Hybrid Ground Source Heat Pump at Weller Elementary School in Fairbanks, Alaska

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September 30, 2014

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Contents

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This project was funded by the Denali Commission.

Abstract

Weller Elementary School in Fairbanks, Alaska has a novel hybrid ground source heat pump (GSHP) that uses a solar collector array with an in-ground loop system to seasonally charge the ground with heat. Thermal energy stored in the ground is extracted over the winter to supplement the school's heating. The hybrid system was installed as a proof-of-concept experiment for potential hybrid systems in Interior Alaska. Solar recharge is effective at raising the ground temperature and thus improves the performance of the heat pump. The heat pump had an average COP of 3.73 during its first year of operation; however, a longer study would provide a better understanding of the extent of solar recharge that is required to maintain the heat pump COP. Further analysis of the costs of the heat pump system as part of the overall assessment of school energy costs is also recommended.

Background

Weller Elementary School in Fairbanks, Alaska has a novel hybrid ground source heat pump (GSHP) that uses a solar thermal collector array with an in-ground loop system to seasonally charge the ground with heat. The heat pump uses the same ground loops to extract heat from the ground during the school year in order to supplement the school's heating system. Solar collectors have been charging the ground since July 2012 and the heat pump has been supplying heat since February 2013. The combined system is a proof of concept for hybrid GSHPs in Interior Alaska.

The Weller hybrid heat pump project was a joint venture between the Fairbanks North Star Borough School District (FNSBSD), PDC Inc. Engineers (PDC), and the Cold Climate Housing Research Center (CCHRC). In 2009 PDC approached the FNSBSD with an interest in designing a solar hybrid heat pump system for a school as a research project. PDC and FNSBSD approached the project with questions about the feasibility of heat pumps in schools in Interior Alaska. CCHRC was invited to evaluate the system's performance.

There is a concern in colder climates that GSHPs may extract more heat from the ground in the winter than can be passively recharged into the ground during the summer. This could result in a gradual decrease in system performance as the ground temperature decreases, and could potentially lead to system failure if ground temperatures decrease to below the operational limits of the heat pump. An active solar thermal recharge strategy may mitigate this issue; however more research is needed to know if this option is viable. PDC engineers wanted to design and evaluate a system that would expand the knowledge base of information regarding the effectiveness of an active solar recharging system coupled with a GSHP in a cold climate.

A school was a good match for this project, as there is almost no heating load in the summer so all of the solar thermal can be routed to the ground and stored. PDC designed the hybrid GSHP system to heat the make-up air for the school ventilation system. The system was designed to supply a small portion of the school's total heat load. The primary objective was to learn about heat pumps and hybrid systems rather than to maximize energy savings. The school district offered Weller School as the test site for the system and coordinated the installation. CCHRC's role was to monitor the system and report on its performance.

This document presents CCHRC's findings from monitoring the Weller Elementary heat pump, solar panels, and ground loop for four years. As the project progressed the initial research questions developed into more concrete questions about solar recharge and heat pump performance. This report presents answers to the following questions:

1. How does the ground respond to the hybrid GSHP system?
2. Does the heat pump recover a significant amount of energy from the solar panels?
3. What is the efficiency (SCOP) of the hybrid ground source heat pump system?
4. What are the challenges to using a hybrid GSHP for space heat in an Interior Alaska school and what lessons can be learned from the Weller prototype?

Design and Construction of the Hybrid System

FNSBSD chose Weller Elementary School as the location for this project because it complemented planned mechanical upgrades. These upgrades provided an opportunity for the installation of the heat pump piping with relatively little inconvenience and incurred cost compared to an independent installation. In addition, the site layout provided favorable conditions for implementation of the hybrid heat pump system. Weller's southern exposure and hilltop location was ideal for the use of the solar thermal panels and ground loop, while the mechanical rooms and school grounds had the space to accommodate additional hardware for the experimental system.

