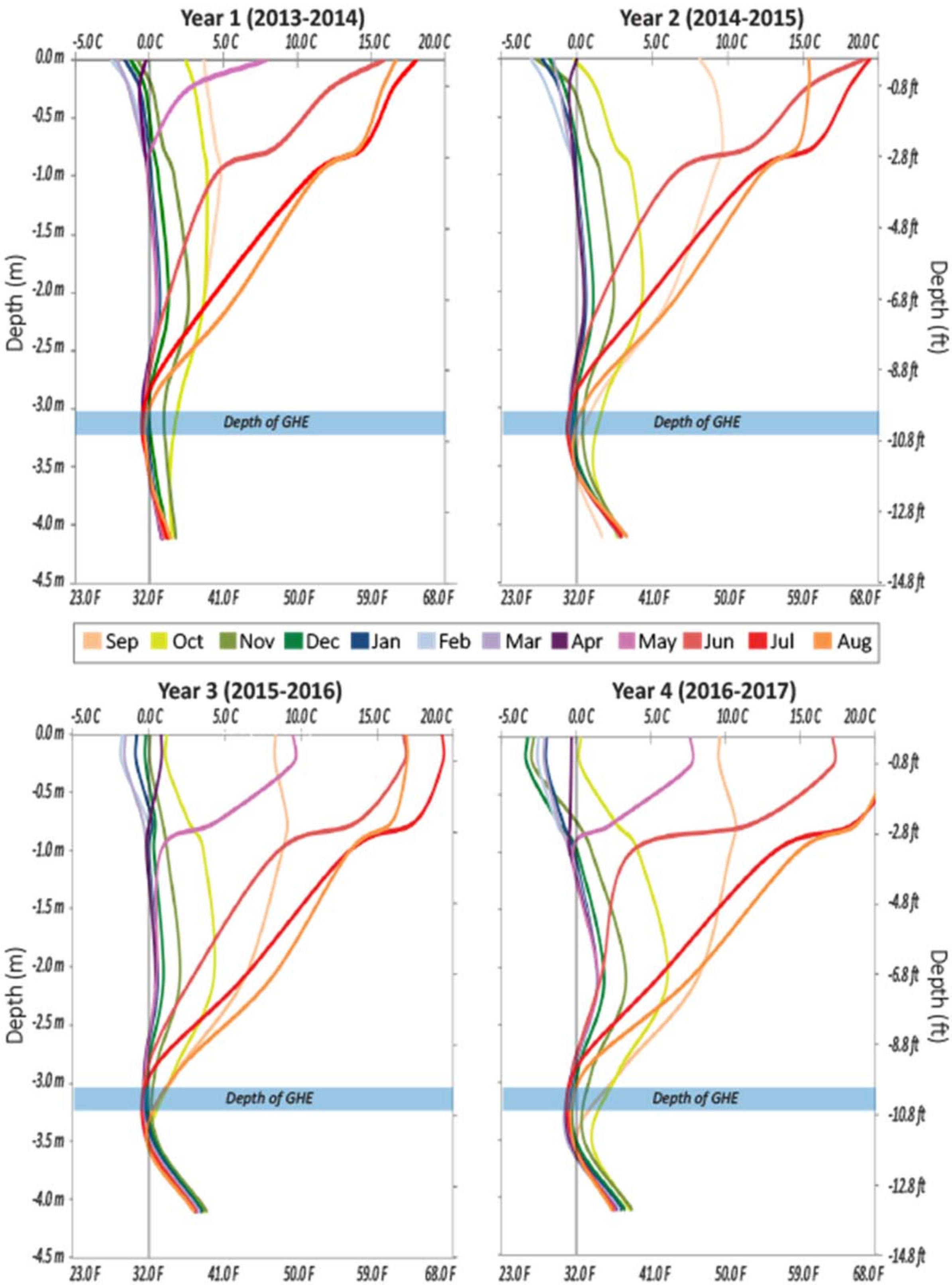

Figure 12. Whiplash curves of the center of the GHE for 4 years. Each winter season starts in September and ends in August. The warming at depth agrees with the baseline data and is possibly the result of rising groundwater.

Permafrost

The permafrost tubes in the GHE show some frozen sections of soil within the area of the slinky coil in the center of the GHE. The frozen ground is not evident above or below the slinky coil zone, as far as can be determined from the permafrost tubes. Figure 13 shows the extent of frozen ground during the third and fourth winter. To date, the ice around the slinky coils has not lasted the full year. There was no ice below the active layer in any other locations or in any previous year.

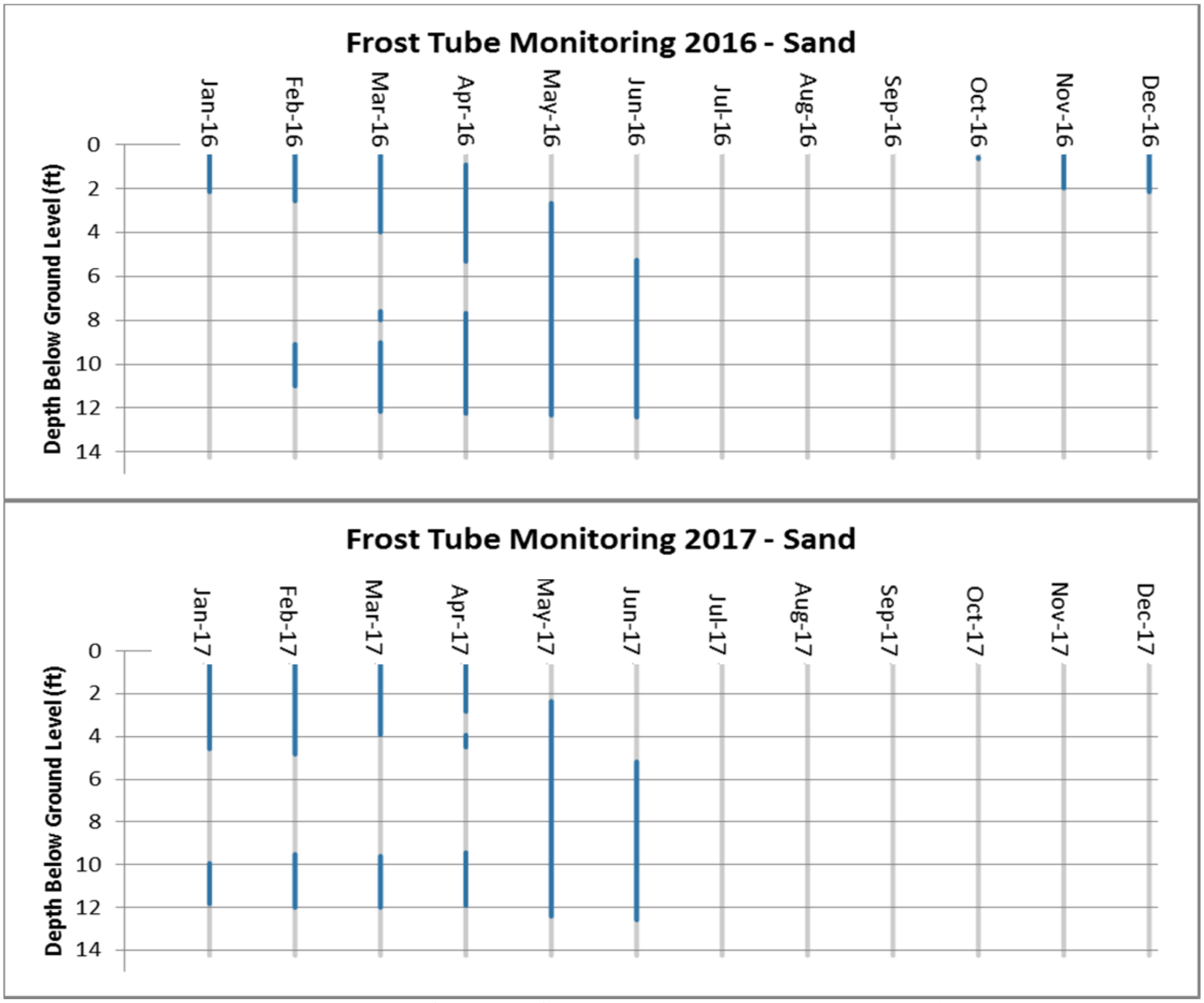

Figure 13. Ice in the center of the GHE under the sand treatment. There was no ice in July or August 2016 or 2017. Presently this is the only location that has recorded frozen soil below the active layer.

Surface treatments

Temperatures in the GHE show the effects of the differing surface treatments. Further down in the ground loop the effects of the surface treatments are harder to discern, especially around the slinky coils where the heat extraction has an overwhelming effect on the ground temperatures. However, the dark gravel is keeping that section of the GHE warmer than the sand or the grass. The grass is the coolest of the three treatments. Figure 14 shows the temperatures within the GHE over time, based on the surface treatments. Data from all the sensors are not available, but the gravel area temperatures trend higher than the other two treatments over time, with the deeper points having higher temperatures than the deeper points of sand and grass areas.

