COLD CLIMATE
HOUSING RESEARCH CENTER

Ground Source Heat Pump Demonstration in Fairbanks, Alaska – 2021 update 8th year of operation

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Disclaimer: The products were tested using the methodologies described in this report. CCHRC cautions that different results might be obtained using different test methodologies. CCHRC suggests caution in drawing inferences regarding the products beyond the circumstances described in this report.

ABSTRACT

Alaskans are continually searching for safe and affordable options to heat their homes and in years with high heating oil prices the installation of residential ground source heat pumps (GSHPs) increases. 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 8 heating seasons. The efficiency in those 8 heating seasons has been variable with ups and downs that have been difficult to explain. Overall, the system COP has averaged 3.0. This is the fourth progress report on the heat pump, the previous 3 can be found online at http://cchrc.org/ground-source-heat-pumps-cold-climates/

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 necessary 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 being 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 the 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 annually. 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 uses a demonstration heat pump to evaluate the long-term performance of a GSHP. The conditions of the soils around the ground heat exchanger are monitored to evaluate the thermal degradation.

This is the fourth interim report in this study, and it is based on the first 8 years of the heat pump operation. The report will discuss:

- the cost and maintenance of the GSHP,
- the efficiency of the GSHP over 8 years, and
- the soil temperature changes in the ground heat exchanger.

Demonstration Heat Pump Location

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). 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 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 wood stove is still used for supplemental space heating.

Fairbanks is in a zone of discontinuous and warm (near thawing) permafrost. Permafrost is defined as soil that has been colder than 0°C (32°F) for 2 or more years. Ice-rich permafrost – soil with more than 50% frozen water within it – provides a stable foundation until it thaws; then it often loses stability, collapses, and shifts. The ice-rich permafrost in the area underlying and around the RTF has been degrading since the land was first cleared 60 years ago (Shannon & Wilson, Inc., 2002). Data collected under the east end of the RTF since 2006 shows that the permafrost table has further degraded an additional 1.2 m (4 ft). In 2020, the top of the permafrost layer under the site was about 12 m (40 ft) below the surface.

Figure 1.CCHRC's Research and Testing Facility. The original building (the right (east) 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

Geothermal Resource Technologies, Inc. determined the soil thermal conductivity was 1.42 W/m·K (0.82 Btu/hr·ft·°F) by conducting a soil thermal conductivity test on the site. The thermal diffusivity was estimated to be 0.055 m^2/day (0.59 ft^2/day).

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 was chosen to be below the line of seasonal frost (about 1.2 m (4 ft)) and above the top of the permafrost (below 9.1 m (30 ft) in 2013). In addition, the 2.7 m (9 ft) depth is the typical installation depth for residential horizontal ground heat exchangers in the Fairbanks area. Models created during this project put the optimum depth for a horizontal coil in this location to between 2.4 and 2.7 m (8 to 9 ft) (Garber-Slaght et at., 2017).

The new heat pump is a residential 21 kW (6 ton) water-to-water unit, selected based on previous installer experience with the model in Fairbanks. It is connected to the existing in-floor hydronic heat delivery system. The heat pump heats a 303 L (80 gal) 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 provides a layout of the GHE and heat pump.