PDC worked with the school district to design a system that would best fit the school's needs and available space. The majority of the building's heat is provided by several oil fired boilers via baseboard radiators. The heat pump was not intended to be the main source of heat for the school but rather to pre-heat the incoming ventilation air which is constantly supplied while the building is occupied. The heat pump is a water-to-air unit. It uses a water-glycol solution to collect low temperature energy from the ground. That low temperature energy is supplied to the evaporator in the heat pump where a refrigeration cycle is initiated which supplies heat to the ventilation supply air at the condenser.

Figure 1. Excavation for the ground loop. Slinky coils were laid in the two trenches and on top of the soil bench between the trenches. This photograph shows half of the ground loop as it was being installed.

The system consists of a ClimateMaster residential 5-ton (17.6 kW) water-to-air heat pump connected to six 1,000 ft. (305m) ground loops arranged as overlapping coils ("slinky coils") laid in horizontal trenches. These trenches, oriented perpendicular to the south-facing wall of the school, are 3 ft. (1m) in width and 100 ft. (30.5m) in length. Three of the six coils are installed 12 ft. (3.6m) below the ground's surface with the other three placed 8 ft. (2.4m) below ground level on a bench between the 12 ft. (3.6m) loops (see Figure 1). The soil around the slinky loops is loess underlain with fractured schist; the area has no underlying permafrost. The site has a southern exposure and very little shade (Figure 2).

Figure 2. Layout of Weller Elementary School. The ground loops are to the south of the building in a cleared area (more cleared since the left photo). The patch of dirt in the right photo is directly over the loop.

On the roof six 4 ft. x 8 ft. (1.2m x 2.4m) Caleffi flat-plate solar thermal panels are installed facing south (Figure 3). Warm fluid from the solar panels runs from the attic down through the interior of the school building and then through the ground loop, heating the ground for later extraction by the heat pump. A schematic of the system is provided in Figure 4.

Figure 3. Solar thermal panels. These fixed panels face directly south.