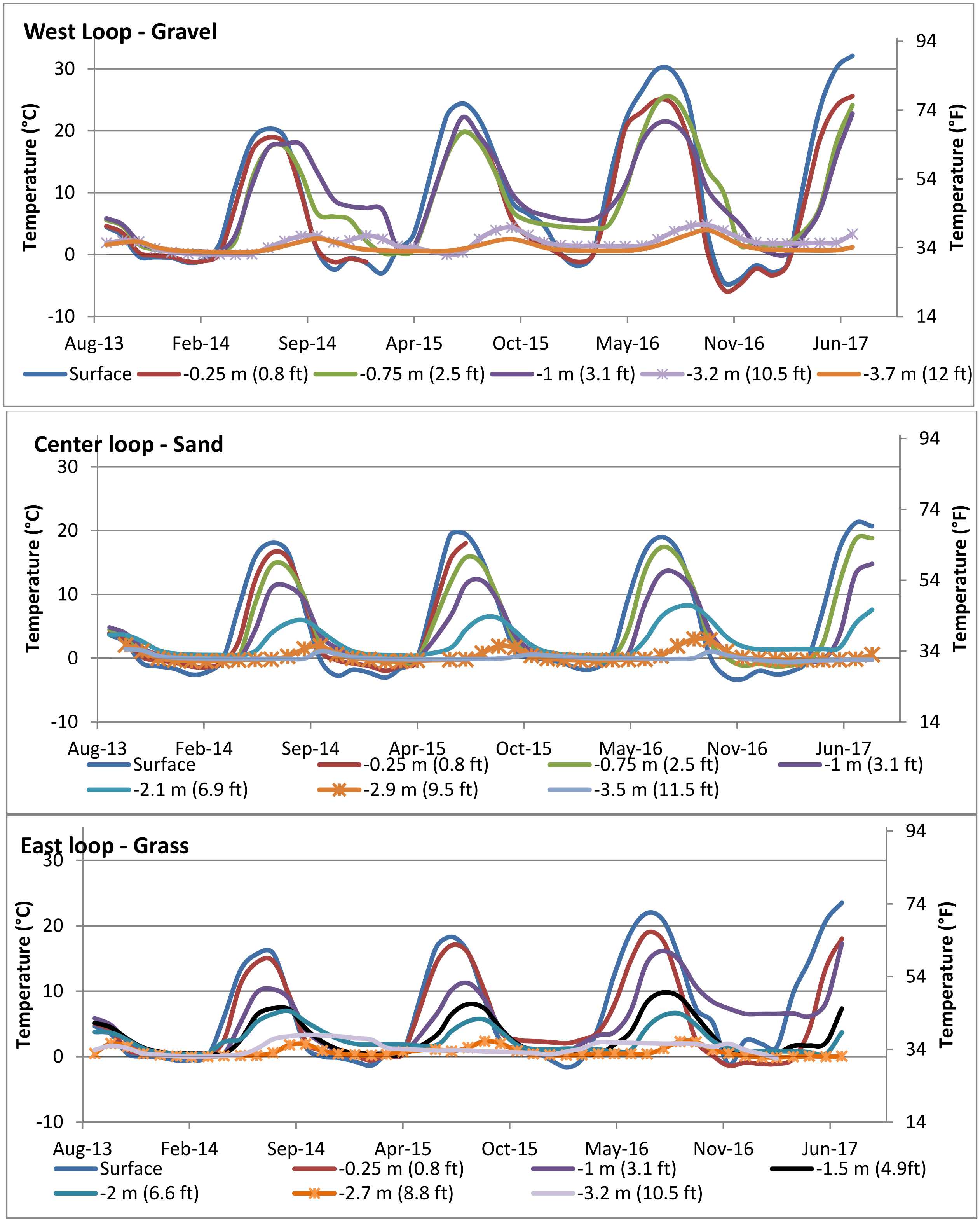

Figure 14. In-ground temperatures over time. The orange starred lines are the closest to the GHE coils. This point has failed in the gravel, but the rest of the points are all generally warmer than the grass and sand. Incomplete data sets indicate a failed sensor.

The temperature sensors in the manifold were set up to determine if the surface treatments were having any effect on the GHE. Figure 15 shows the fluid returning from the gravel loops is always slightly warmer than the other two surface treatment loops. The differences in the surface treatments are noticeable in the fall of 2015, with the gravel 0.5°C (1°F) warmer than the sand loops and 1°C (1.8°F) warmer than the grass loops. As winter progressed the gravel loops stayed warmer than the other loops but there was not as much of a difference. The sand loops ended the winter season with the coldest temperatures.

According to the manufacturer's information on this heat pump model, a 0.6C° (1F°) change in the incoming temperature for the heat pump creates a 0.044 change in the COP of the heat pump (this excludes the effects of phase change). The 1C° (1.8F°) increase in the temperatures coming back from the ground loop could improve the COP by 0.08.

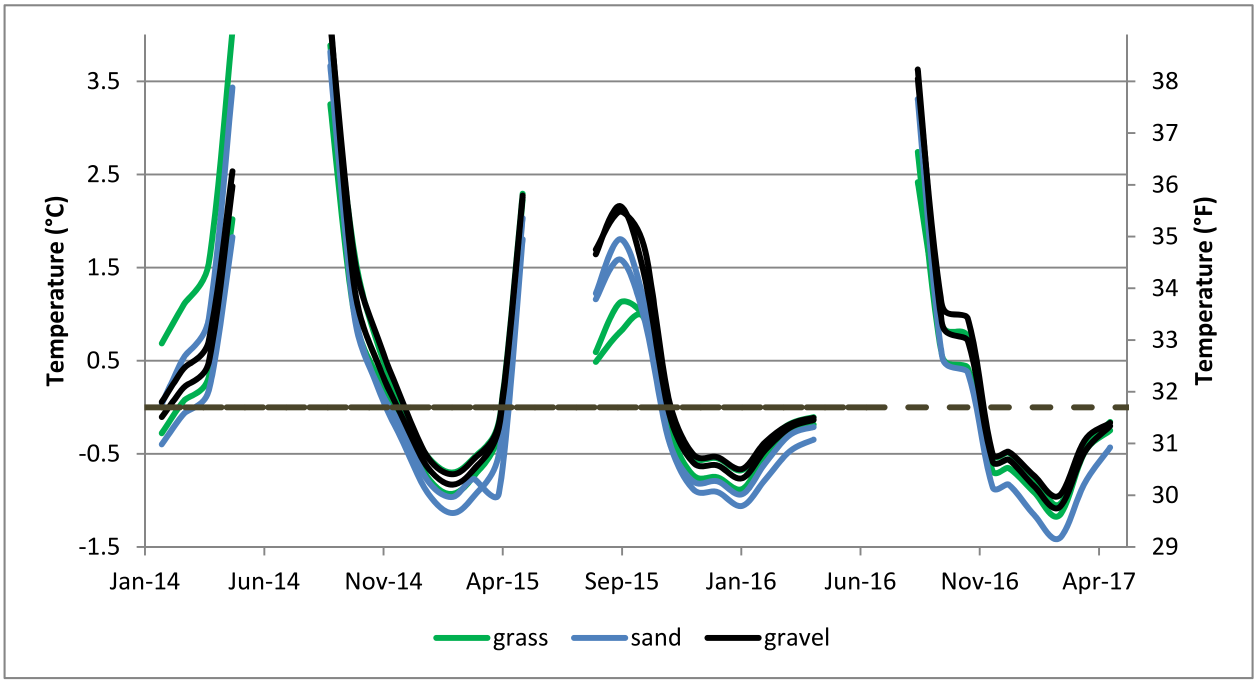

Figure 15. Temperatures of the fluid returning from the GHE. The temperatures in the beginning of 2014 do not have the effects of the summer on the surface treatments as the system was not complete until September 2013. Holes in the data are due to no fluid returning to the building because the system is off in the summer.

Heat delivered

The heat delivered to the building was tracked along with the electrical use of the heat pump. Heat delivered is presented in Table 7. Knowing the heat delivered and the electrical input allows for the calculation of the energy removed from the GHE shown in Table 8 (the GHE flow and temperature meter was unable to accurately record the energy removal from the ground directly). The higher electrical use but lower amount of heat delivered to the building during the third winter is an indication of the loss in efficiency. Year 1 does not include a full year of data so it is not easily comparable. In addition, the masonry stove was fired on a regular basis during year one, offsetting the heat load.