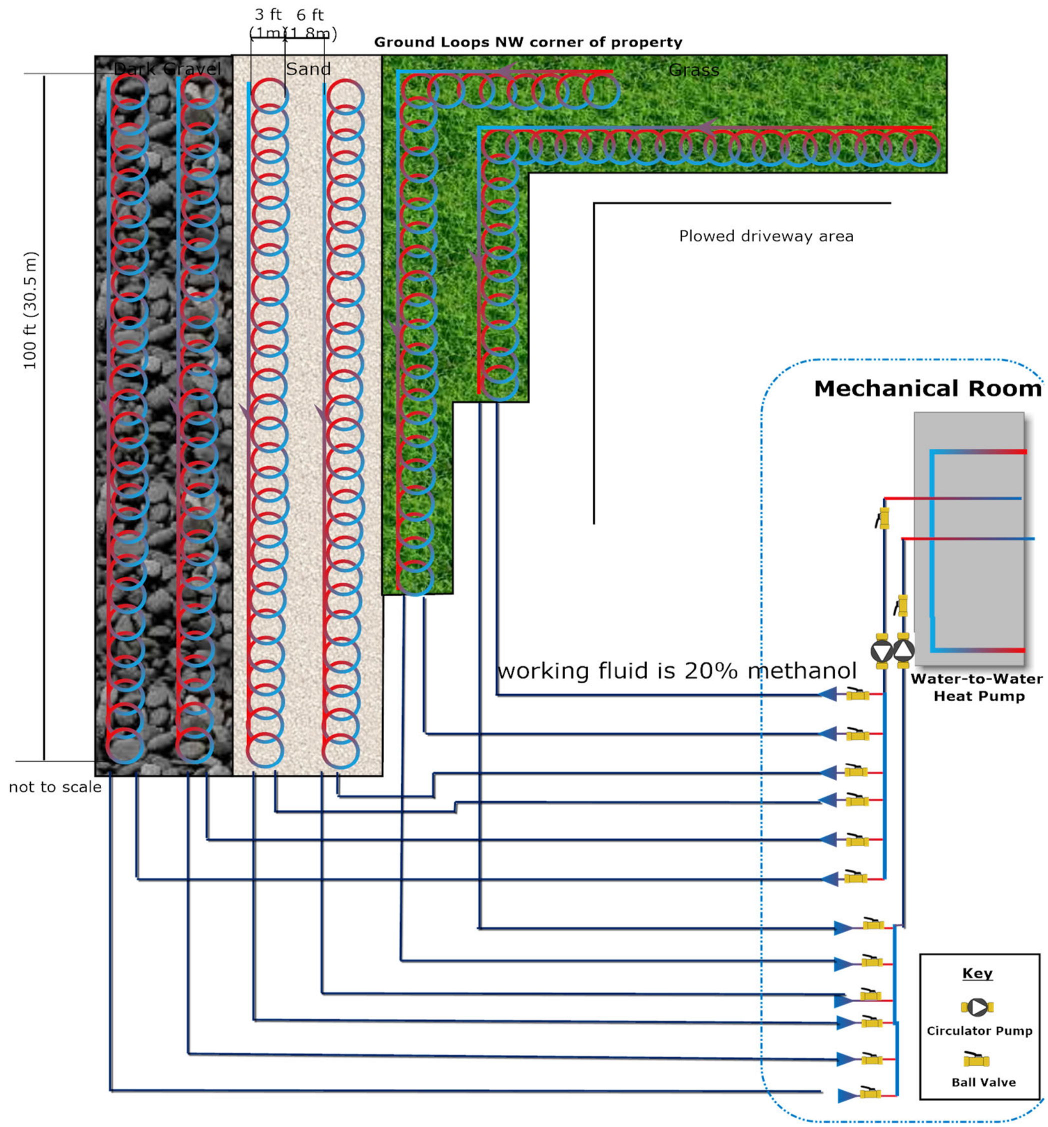

Figure 2. Schematic of the heat pump layout. The GHE is to the northwest of the RTF. (The schematic is not to scale; north is up)

Maintenance and History

The heat pump was installed between May 2013 and October 2013. The GHE was installed in May 2013 to take advantage of the stability of the frozen active layer at the soil surface. Six 2.7 m (9 ft) deep trenches were dug while the first 0.6 to 1.2 m (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 and the unit was started and commissioned. The data collection system came online in November 2013. Figure 3 provides a timeline of mechanical repairs.

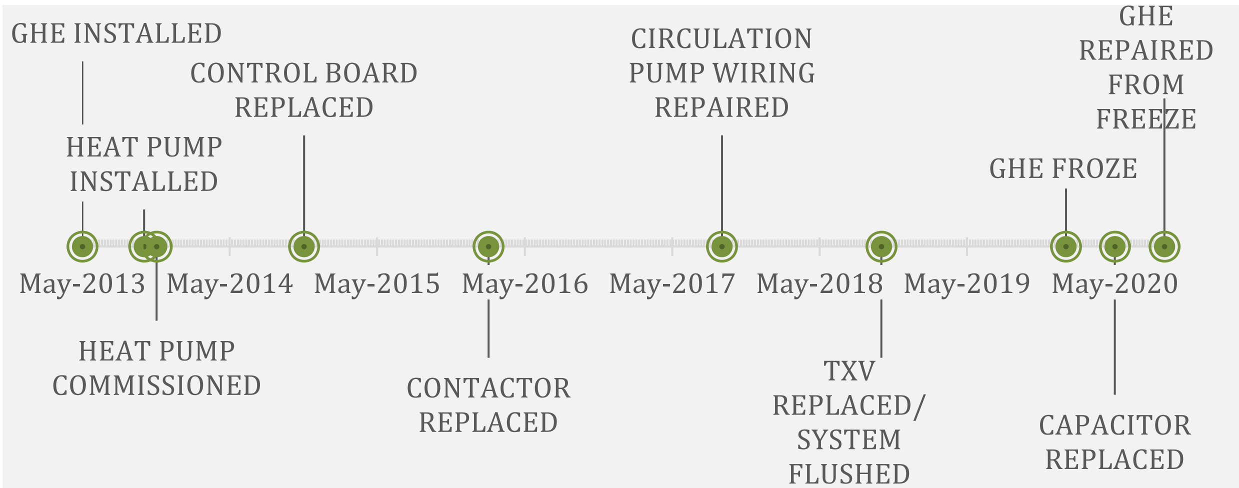

Figure 3. Timeline of heat pump repairs.

The heat pump itself required two warranty callbacks in the first 4 years, both related to faulty electrical parts. In November 2014, an electrical contact and the control board were replaced, and in February 2016 a contactor was replaced.

When the heat pump was turned on in September 2017 the system was not working properly and the exterior of the compressor was accumulating ice. One of the circulation pumps for the ground loop was not getting it's full power and the flow to the ground loop had dropped such that the heat pump was not getting enough thermal energy to operate correctly. The pump was fixed by correcting the electrical connection.

In Fall 2018, the heat pump thermal expansion valve (TXV) had to be replaced and the system had to be purged of contaminated refrigerant from the value deterioration and replaced with clean refrigerant. The low COPs in year 4 may be related to degradation in this valve, which released metal bits into the refrigerant that the heat pump was unable to filter out itself. The very low COP in September 2018 indicated a complete TXV replacement was needed.

In January 10, 2020 a building relay failed and stopped the delivery of heat from the heat pump to the in-floor distribution system (the back-up boiler stepped in during this time). With no call for heat from the heat pump it stopped running regularly. The problem was not discovered until January 17th, when the heat pump was restarted and there was no flow through the GHE. While there had been no flow in the GHE, the outside air temperautue had been consistently -34°C to -40°C (-30°F to -40°F) and the pipes between the GHE and the building had frozen where they entered the building. The pipes had become exposed due to subsidence of soil beside the building. The area around the exterior pipes was tented with a heater and the pipes thawed due to a combination of applied heat and warmer weather.

Once they were thawed the heat pump came back online, however, 7 days after thawing the pipes, a building control error turned off the heat pump and the pipes froze a second time.