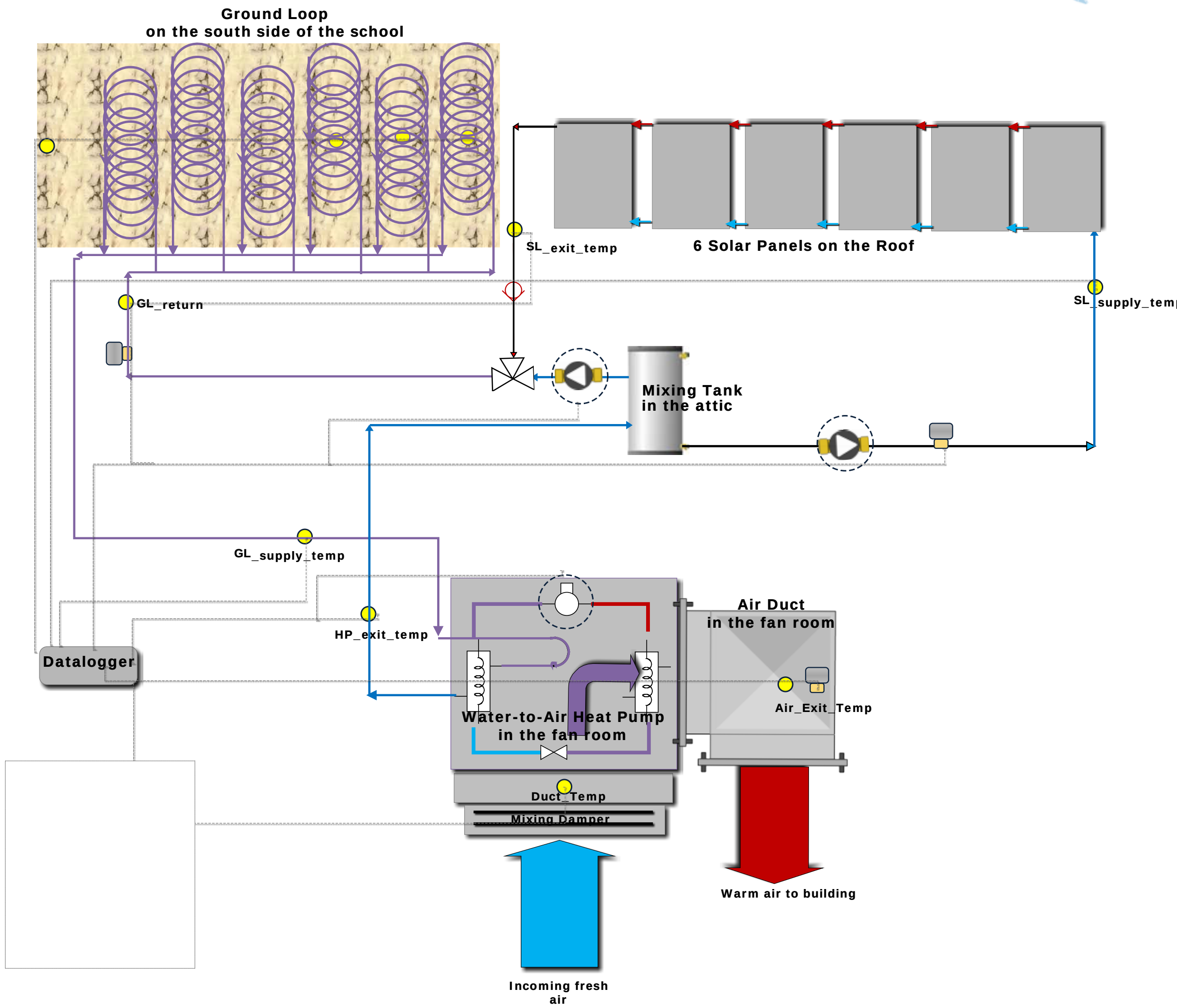

Figure 4.Weller heat pump schematic. The combination of solar thermal panels and ground source heat pump make this a hybrid system.

A large duct brings outside air into the school. A smaller duct pulls a portion of the air to a mixing chamber where the outside air is tempered with air from the fan room. The tempered air then goes to the heat pump, which sits directly below the large duct. The heat pump boosts the temperature of the mixed air and then returns it to the large duct (see Figure 5).

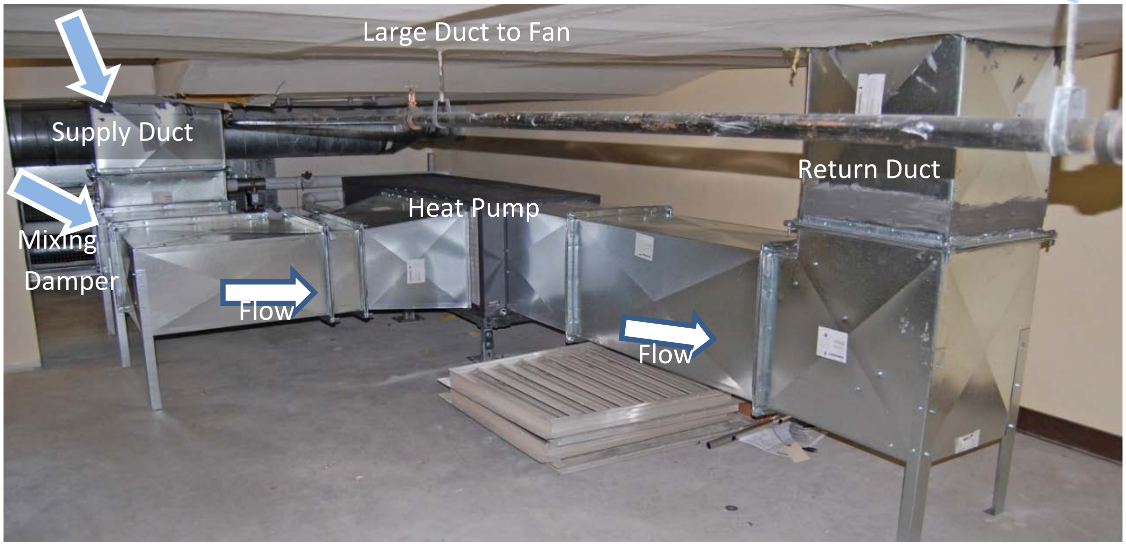

Figure 5. The Weller heat pump. The heat pump sits beneath the large duct that feeds the building ventilation fan.