Table 7. Heat Delivered

	Year 1 (winter 2013-14)		Year 2 (winter 2014-15)		Year 3 (winter 2015-16)		Year 4 (winter 2016-17)	
	Electric Use (kWh)	Energy Delivered (kWh)	Electric Use (kWh)	Energy Delivered (kWh)	Electric Use (kWh)	Energy Delivered (kWh)	Electric Use (kWh)	Energy Delivered (kWh)
Aug.	-	-	-	-	13	46	-	-
Sept.	-	-	129	537	154	543	146	342
Oct.	-	-	229	892	433	1,451	803	2051
Nov.	97	379	885	3,216	1,332	4,123	1,370	4479
Dec.	1,115	3,870	971	3,479	1,871	5,517	2,133	6593
Jan.	962	3,405	1,636	5,210	1,104	3,250	2,096	5589
Feb.	908	3,167	1,272	3,966	1,129	3,368	1,471	3932
Mar.	306	1,145	740	2,347	593	1,677	1,442	3816
April	297	1,109	132.	419	272	758	286	699
May	24	96	14	32	39	144	83	228
June	-	-	9	0	-	-	-	-
July	-	-	5	0	-	-	-	-
Total	3,712	13,171	6,026	20,107	6,946	20,877	9,832	27,729

Table 8. Energy Extracted from the Ground

	Year 1 (winter 2013-14)	Year 2 (winter 2014-15)	Year 3 (winter 2015-16)	Year 4 (winter 2016-17)
	Energy from Ground (kWh)	Energy from Ground (kWh)	Energy from Ground (kWh)	Energy from Ground (kWh)
Aug.	-	-	33	-
Sept.	-	408	389	196
Oct.	-	663	1,018	1,248
Nov.	282	2,331	2,791	3,109
Dec.	2,755	2,508	3,646	4,460
Jan.	2,443	3,574	2,146	3,493
Feb.	2,259	2,694	2,239	2,461
Mar.	839	1,607	1,084	2,374
April	812	287	486	413
May	72	18	105	145
June	-	-	-	-
July	-	-	-	-
Total	9,603	16,418	14,271	18,053

COP

The efficiency of the heat pump varied over the course of each heating season. It tended to be higher in the fall when the GHE was the warmest and decrease throughout the winter. However, as the heating demand of the building lessened in the spring, the COP improved as the heat pump delivered lower temperature heat to the building. Monthly COPs are presented in Table 9 while Figure 16 shows the trend for the COP. COP is calculated by taking the sum of the heat delivered to the building and dividing it by the sum of the electricity used by the heat pump over that time period.

Table 9. Heat Pump COP

	Year 1 (winter 2013-14)	Year 2 (winter 2014-15)	Year 3 (winter 2015-16)	Year 4 (Winter 2016-2017)
September		4.15	3.52	2.34
October		3.9	3.34	2.55
November	3.9	3.63	3.09	3.27
December	3.47	3.58	2.95	3.09
January	3.54	3.18	2.94	2.67
February	3.48	3.12	2.98	2.67
March	3.73	3.17	2.82	2.65
April	3.73	3.17	2.78	2.44
Annual	3.69	3.34	3.01	2.82

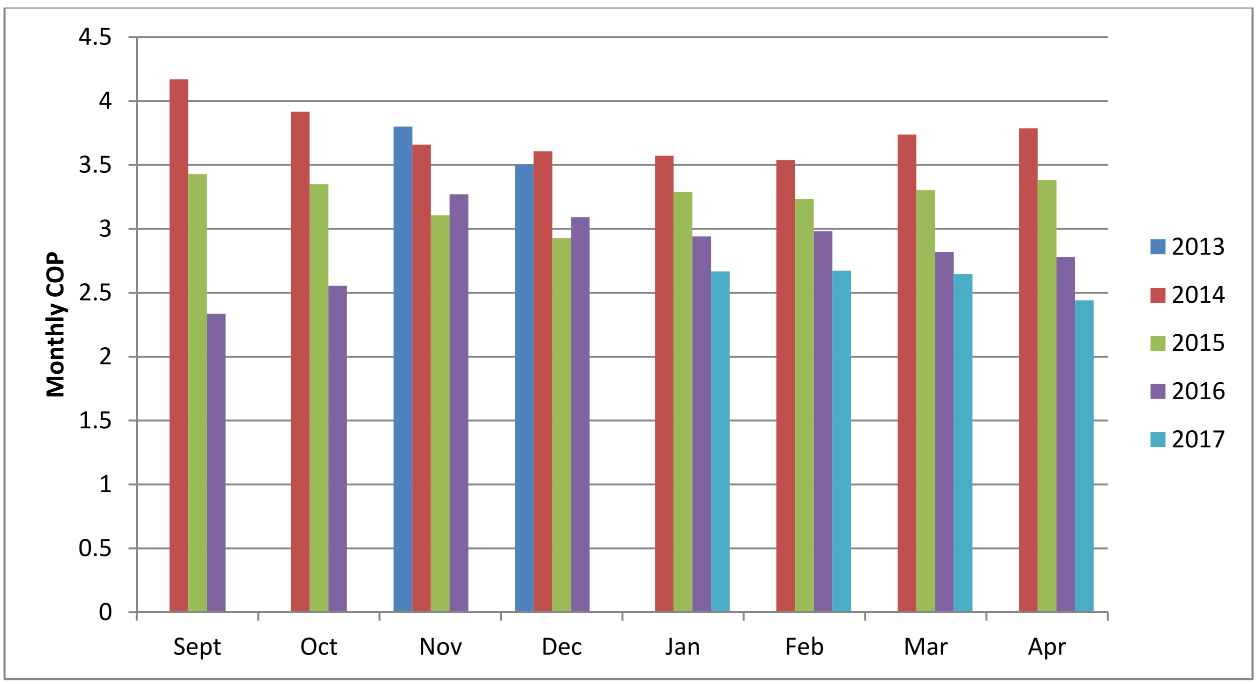

Figure 16. Heat Pump COP over time. The efficiency of the heat pump system is degrading as the ground temperature decreases.

The COP for the heat pump is trending lower over time, with a 24% decline in the annual COP over 4 years. The average decline has not varied much with a 9.4% decline in the first 2 years, at 9.8% between the second and third winter, and dropping only 6.3% between the third and fourth winters. The severity of the winter can affect the efficiency of the heat pump, with lower outside temperatures calling for higher delivery fluid. Heating degree days (HDD) is a measure of demand for heat in a building and is dependent on outside temperature. HDD can be used to judge the severity of a winter in comparison to other years. Table 10 provides a comparison of the HDD for the heat pump study. Year 4 was the most severe winter with almost 1,000 more HDD than Year 3. This more extreme heating demand could also factor into the lower COP in year 4.

Table 10. Heating Degree Days.

	Year 1 (winter 2013-14)	Year 2 (winter 2014-15)	Year 3 (winter 2015-16)	Year 4 (Winter 2016-2017)
°C HDD_{18}	6,921	6,769	6,487	7,535
°F HDD_{65}	12,459	12,184	11,676	13,563

Life Cycle Assessment

Life cycle assessment (LCA) provides a standardized method for evaluating the human health and environmental impacts resulting from a broad range of activities, such as construction, manufacturing, agriculture, and many others. The output of an LCA is separated into four categories to describe the type and magnitude of environmental impacts: resource use, human health, ecosystem, and climate change. LCA can be used to identify which materials or processes have the most significant impacts for a specifically defined case, thereby providing an opportunity to avoid materials and processes that create unacceptable environmental or human health burdens. For example, an LCA for a house design might reveal that an insulation upgrade choice creates a large climate change impact due to its manufacturing inputs that cannot be mitigated by fuel savings. The LCA could be used to help in the selection of a different insulation choice that satisfies the goals of the designer in terms of fuel savings and climate change impacts. The results of such LCAs apply just to the case studied and cannot be broadly generalized, and the goal for understanding and reducing the impacts of an activity are uniquely specific to those carrying out the LCA.

Methodology

The LCA was conducted for the CCHRC GSHP using SimaPro version 7.3 in February 2014. The goal of the LCA was to understand the relative human health and environmental impacts of the installation and operation of a GSHP system in the RTF relative to other common heating system options. The intended audiences for this LCA information are CCHRC researchers and technical peers in the fields of research, design, and construction in cold climate regions. Because a professional review was not part of the project scope, the LCA results are not intended to support comparative assertions in the public realm.

All heating scenarios were analyzed for the initial impacts of constructing the heating equipment plus the impact of providing one year of heat for the RTF office area (23,475 kWh, 8.01 x10^7 BTU). A COP of 3.1 was used to characterize the efficiency of the CCHRC GSHP. The default libraries within SimaPro 7.3 were used to provide data inputs for the life cycle inventories. Custom library entries were created to characterize the electricity generation sources for Alaska statewide using data from Deru and Torcellini (2007) and Interior Alaska using data from Golden Valley Electric Association (2012). The impact assessment methods used for this LCA were Impact 2002+ and ReCiPe endpoint (H). An explanation of LCA terms is available in Appendix A.

For this LCA, CCHRC analyzed several heating systems to help understand the potential human health and environmental impacts from the installation and operation of a GSHP system at CCHRC relative to conventional options. The heating systems analyzed included:

- Oil-fired boiler, which represents a typical heating system in Interior Alaska;
- Condensing oil-fired boiler, which represents the highest efficiency heating oil option;
- Condensing, modulating natural gas-fired boiler, which represents the maximum efficiency possible using combustion fuels; and
- GSHP with a horizontal ground heat exchanger, which represent the novel heating system to be assessed in comparison to the conventional combustion fuel systems.