The pipes thawed naturally with warming temperatures; however, the heat pump failed to come back online at this time. The pressure in the refrigeration loop was leak-checked, given the GSHP's 2018 repairs, as a troubleshooting measure. The capacitor was identified as an issue to be replaced. During system restart, the ground loop circulation pumps could not reach design operating pressure, as air had infiltrated the loop. Air purging and pump cycling were performed to get the system near design operating pressure. In Sepember 2020 the installation contractor was able to visit the site and put a sealing additive (Fernox leak sealer) into the ground loop fluid. Once the air leak was sealed, pressure was restored to the ground loop and the heat pump came back online In October 2020.

Data Collection

The automated data collection system is composed of several components listed in Table 1. More details on the data collection system can be found in Garber-Slaght et al., 2017.

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	-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°C)
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%

The Economics of the CCHRC Heat Pump

Installation Costs

The costs for the overall heat pump installation (minus the Thermal Conductivity test ($5,457) and the data collection system) are presented in Table 2. This installation was more expensive than a typical residential installation due in part to this being a research project and 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 2. CCHRC 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 heat pump system had minimal maintenance costs its first 5 years (it was under warranty the first 3 years). Year 6 had a big repair in replacing the thermostatic controlled expansion valve (TXV) valve and flushing the refrigerant system. Table 3 breaks down the annual maintenance costs by year.

Table 3. Annual Maintenance Costs

	Year 1*	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8
Annual Maintenance Costs		warranty	warranty		$125	$1,072		$275

*partial year

Over the course of the study thus far, the system has used 48,303 kWh of electricity. This amounts to $11,592 in heating costs at an eight-year constant $0.24 per kWh (the actual rate CCHRC paid). Figure 4 shows the electrical cost trends by year.

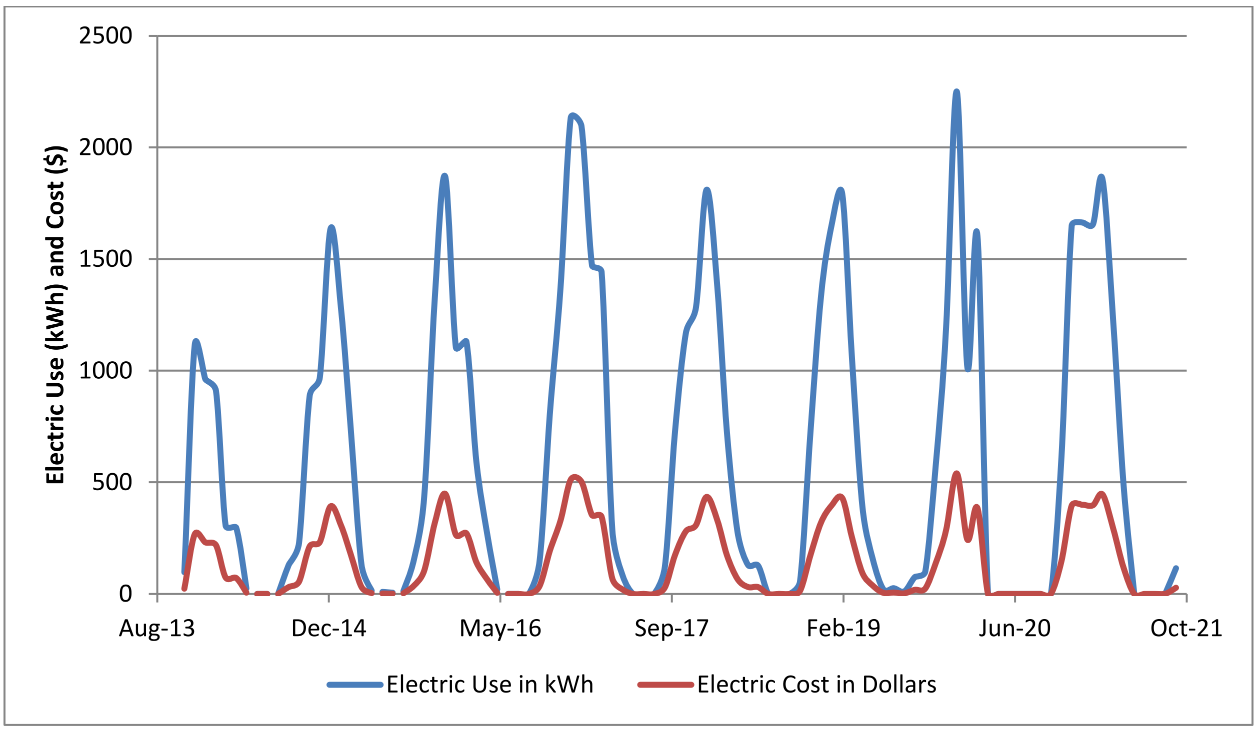

Figure 4. Electrical use of the heat pump system. Year 7 has no heat pump costs after January 2020 when the GHE froze.

Table 4 breaks out electrical 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 and 2019, CCHRC turned off the heat pump when the heating season was over in late May and kept it off into September. The summers of 2015 and 2019 provide an example of how much the heat pump costs in idle mode. Year 7 does not have complete data starting in January 2020 as the heat pump was not functioning all the time.