The installation of the Weller hybrid heat pump system began during the summer of 2010 with the ground loop installation by McM Roe Inc. and school district personnel. The loop was completely installed by September 2010, followed by the placement of the rooftop solar panels in January 2011 by school district personnel. The total system was finalized in May 2011 with the installation of the heat pump and all necessary plumbing and wiring by school district personnel.

The heat pump was initially started in September 2011 but the heat pump failed the following month, a failure which was not resolved until February 2012. This failure was possibly caused by low refrigerant levels within the heat pump; a separate error within the heat pump control system delayed the system's full operation until February 2013.The unit was finally commissioned and completely operational in February 2013. Further information and analysis of the maintenance history of the heat pump are provided throughout the following sections. Figure 6 provides a timeline of major events in this project.

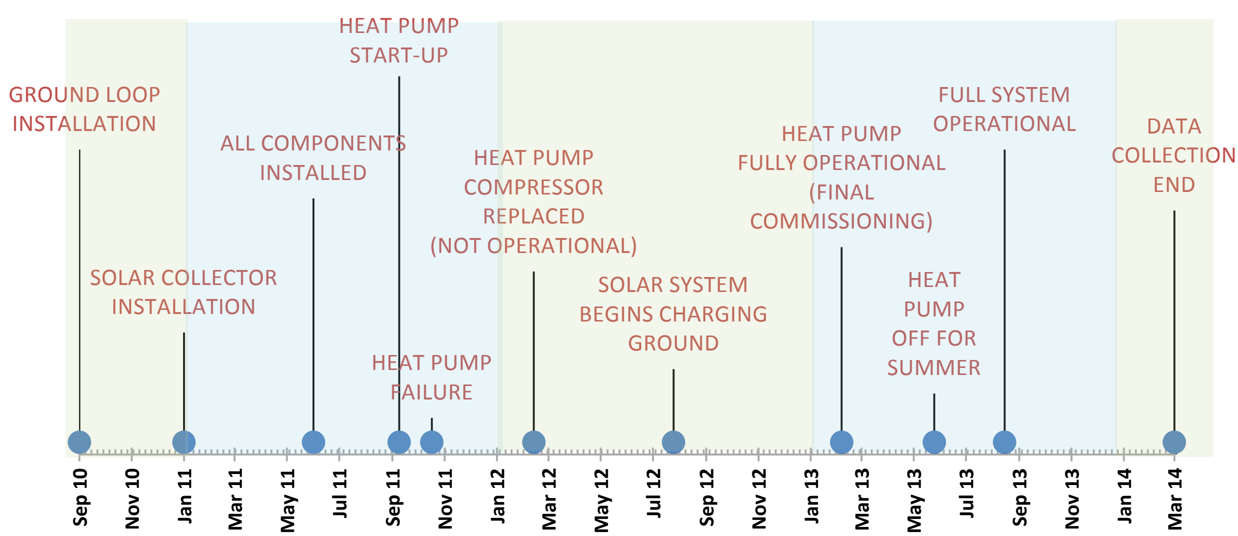

Figure 6. Timeline of significant events. The long commissioning process for the hybrid GHSP system allowed the school district to learn about the technology.

Monitoring and Instrumentation

An automatic data logging system was installed to monitor and evaluate the heat pump system performance and changes in the thermal regime of the ground. Figure 4 shows sensor locations within the heat pump system. These sensors are categorized into three systems: electrical, mechanical, and ground loop. A list of the sensors used to monitor the Weller heat pump project and their respective measurements is provided in Table 1.