The LCA impact assessments illustrated below are separated into four categories: impacts to human health, ecosystem quality, natural resources, and climate change. Two impact assessment methods were used, one of which combines climate change into the human health category, leaving only three impact categories. Examples of the environmental and health burdens tallied in the impact assessments include:

- Particulate matter emissions from a combustion heating appliance that result in an associated health burden to people who breathe the air,
- Mercury emissions from a coal-fired electric power plant that impact to terrestrial and aquatic ecosystems that receive the mercury,
- Depletion of non-renewable energy sources to provide heat and electricity to the heating appliances (e.g. oil for a boiler, coal for electricity production to power the GSHP).

All the impacts within these categories are converted into common units and tallied such that the LCA scenarios have relative scores for comparison. The higher the score, the larger the impact. The impact assessment results only have meaning for comparison within the impact assessment options, and cannot be used meaningfully outside of the specific LCA.

LCA Results

Two impact assessment methods were used to estimate and compare the potential human health and environmental impacts attributable to the heating scenarios. The results from the first impact assessment method are illustrated in Figure 17, which illustrates that the GSHP heating scenario has a substantially larger burden to human health than the combustion heating appliance scenarios. This is largely due to the emissions of sulfur dioxide, oxides of nitrogen, and aromatic hydrocarbons to the air from the electric power production using mostly coal fired power plants. The impacts to ecosystem quality are relatively minor across all the heating scenarios, although it is greatest for the GSHP. The impacts to climate change and natural resources are all relatively large for all the heating scenarios and do not vary significantly, although the GSHP has slightly less impact to natural resources.

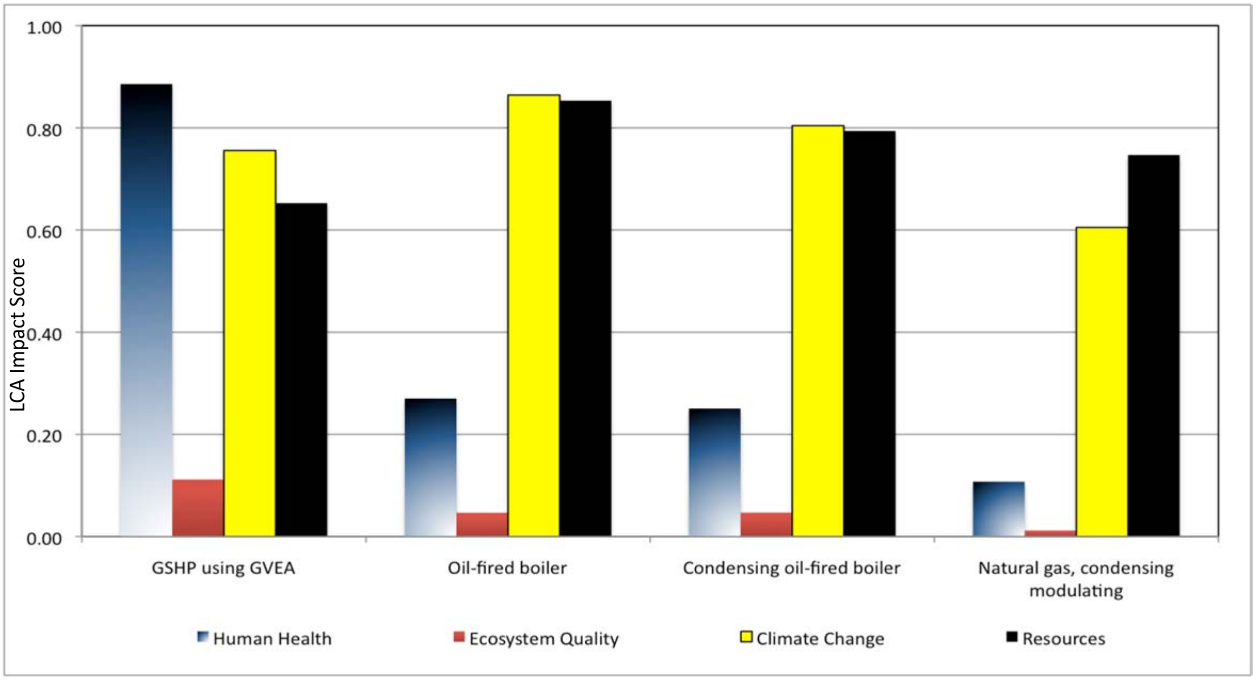

Figure 17. Impact assessment #1 for varying heat sources. Normalized results per damage category for the heating scenarios using the IMPACT 2002+ impact assessment method.

Using a second impact assessment method provides a similar picture, but with some notable differences. As shown in Figure 18 the GSHP heating scenario still has the largest human health impact, although the magnitude of the difference is not as significant as shown in Figure 17. This can be partially explained by the fact that the climate change impacts are included in the human health category in Figure 18 which serves to lessen the differences between the heating scenarios. Impacts to ecosystem quality remain relatively minor, and the impacts to natural resources are similar across the scenarios with the GSHP again showing the least impact.

Figure 19 shows an impact assessment of the GSHP heating scenario with several hypothetical electricity sources. The U.S. nationwide electricity sources are approximately 71% fossil fuels, 20% nuclear power, 7% hydropower, and a minor amount of other renewable energy sources (Deru and Torcellini, 2007). The largest difference in Alaska's statewide electricity fuel sources are that it does not include nuclear power and has more hydropower (23%), whereas the total fossil fuel contribution in Alaska at 77% is similar to the U.S. nationwide (Deru and Torcellini, 2007). The GVEA electricity fuel sources for Interior Alaska are overwhelmingly from fossil fuels (93%), with the remaining 7% coming from renewables (Golden Valley Electric Association, 2012). Despite these variations, they do not substantially change the human health and environmental impacts of the GSHP heating scenario.

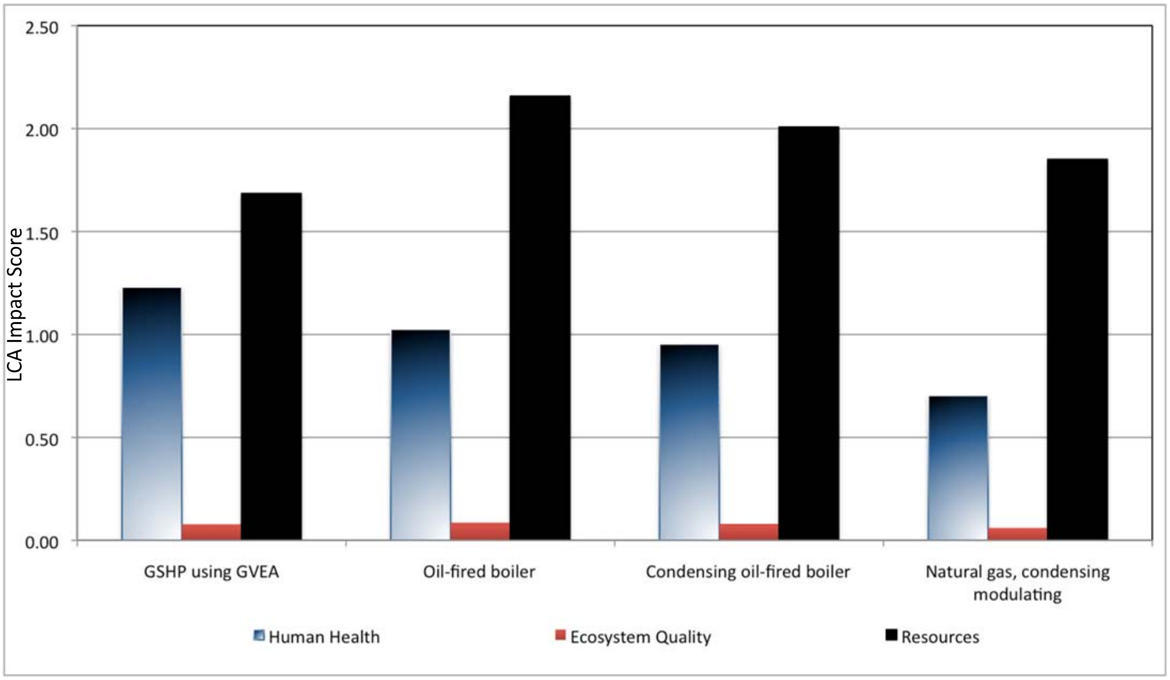

Figure 18. Impact assessment #2 for varying heat sources. Normalized results per damage category for the heating scenarios using the ReCiPe endpoint (H) impact assessment method.