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)	Year 5 (winter 2017- 18)	Year 6 (winter 2018-19)	Year 7 (winter 2019-20)	Year 8 (winter 2020-21
August	-	-	$3.12	-	-	-	$18.28	-
September	-	$30.96	$36.96	$35.14	$28.81	$13.33	$24.25	-
October	-	$54.96	$104.16	$192.69	$174.98	$175.75	$139.74	$147.04
November	$23.28	$212.40	$319.68	$328.81	$279.82	$319.54	$286.62	$395.91
December	$267.60	$233.04	$449.04	$511.98	$308.35	$396.19	$540.06	$399.37
January	$230.88	$392.64	$264.96	$503.13	$434.54	$430.07	$243.66	$397.52
February	$217.92	$305.28	$270.96	$353.14	$330.42	$255.60	$384.69	$445.44
March	$73.44	$177.60	$142.32	$346.12	$174.30	$93.80	$0.26	$291.80
April	$71.28	$31.68	$65.28	$68.74	$67.11	$38.04	-	$117.81
May	$5.76	$3.36	$9.36	$19.94	$31.44	$4.92	-	-
June	-	$2.16	-	-	-	$6.17	-	-
July	-	$1.20	-	-	-	$2.68	-	-
Annual Total	$890.16	$1,445.28	$1,662.72	$2,359.70	$1,829.78	$1,736.09	$1,619.28	$2,194.90

*Years 1 and 7 are partial years

Savings of the Heat Pump Over Using Oil

The amount of operational 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. Heating oil prices have been variable since the start of this project; Table 5 shows the change in heating fuel costs over the first 8 years of heat pump operation. The cost of electricity has remained consistent at $0.24/kWh over the first 8 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 8 years of operation, using the real cost of fuel over that time. 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 is similar to the one the heat pump replaced; however, the high efficiency of this model is not typical of most boilers in the area.

When oil prices slipped below $2.45 per gallon in the third winter, the operational savings advantage of the heat pump ceased. In fact, using the oil condensing boiler would have saved $207 instead of using the heat pump in the third heating season. In 8 years, the heat pump has saved a combined total of $161 over using the oil-fired condensing boiler that is 96% efficient. Replacing an 80% efficient boiler would have increased the eight-year savings to $2,143. Had fuel prices remained near $4 per gallon the heat pump system would have saved an estimated $6,144 over the 96% efficient boiler and $8,745 over the 80% efficient boiler in 8 years.

The cost savings of the heat pump were greater when maintenance was considered. The heat pump offset about $350/year of boiler maintenance costs. Over 8 years the maintenance costs of the heat pump have totaled $1,472; while annual boiler maintenance would have been about $2,800. That is roughly $1,328 in maintenance savings in 8 years and $1,489 in overall actual cost savings.

Table 5. Average Annual 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)	Year 5 (winter 2017- 18)	Year 6 (winter 2018-19)	Year 7 (winter 2019-20)	Year 8 (winter 2020-21)
Annual price/gallon	$3.94	$3.26	$2.30	$2.37	$2.73	$2.82	$2.53	$2.56

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)	Year 5 (winter 2017-18)	Year 6 (winter 2018-19)	Year 7 (winter 2019-20)	Year 8 (winter 2020-21)
August	-	-	-	-	-	-	($1.33)	-
September	-	$27.78	$9.75	($10.93)	$1.63	($12.93)	($0.78)	-
October	-	$113.62	($3.56)	($44.97)	$0.63	($40.85)	($1.92)	($6.99)
November	$18.12	$146.29	($10.57)	($17.23)	($0.55)	$20.59	($17.89)	($42.56)
December	$161.28	$135.95	($34.56)	($38.21)	($10.03)	($12.34)	($112.45)	($35.52)
January	$158.10	$93.83	($47.31)	($79.05)	($2.68)	($64.01)	-	($26.53)
February	$147.28	$42.69	($60.87)	($55.53)	$4.27	$3.50	-	($28.21)
March	$57.70	$53.31	($35.22)	($59.62)	$9.25	$7.53	-	($0.50)
April	$58.42	$21.92	($21.29)	($17.95)	$0.55	$3.00	-	$2.06
May	$2.65	$3.83	($3.67)	($4.44)	($20.65)	($1.11)	-	-
June	-	-	-	-	-	($6.17)	-	-
July	-	-	-	-	-	($2.68)	-	-
Annual Total	$603.55	$639.22	($207.30)	($327.94)	($17.58)	($105.46)	($134.38)	(138.24)

*Year 1 and Year 7 are partial years

CCHRC GSHP Results

Observed GHE Temperatures

Temperatures recorded in and underneath the GHE show colder soils (Figure 5b) over the 8 years the heat pump has been in use when compared to the baseline data (Figure 5a). 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 4C° (5.4 to 7.2F°) higher.