The electrical monitoring system uses voltage transducers and current transformers to record the power consumption of the heat pump, the ground loop pump, and the solar loop pump. While the solar pump uses single-phase power, the heat pump and the ground loop pump use three-phase power. Using the voltage transducer and current transformer measurements, a power-metering program calculates the real power for each of these pumps.

The mechanical monitoring system consists of two BTU meters and an airflow meter. Both the solar and ground loops use Onicon BTU meters to measure and record temperatures, flow, and heat energy of the fluid. The Ebtron Airflow measurement system measures and records the duct temperature and air flow rate in the duct.

Table 1. Data-logging system sensors and locations.

Sensor System	Sensor Type	Sensor Name	Sensor Location
Mechanical	Onicon System 10 BTU Meters	HP_exit_temp	Fluid loop exiting the heat pump
		GL_supply_temp	Fluid loop supplied to the heat pump
		GL_flow_rate	Fluid loop between the ground loop and the heat pump
		GL_HP_BTU_rate	
		SL_exit_temp	Fluid loop exiting the solar panels
		SL_supply_temp	Fluid loop supplied to the solar panels
		SL_flow_rate	Fluid loop between the solar panels and the mixing tank
		SL_BTU_rate	
	Ebtron Hybrid HP1 Airflow Meter	Air_Exit_Temp	Heated air exiting the heat pump
		Air_Flow	
	Thermistor	Duct_Temp	Air temperature entering the heat pump from the mixing duct
		GL_return	Fluid loop returning to the ground loop
Electrical	Labjack U6 Power Meter	Circ	Ground loop circulation pump
		HP	Heat pump
		Solar	Solar loop circulation pump
Ground loop	Maxim DS 18B20+PAR	Center	The center loop of the ground loop field
		Shallow ground Loop	The shallow slinky loop at 8 ft. (2.4 m) depth
		Undisturbed	Outside of the ground loop field, to the east
		West Edge	First loop on the west side of the ground loop field

Ground temperature measurements are obtained using Maxim digital, one-wire temperature sensors. Three temperature strings are positioned within the ground loop excavation with a fourth string installed beyond the disturbed site. The configuration of three of the strings is shown in Figure 7 with temperature measurements collected at depths of 1 ft. (0.3m), 4 ft. (1.2m), 6 ft. (1.8m), 8 ft. (2.4m), 10 ft. (3.0m), 12 ft. (3.7m), 14 ft. (4.3m), 18 ft. (5.5m), and 22ft (6.7 m) below the surface (the string outside of the ground loop had the same configuration).