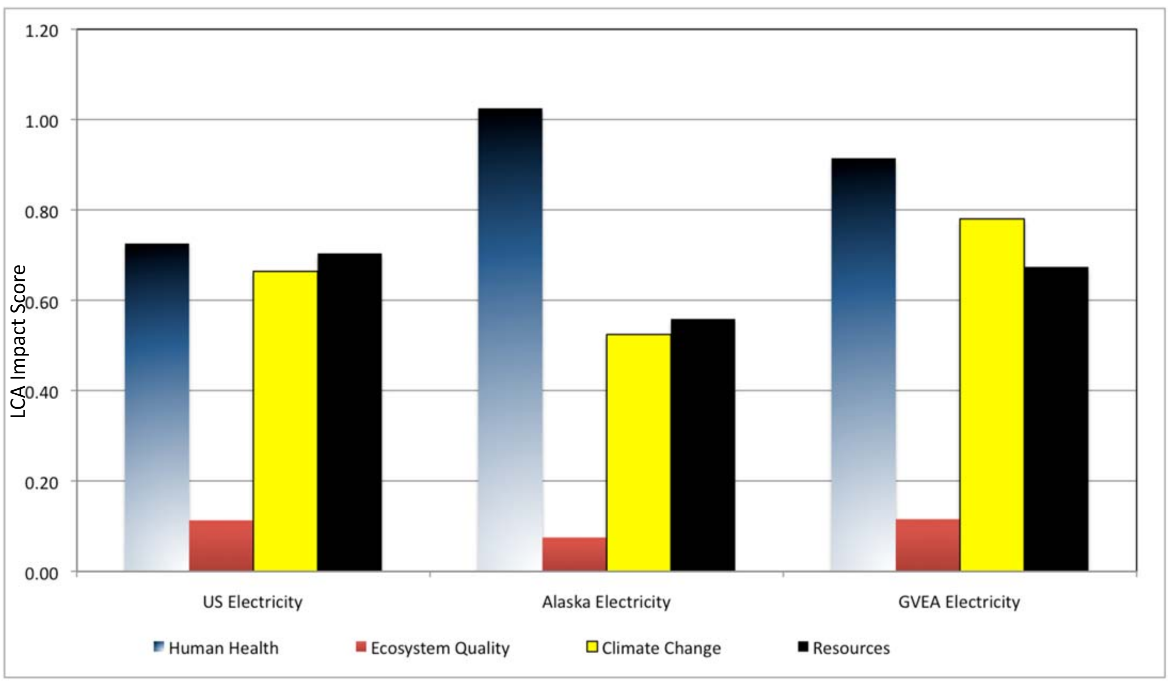

Figure 19. Impact assessment for GSHP heat by electricity source. The impacts of the heating equipment are small compared to fuel usage.

LCA Interpretation

Considering the findings from both impact assessment methods, it appears that there are not large differences in the overall potential impacts between the GSHP and combustion fuel heating scenarios for the

CCHRC RTF. The GSHP scenario has slightly-to-significantly greater human health impacts relative to the combustion heating appliance scenarios, and slightly lesser natural resource impacts. There are no appreciable differences in the categories of climate change or ecosystem quality impacts. Therefore the motivations to choose a GSHP for this scenario appear to be primarily economic in nature, or originating from other preferences such as removing the need for on-site fuel storage, less maintenance, or removing combustion from the building envelope.

GHE Numerical Model

A numerical finite-element model of the ground in and around the GHE was developed to analyze questions that cannot easily or cost effectively be answered with the demonstration project. The model was constructed to simulate the heat transfer and phase change behavior of the ground surrounding the GSHP. This analysis allowed CCHRC to look at the performance of the system in the long term. It also evaluated the optimum depth for a ground coil at varying energy draws from the GHE.

Methodology

The modeling was performed using Comsol Multiphysics version 5.2a. Thermal properties (e.g. heat capacity, porosity, water content) were characteristic of the silty soil in the surrounding area. Conductivity and thermal diffusivity were from the TC test conducted in 2012. Phase change behavior was numerically implemented using a pseudo-heat capacity method over a narrow temperature range immediately below 32°F (0°C).

Model simulations were run for 10 years starting from an initial soil temperature distribution recorded just after installation. The PARDISO solver was used to solve the time-dependent model, which is a direct solver optimized for shared memory systems and solving sparse matrix systems. Time stepping is adaptive, and a more restrictive maximum step of 3,600 seconds was added to assure phase change behavior was not “stepped over” by the pseudo-heat capacity implementation.

Both two- and three-dimensional models were built. The two-dimensional model was a symmetric vertical cut from the ground surface extending 30 meters down by two meters wide; with a line of symmetry directly below the center-line of the GHE. This geometry was determined using the three-dimensional model which indicated that the heat flux (and all associated physical phenomena) occurred primarily in the vertical direction except in the immediate vicinity of the GHE coils. Here, some off-vertical heat flux extended less than one meter horizontally. Therefore the two-meter system was able to adequately capture the thermal behavior at a substantial computational saving.

Model Inputs and Specifications

The model parameters and boundary conditions were specified to approximate the conditions at the test location as closely as possible without introducing substantial and unnecessary complexity. In some instances, analytical functions were used to approximate actual conditions. For example, the air temperature at the top boundary of the model domain was modeled as a sinusoidal function of a 1-year period with an amplitude, phase offset, plus a constant component to match the climatic average at the testing location. Also, the heat pump thermal demand (from the ground) was approximated as a truncated sinusoidal function with zero demand in the warmer months. Examples of both functions are shown in Figure 20 where day 0 corresponds to Jan 1. The same profiles were used for each year of the 10-year simulations.

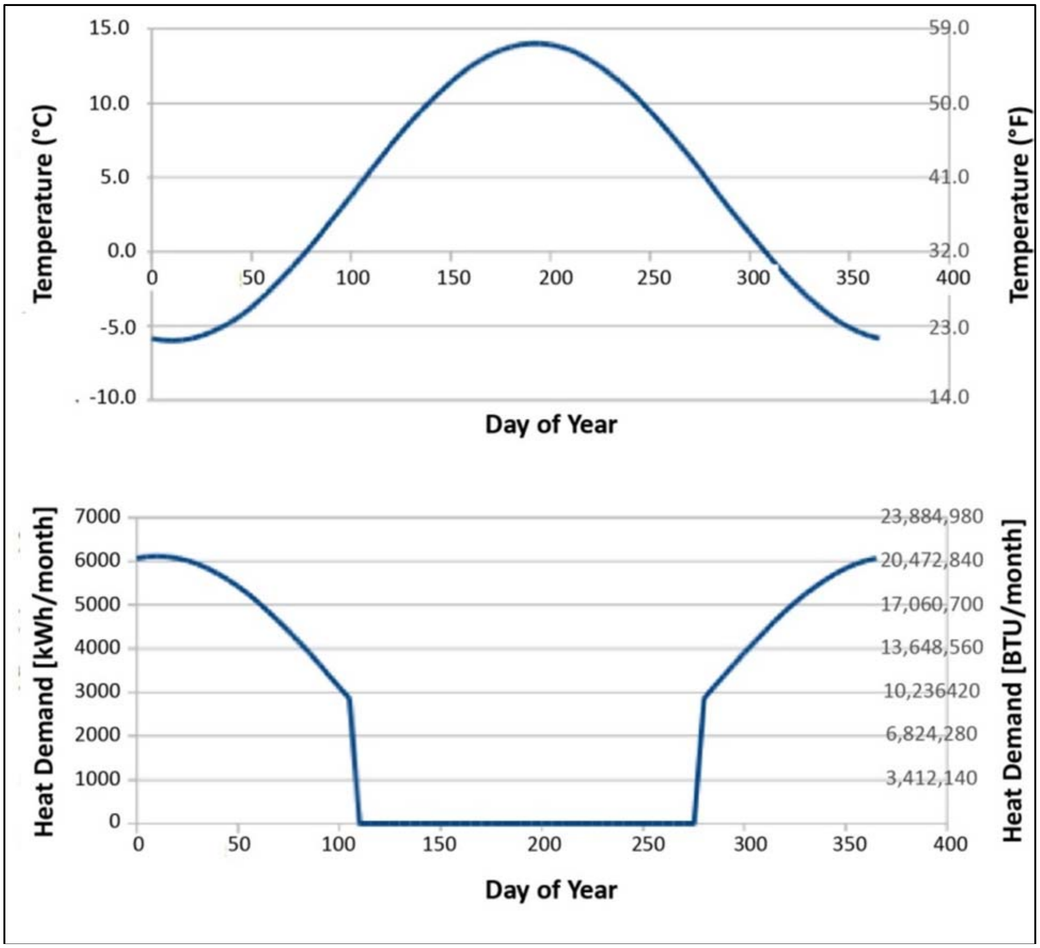

Figure 20. Example functions for the numerical model. The top graph shows the top soil temperature function and the bottom is the heat extraction function.

Numerical Model Results

Figure 21 shows the temperature at several depths (in meters) over the initial 3-year period of the simulations. The depths shown closely approximate the temperature sensor depth locations in the field study. There is a gradual decline in temperature near the heat pump energy extraction depth (2.7 to 3.2 m, 9 to 10.5 ft.), with more consistent periodic temperatures at the shallower and deeper depths. This repeatability from year to year is due to the fact that the same air temperature profile (climatic average) was used for each year of the simulation.