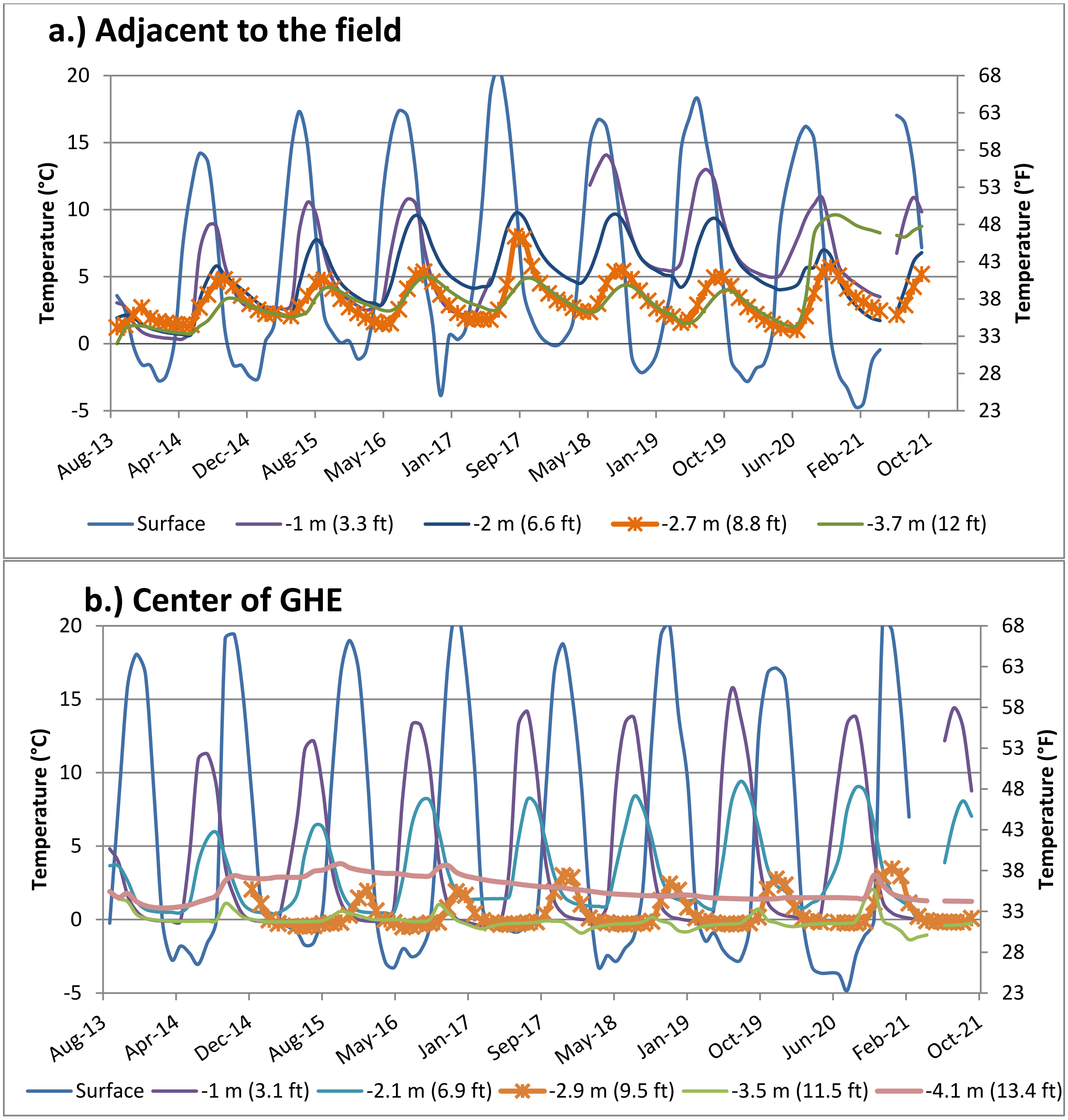

Figure 5. In-ground temperatures over time, a.) temperatures outside of the influence of the GHE, b.) temperatures in the center of the GHE. The orange starred line is nearest to the ground heat extraction coils. Temperatures are cooler in the GHE than in the field next to the GHE.

Figure 6 shows a different view of how the GHE is affecting ground temperature. The 2.7 m (9 ft) depth of GHE dotted line in the diagram is where the slinky coils were designed to be, however with a large excavation, backfilling, and leveling, it is likely that the coils are not exactly at 2.7 m (9 ft). Temperatures just below 2.7 m (9 ft) started dropping to freezing the first winter of heat extraction and stayed near freezing throughout the rest of the study. They have not remained below 0°C for longer than 2 consecutive years so this area is not considered permafrost.