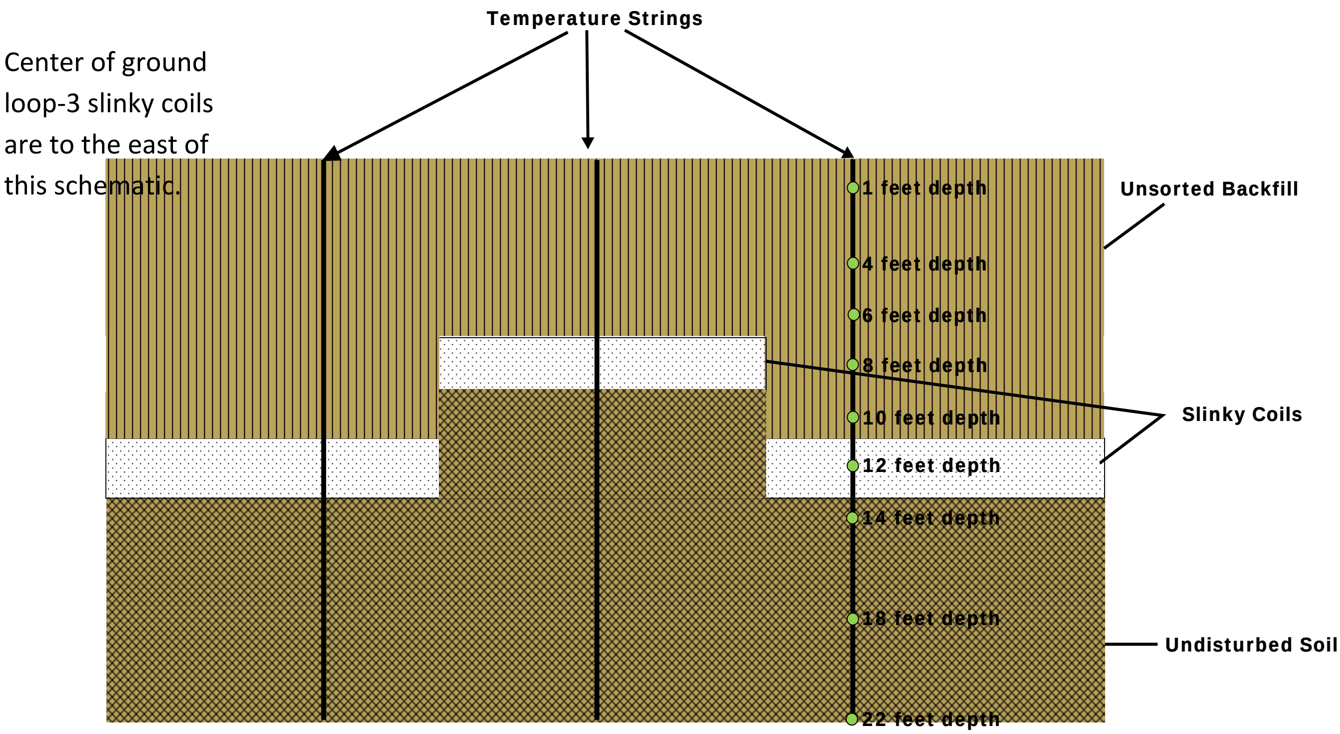

Figure 7.Underground sensor locations. A fourth string is outside the ground loop field in an area undisturbed by the excavation.

Methodology

CCHRC originally planned to study the temperatures in the soil around the ground loops with the heat pump running but without contribution from the solar panels, but the failure of the heat pump during the first year disrupted this plan. The solar panels were operational the second summer, 2012, and began charging the ground with heat before the heat pump was fully operational. This change provided the opportunity to understand the subsurface thermal regime around the ground loop after installation but prior to heat extraction or rejection by the hybrid heat pump system. Trumpet curves of the ground temperatures were created and compared across the 3.5-year period from October 2010 to December 2013.

The coefficient of performance (COP) is a standard measure of a heat pump's efficiency, relating the heat delivered by the heat pump to the electricity required to deliver that heat. The COP of heat pumps is laboratory-tested and published in the specifications guide for the unit. Calculating the COP of a field-installed heat pump introduces inefficiencies in the heat pump system and uncertainties in the data that are otherwise tightly controlled for in the laboratory setting. Because of these inefficiencies and lack of control, field-calculated COP is often different than laboratory-calculated COP.

For the Weller heat pump, the COP is calculated using the relation in Equation 1. The fan power adjustment referenced in this equation is obtained using Equation 2, which can be found in the ANSI/AHRI/ASHRAE ISO Standard 13256-1 (ASHRAE, 2012). The fan power adjustment is used to separate the fan power required to overcome internal resistance (power that is considered in the COP calculations) from the part of the fan power that is used for distribution (not part of the COP). The airflow and external static pressure in this equation are determined experimentally. In the case of the Weller heat pump, an average airflow of 710 liters/s (1,505 CFM) and an external static pressure of 25 Pa were measured with the Ebtron flow meter and a hand-held digital pressure gauge. The calculated Fan Power Adjustment using Equation 2 yielded 59 W.