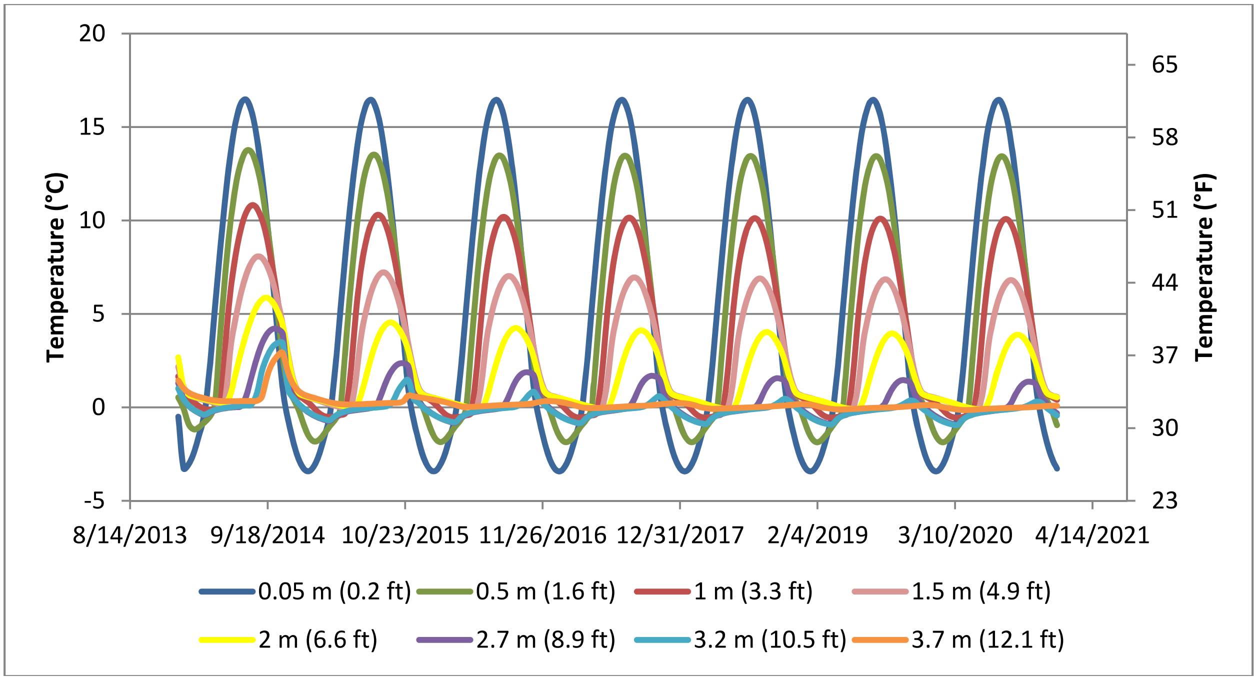

Figure 21. Modeled temperature over time. There is a gradual loss in temp around the GHE coils between 2.7 to 3.2 m (9 to 10.5 ft.).

The simulated ground temperatures at depth agree fairly well with the actual temperatures considering the approximations of the heat demand and surface boundary conditions (see Figure 22). The depth slightly above the GHE coils at 2.7 meters shows a slight below-freezing temperature at its coldest; around -1°C (30°F), while the actual data recorded are around 0°C (32°F) indicating the soil is at the freezing point. The model simulation uses a pseudo-heat capacity method to capture the latent heat terms (i.e. a large heat capacity centered around the freezing point with an integral value equal to the latent heat of fusion). This finite temperature range causes the model to indicate slightly below freezing temperatures during phase change, and any temperature between around 0 to -1°C (32°F to 30°F) indicates phase change. It is possible to adjust soil properties (e.g. thermal conductivity and heat capacity) or customize the heat demand or air temperature profiles to tune the model for closer agreement, however the overarching goal of predicting longer-term behavior would be largely unaffected by this fine-tuning and was not performed.

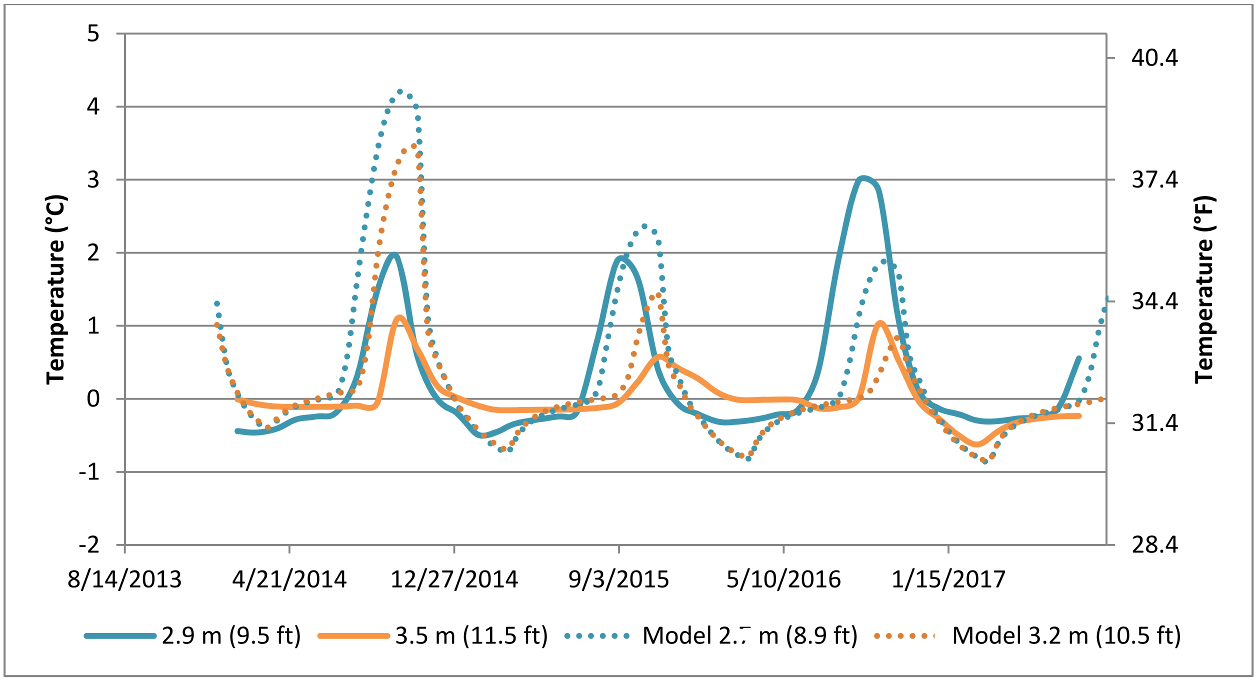

Figure 22. Modeled ground temperature compared to actual ground temperature. Modeled temperatures below freezing are indications of phase change and not necessarily precise temperatures. All measurements are depth below the surface.

During model simulations over 10 years, stabilization was generally observed after 5 years as the longer-term modeled temperatures shown in Figure 23 indicate.

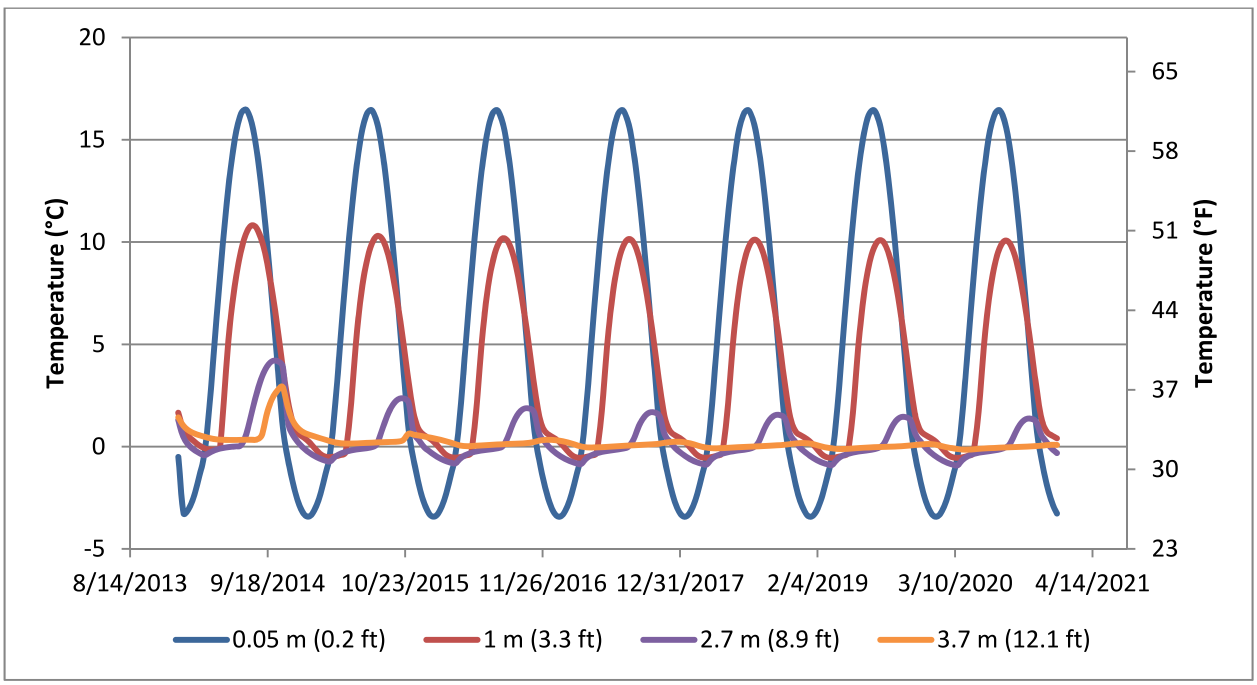

Figure 23. Modeled ground temperature over time. The consistent temperatures near the surface are the result of consistent air temperatures each year.