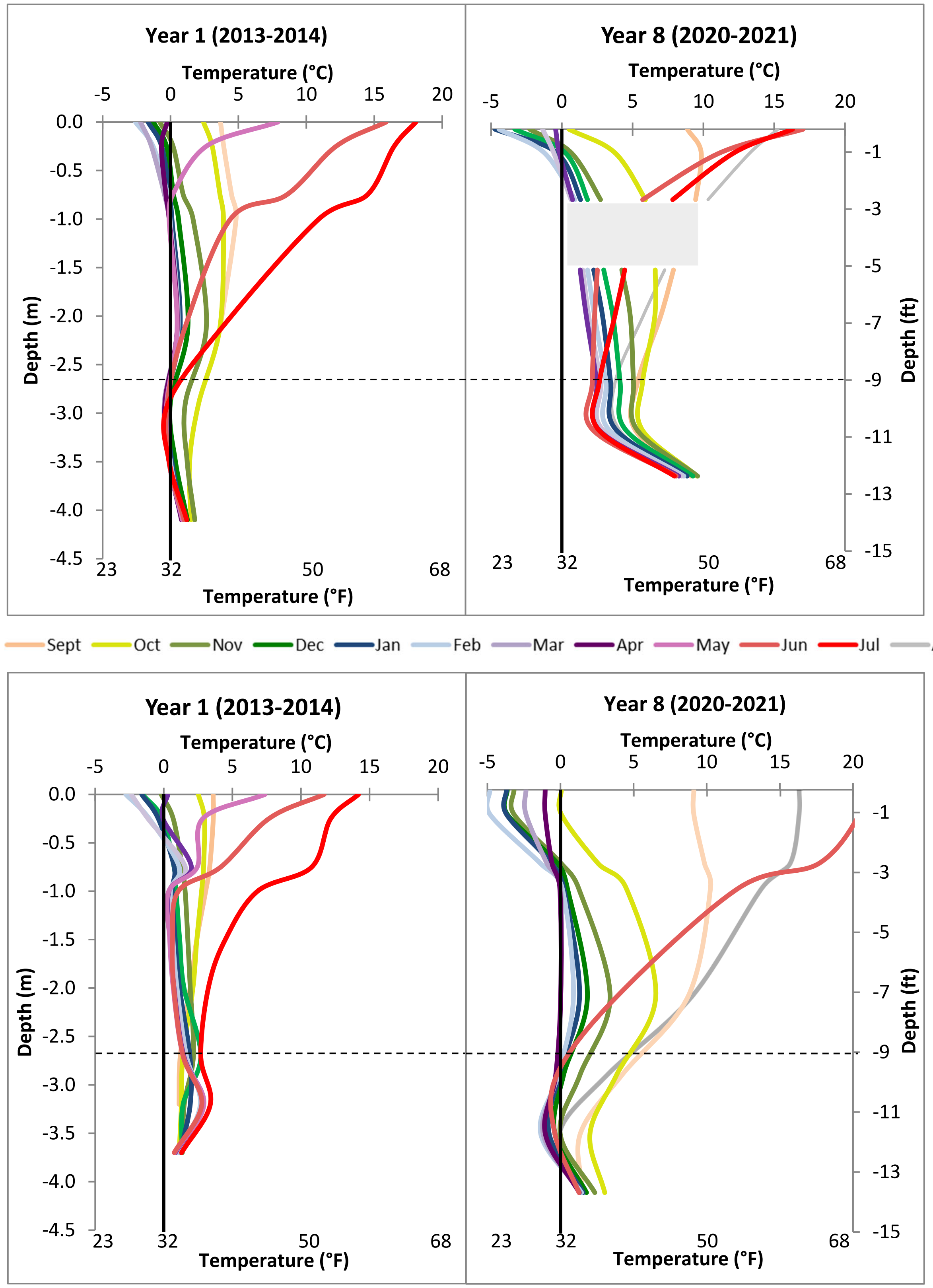

Figure 6. Trumpet curves of the ground temperature changes over 8 years. The top graphs are in the field adjacent to the GHE, and the bottom graphs are through the center of a central slinky coil in the GHE. Missing data is due to failed sensors.

Frozen Soil

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. Figure 7 shows the extent of frozen ground during two years of the study. To date, the ice around the slinky coils has not lasted the full year. There was no ice below the active layer (the top layer of soil that freezes and thaws seasonally) in any other metered location.

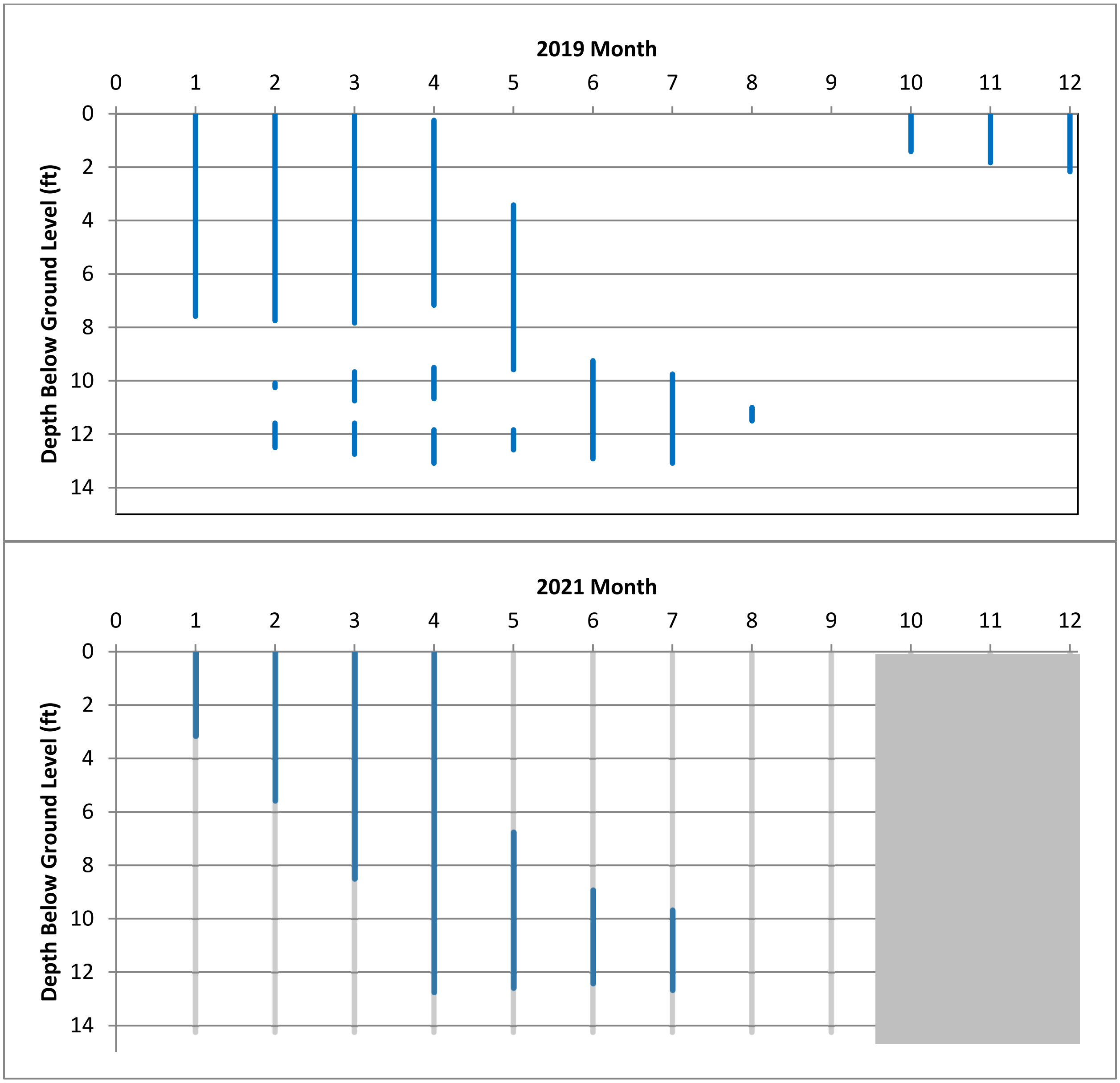

Figure 7. Ice in the center of the GHE under the sand treatment. This is only location that has recorded frozen soil below the active layer. The 2021 chart ends with the September data.

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 were unable to accurately record the energy removal from the ground directly).

Table 7. Heat Delivered to the RTF.