The heat pump COP varies as a function of the heat absorption reservoir temperature and the equipment manual provides this performance information for temperatures from -7°C to 21°C (20°F to 70°F). In order to simulate the varying performance as the ground temperature varied throughout the simulation, a least-squares linear fit to the performance data was obtained and is shown in Figure 24. This was then used to specify the expected COP. For example, Figure 25 shows the expected COP as f(x)=0.08x+3.5 based on the simulation temperatures, compared to the actual COP. The first year of actual recorded COP values were slightly higher than those predicted by the simulation, and may be due to several different factors such as the heat supply temperature. The performance data used for the model was based on an assumed constant supply temperature of 38°C (100°F), whereas the actual supply temperature ranged from 27°C to 43°C (80 to 109°F). COP values are not shown during the summer months when it is assumed not to be in operation. The second year COP values correlate well with the modeled values early in the year but are less later in the year.

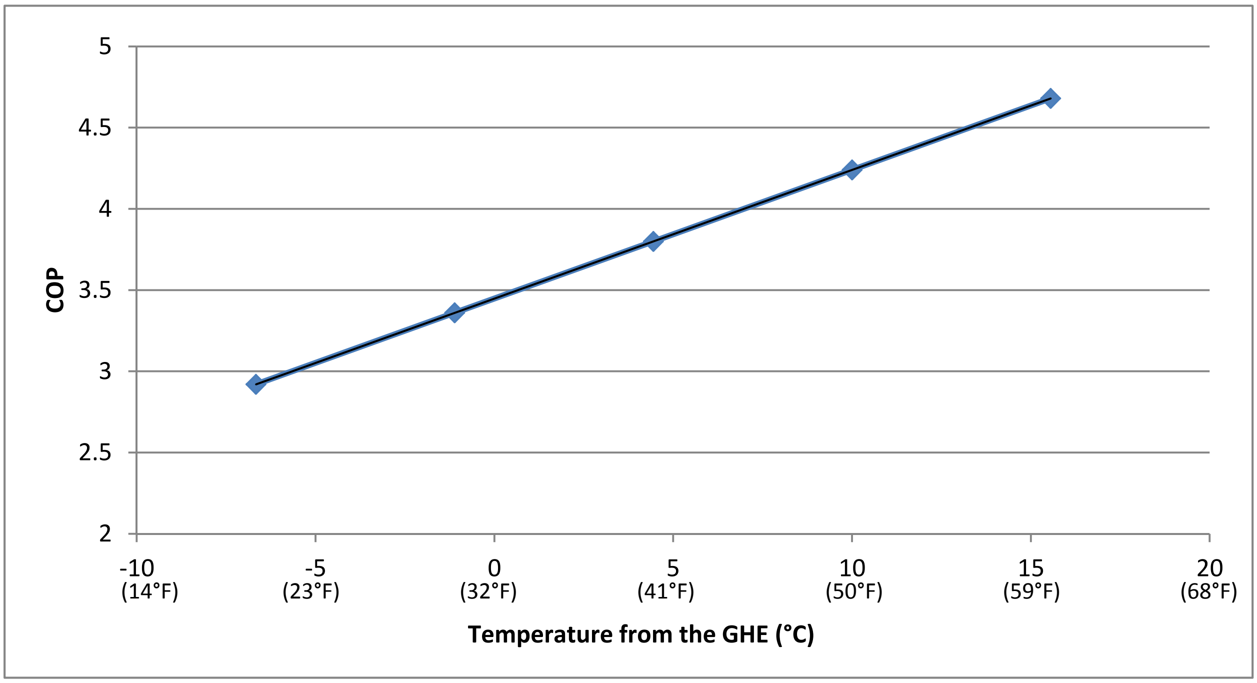

Figure 24. Least-square linear fit of performance data. This function is based on the manufacturer's manual.

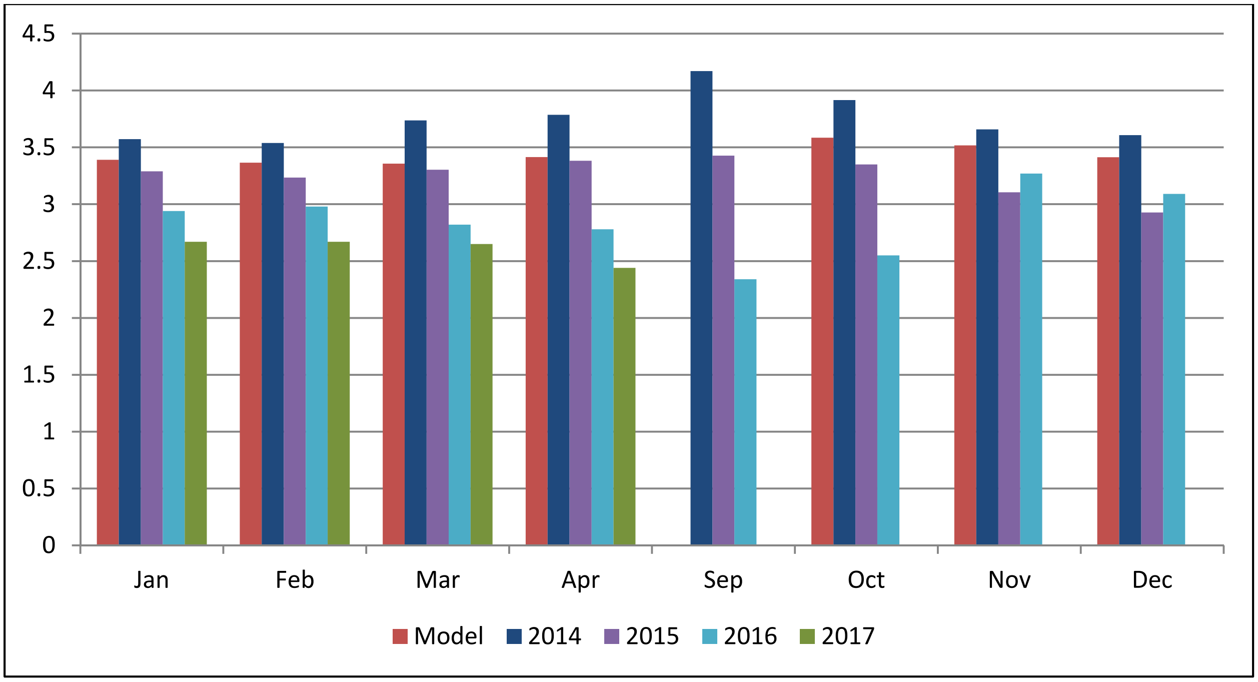

Figure 25. Model COP compared to actual COP. The modeled COP only modeled COP after one year of use; therefore COP values for the third and fourth winter are lower than modeled values which is expected.

The next task of the model was to determine the expected performance of the heat pump *if the GHE had been installed at a different depth*. To assess this, the heat removal term in the model (the depth of the GHE coils) was placed at different depths in the model domain. The gravel surface treatment was used for this model. Depths ranging from 1 to 4 m (3.3 to 13 ft.) every 0.5 m (1.6 ft.) were examined. This model did not take into account the existing permafrost that is more than 6 m (20 ft) below the current GHE. Figure 26 shows the yearly expected COP of the heat pump system if the GHE coils had been installed at these depths. The simulations indicate that deeper depths result in higher COP, with a diminishing return after 2.5 m (8 ft.), however the range of COP is very narrow indicating that depth after 2.5 m only weakly affects GSHP efficiency in this case. It may have a larger effect in other installations. The performance at all depths stabilizes after about 5 years.

It is interesting to note that the shallowest depth (1 m, 3.3 ft.) has slightly higher average COP than 1.5 m (4.9 ft.) after 10 years (although both depths have significantly low COP values). This is a change from year 1, and is likely due to some small amount of passive surface energy recharge during the warmer summer months. Although this effect is small, the implication seems to be that surface energy recharge is not significant in the natural state at depths below around 1 meter.

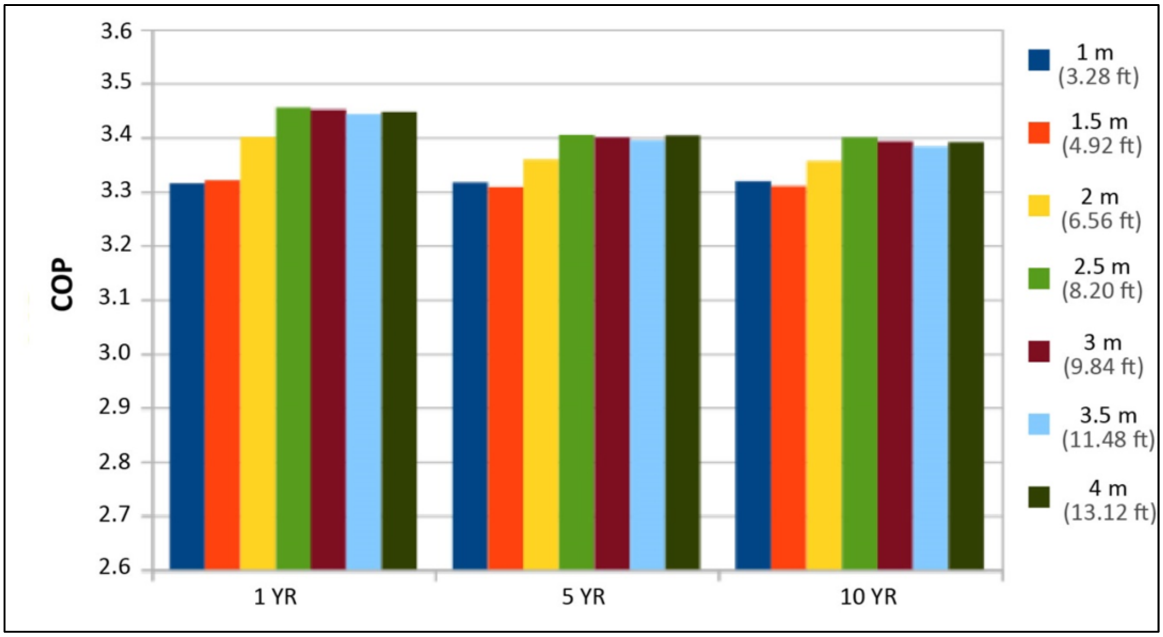

Figure 26. Modeled annual COP. This is based on the heat load for the CCHRC RTF.

The same range of simulations was performed assuming 50% greater heating demand. Figure 27 shows the yearly average expected COP at each depth of GHE installation with the higher heating load. A couple notable conclusions stand out in this analysis. First, the average COP only drops by 0.1-0.2, indicating that the ground does not become substantially colder although a larger heat demand is being placed on it presumably due to ground ice formation. Second, surface recharge at the most shallow depth becomes more prevalent compared to the next level of depth (i.e. 1.0 versus 1.5 m depth, 3.2 to 4.9 ft.). The same increase in COP with diminishing returns is observed with 2.5 m (8.2 ft.) depths being the most likely best option (assuming deeper burials involve greater installation costs).

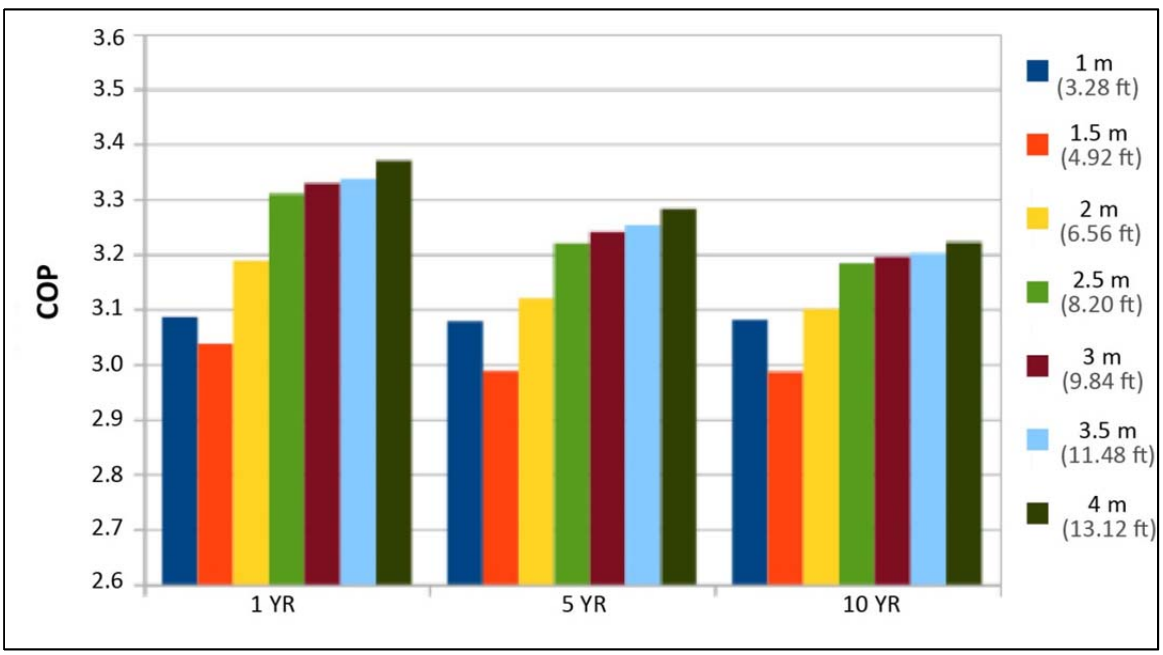

Figure 27. Modeled annual COP with a higher heat load. This is based on 50% more heat extraction than the CCHRC RTF.

Conclusions

The original ACEP/CCHRC report found that a GSHP with a COP of 2.5 or greater would be cost effective in Fairbanks (based on $2.87 per gallon heating oil and $0.17/kWh electricity) (Meyers et al., 2011). That being said, the cost effectiveness of a GSHP depends on the cost of oil versus electricity, which has not been favorable to GHSPs in 2016 or 2017 in Fairbanks. However, oil prices are not expected to stay low (U.S. Energy Information Administration, 2016). The LCA found the GSHP to be roughly equivalent to traditional oil and gas boilers in terms of human health and environmental impact; this makes the decision to install a GSHP mostly economic.

The COP for the heat pump is trending lower over time; with a 24% decline in the annual average over 4 years. The decline in COP slowed slightly in year four from 9% down to 6%, this potentially indicates stabilization in the near future. Modeling suggests that the decline will level out around year 5. Changes in the groundwater may also be affecting the ground temperature and heat pump COP; future study will focus more on the groundwater factor.

Additionally, the numerical model helped to determine the optimum depth for a GHE in this application. There are diminishing efficiency returns deeper than 2.5 m (8 ft.); once past 2.5 m the depth of the GHE is a weak indicator of efficiency for the RTF heat pump. A different system will produce different results; for example the depth of the GHE will have more effect on a system with 50% more heat extraction. The various ground coverings create minimal changes in soil temperature, leading to a potential COP improvement of 0.08.

Four years of operation is certainly not long enough to see all the changes the heat pump will create in the soil thermal regime. This heat pump demonstration will be monitored for at least another 6 years to verify the degradation in the soil temperatures and the COP.

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Appendix A: LCA Glossary

Life Cycle Assessment (LCA)

A method for evaluating the human health and environmental impacts resulting from specific activities. A LCA uses life cycle inventory data combined with an impact assessment method to create output for interpretation. The principles and framework for LCA are formally defined by ISO standard 14040.

Life Cycle Inventory (LCI)

Libraries of information that characterize the material flows, energy consumed, and emissions released in the creation of products and services.

Impact Assessment

A methodology for translating material and energy flows from the creation of products and services into potential environmental and human health impacts. Specific impact assessment methods commonly used in LCA include Impact 2002+ and ReCiPe. These impact assessment methods aggregate output information into four damage categories:

- *Climate change* (gaseous emissions with the ability to contribute to global warming);
- *Ecosystem quality* (toxic effects of emissions to aquatic and terrestrial environments, occupation of land, acidification of land and water, etc.);
- *Human health* (damage from toxicity of emissions, ozone layer depletion, ionizing radiation, etc.); and
- *Natural resources* (consumption of non-renewable energy resources, mineral extraction, etc.).

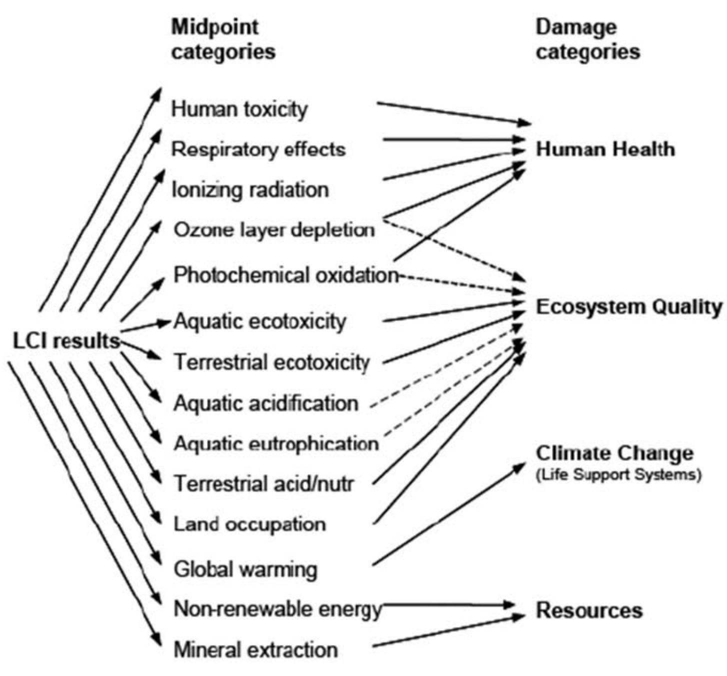

Figure A1. LCA flow of information. This graphic is an example of how an LCA evaluates the input data. This graphic is specific to Impact 2002+. PRe (2016) SimaPro Database Manual: Methods Library. Retrieved from: https://www.pre-sustainability.com/download/DatabaseManualMethods.pdf