	Year 1* (winter 2013-14)	Year 2 (winter 2014-15)	Year 3 (winter 2015-16)	Year 4 (winter 2016-17)	Year 5 (winter 2017- 18)	Year 6 (winter 2018-19)	Year 7* (winter 2019-20)	Year 8 (winter 2020-21)
	Energy Delivered (kWh)	**Energy Delivered (kWh)**	**Energy Delivered (kWh)**	**Energy Delivered (kWh)**	**Energy Delivered (kWh)**	**Energy Delivered (kWh)**	**Energy Delivered (kWh)**	**Energy Delivered (kWh)**
August	-	-	46	-	-	-	229.3	-
September	-	537	543	342	458	5	317.6	-
October	-	892	1,451	2,051	2,642	1,612	1,885.6	2,241
November	379	3,216	4,123	4,479	3,935	4,267	3,598.4	5,424
December	3,870	3,479	5,517	6,593	4,219	5,329	5,829.3	4,509
January	3,405	5,210	3,250	5,589	4,219	5,485.2	2,511	5,388
February	3,167	3,966	3,368	3,932	4,419	3,706	4,003	5,857
March	1,145	2,347	1,677	3,816	2,415	1,371.5	-	4,000
April	1,109	419	758	699	8 78	555.5	-	1,640
May	96	32	144	228	145	51.6	-	-
June	-	0	-	-	-	-	-	-
July	-	0	-	-	-	-	-	-
Annual Total	13,171	20,098	20,877	27,729	24,853	22,383	18,374	29,059

*partial years

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)	Year 5 (winter 2017- 18)	Year 6 (winter 2018-19)	Year 7* (winter 2019-20)	Year 8 (winter 2020-21)
	Ground Energy (kWh)	**Ground Energy (kWh)**	**Ground Energy (kWh)**	**Ground Energy (kWh)**	**Ground Energy (kWh)**	**Ground Energy (kWh)**	**Ground Energy (kWh)**	**Ground Energy (kWh)**
August	-	-	33	-	-	-	153	-
September	-	408	389	196	338	-	217	-
October	-	663	1,018	1,248	1,913	880	1,303	1,628
November	282	2,331	2,791	3,109	2,769	2,936	2,404	3,774
December	2,755	2,508	3,646	4,460	2,934	3,678	3,579	2,845
January	2,443	3,574	2,146	3,493	2,934	3,693	1,496	3,732
February	2,259	2,694	2,239	2,461	3,042	2,641	2,400	4,001
March	839	1,607	1,084	2,374	1,689	981	4	2,784
April	812	287	486	413	598	397	-	1,149
May	72	18	105	145	14	31	-	-
June	-	-	-	-	-	-	-	-
July	-	-	-	-	-	-	-	-
Annual Total	9,459	14,090	13,937	17,899	16,231	15,237	11,556	19,914

*partial years

Coefficient of Performance (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 decreased throughout the winter. However, as the heating demand of the building lessened in the spring, the COP improved because the heat pump delivered lower temperature heat to the building. Monthly COPs are presented in Table 9 while Figure 8 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. All COP calculations include the energy of the circulation pumps so they should be considered system COPs.

Table 9. Heat Pump COP.

	Year 1 (winter 2013-14)	Year 2 (winter 2014-15)	Year 3 (winter 2015-16)	Year 4 (winter 2016-17)	Year 5 (winter 2017- 18)	Year 6 (winter 2018-19)	Year 7 (winter 2019-20)	Year 8 (winter 2020-21)
September		4.15	3.52	2.34	3.81		3.14	
October		3.9	3.34	2.55	3.62	2.20	3.24	3.66
November	3.9	3.63	3.09	3.27	3.37	3.20	3.01	3.29
December	3.47	3.58	2.95	3.09	3.28	3.23	2.59	3.24
January	3.54	3.18	2.94	2.67	3.28	3.06	2.47	3.25
February	3.48	3.12	2.98	2.67	3.21	3.48	2.50	3.16
March	3.73	3.17	2.82	2.65	3.33	3.51		3.29
April	3.73	3.17	2.78	2.44	3.14	3.50		3.34
Seasonal Average	3.64	3.49	3.05	2.71	3.38	3.17	2.83	3.32

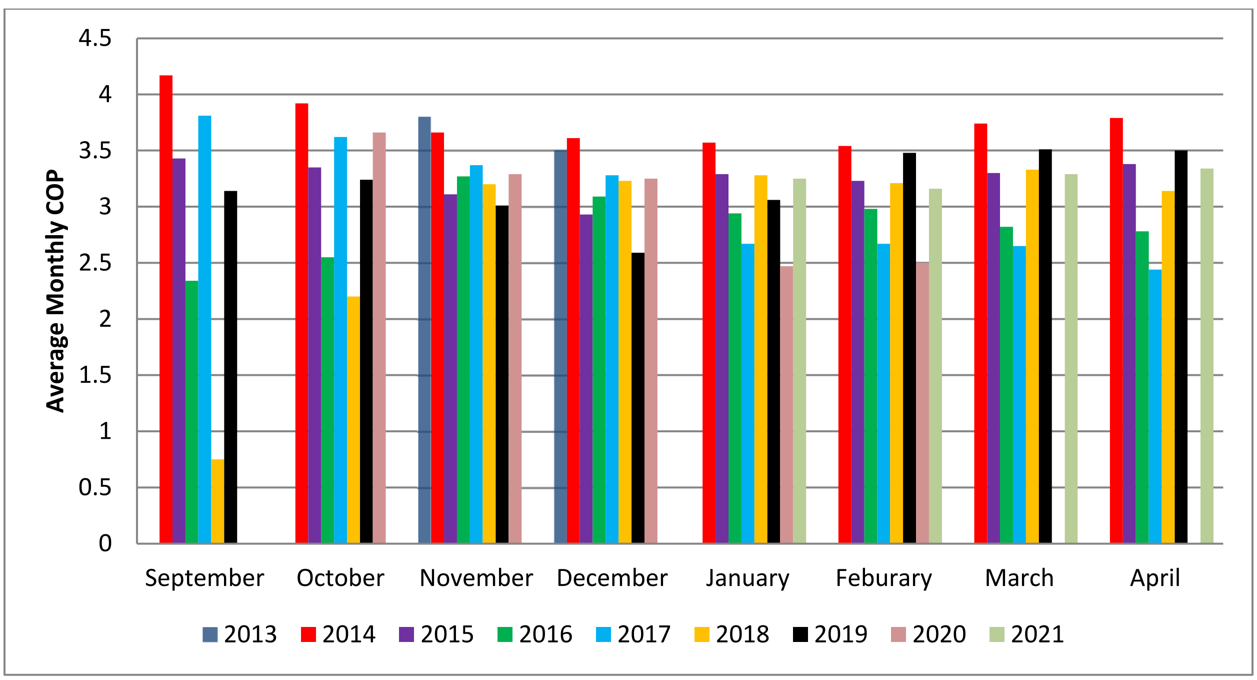

Figure 8. Heat Pump COP over time. The extremely low COP in September 2018 is most likely due to the failing TXV, which was replaced in October 2018.

Discussion

It was expected that the COP of this system would degrade over time until it reached an equilibrium state where the COP leveled out. Models predicted the equilibrium state to be reached after the fifth heating season (Garber-Slaght et al., 2017). However, the COP has not degraded in a linear fashion. Multiple variables are likely the cause for the variation in the COP. Mechanical failures in the heat pump and circulation pumps are most likely the reasons for the lowest COPs.

The severity of the winter can affect the efficiency of the heat pump, with lower outside temperatures calling for higher temperature 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 year of the study, but the differences between the 8 years are not large; HDD probably does not account for the variations in COP.

Table 10. Heating Degree Days.

	Year 1 (winter 2013-14)	Year 2 (winter 2014-15)	Year 3 (winter 2015-16)	Year 4 (winter 2016-17)	Year 5 (winter 2017- 18)	Year 6 (winter 2018-19)	Year 7 (winter 2019-20)	Year 8 (winter 2020-21)
°C HDD_{18}	6,921	6,769	6,487	7,535	6,919	6,473	7,507	7,484
°F HDD_{65}	12,459	12,184	11,676	13,563	12,454	11,652	13,512	13,472

The wood burning masonry stove provides heat to the same area as the GSHP. Its use is variable from winter to winter (based on building staff). Table 11 shows a summary of the wood energy added to the building for each winter. As You et al. (2016) point out; supplemental heating systems can help the longevity of the GHE by lowering the amount of heat extracted from the GHE in a year. Years 1, 3, and 5 all had high wood energy usage, this may have contributed to higher end of year COPs in years 1 and 5, but year 3 did not follow this pattern. Wood burning was not metered after year 7.

Table 11. Annual wood energy added by masonry stove use.

	Year 1 (winter 2013-14)	Year 2 (winter 2014-15)	Year 3 (winter 2015-16)	Year 4 (winter 2016-17)	Year 5 (winter 2017- 18)	Year 6 (winter 2018-19)	Year 7 (winter 2019-20)
Annual wood (kWh)	7,139	10.9	5,578	2,873	5,023	1,876	1,597
Annual wood (MMBTU)	24.3	0.04	19.0	9.8	17.1	6.4	5.4

Table 12 provides a summary of the energy delivered by the heat pump and the annual average system COP. Overall, the COP dropped for the first 4 years but seems to be level around 3.0. Low COPs in years 4 and 7 could be tied to mechanical failures in the heat pump and ground loop.

Table 12. Annual energy summary.

	Year 1* (winter 2013-14)	Year 2 (winter 2014-15)	Year 3 (winter 2015-16)	Year 4 (winter 2016-17)	Year 5 (winter 2017- 18)	Year 6 (winter 2018-19)	Year 7* (winter 2019-20)	Year 8 (winter 2020-21)
Annual energy from the ground (kWh)	9,459	14,086	13,931	17,897	17,229	15,750	11,481	19,914
Annual Electricity Used (kWh)	3,712	6,012	6,926	9,832	7,750	7,234	6,823	9,152
Total Heat Delivered (kWh)	13,171	20,098	20,877	27,729	22,437	22,383	18,374	29,059
Annual COP	3.5	3.3	3.0	2.8	2.9	3.1	2.7	3.2

*partial year

Groundwater around the RTF has been rising for the past few years; this has added a new and unevaluated variable to the changes in efficiency. It is a large mass of unfrozen water that is moving so it is constantly above freezing. The water is within 1.2 m (4 ft) of the ground's surface in some locations. It is very likely the slinky coils are sitting in moving groundwater at times throughout the year. The groundwater could increase the heat transfer from the soil to the GHE; and has the potential to create a reservoir of higher temperatures for the heat pump to draw energy from.

Overall, the fluid temperature from the GHE to the heat pump has fallen from an average of 1.3°C (34.3°F) in year 1 to -0.3°C (31.5°F) in year 7. According to the manufacturer's performance documentation, a 0.6C° (1F°) change in ground temperature creates a 0.044 change in COP, if all other variables were constant that would account for a 0.07 drop in COP.

Conclusions

CCHRC's ground source heat pump was barely cost effective in its 8 years of service, as heating fuel prices have remained low the heat pump costs more to operate than a fuel-efficient oil-fired boiler. The heat pump itself operates at a COP around 3 which is better than one would expect at 0°C ground temperature. The groundwater could be contributing to this higher-than-expected COP with better heat transfer than the soil alone.

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