$$COP = \frac{Heat\ added\ to\ the\ air\ [W]}{(Electricty\ for\ the\ heat\ pump - Fan\ power\ adjustment)[W]} \tag{1}$$

$$Fan\ Power\ Adjustement[W] = \frac{Airflow\ [l/s]\ x\ External\ static\ pressure\ [Pa]}{0.3x10^3} \tag{2}$$

In addition to the COP of the heat pump, CCHRC also calculated the *system* coefficient of performance (SCOP) which accounts for the power required for the ground and solar loop circulation pumps and the distribution fan that is part of the heat pump. The SCOP for the Weller project is complicated by the addition of energy from the solar collectors. The energy from the solar panels routes directly to the ground loop. After the ground loop the fluid is routed to the heat pump; unfortunately, the system is not set up to determine if all the energy from the solar panels is discharged to the ground before the loop returns to the heat pump. Because both systems can run at the same time, it is not possible to separate the SCOP of the Weller system from the contribution of the solar panels. Given this limitation, the SCOP is calculated using Equation 3.

$$SCOP_{heatpumpsystem} = \frac{Heat\ added\ to\ the\ air\ [W]}{Electricty\ for\ the\ heat\ pump[W\} + Electricty\ for\ the\ circulation\ pumps[W\}} \tag{3}$$

In an effort to quantify the effectiveness of the energy storage and recovery in the ground, the energy going to and being recovered from the ground was calculated. When the temperature of the fluid returning to the ground was greater than the temperature entering the heat pump, the amount of solar energy absorbed by the ground (from the Onicon BTU meter) was summed. When the fluid temperature entering the heat pump was greater than the fluid temperature leaving the heat pump, the ground loop energy used by the heat pump (from the Onicon BTU meter) was summed. In some instances energy was going into the ground and to the heat pump at the same time.

Results and Discussion

Due to the sequence of events of the heat pump system, the data analysis has been divided into several distinct periods of time; these time periods are indicated in Table 2.

Table 2. Periods of data analysis

Date	Event	Notes	Data Analysis
September 9, 2011 to October 17, 2011	Initial start-up of the heat pump without the solar panels working	The heat pump failed on October 17, 2011	• Failure analysis
July 23, 2012 to December 2013	Solar panels charged and solar collection system functional	Solar energy enters the system whenever the panels are 6.7°C (12°F) warmer than the mixing tank fluid temperature.	• Ground loop temperature changes • Energy from the solar panels
February 10, 2012 to February 13, 2012	The compressor was replaced, but the system stalled due to low refrigerant	The heat pump system experienced an electrical malfunction	• Failure analysis
February 6, 2013 to May 23, 2013	All systems operational	The heat pump was commissioned and controls were refined to optimize the system	• COP • SCOP
September 2013 to March 2014	All systems operational		• COP • SCOP

Ground Temperature Data

The ground temperatures were recorded in 15-minute intervals starting in October 2010. Collection for the undisturbed temperature string ended in July 2013 when equipment replacing the school's septic system severed the wire connecting the sensors to the data logger. Temperature collection from the ground loop strings ended in January 2014 when an electrical surge rendered the data collection computer inoperable. This ground data is expressed using trumpet curves, which display the ground temperatures by assigning the vertical axis to the various depths at which temperature measurements are taken and assigning the horizontal axis to the monthly average of temperature at each depth.

The temperatures from the temperature string outside the influence of the ground loop tend to be lower than expected when compared to temperatures over the ground loop (Figures 8 and 11). The active layer in 2012 was 7.5 ft. (2.3m) compared to 4.75 ft. (1.4m) on the west edge of the ground loop in 2011 before system components started working. It is possible that the surface above the undisturbed string was plowed to create an emergency vehicle access. The lower than expected temperatures and the lack of definitive explanation make it difficult to rely on the undisturbed data as a baseline for comparison, therefore this data is not used in the subsequent analysis as a basis for comparison to the temperature data from within the ground loop field.

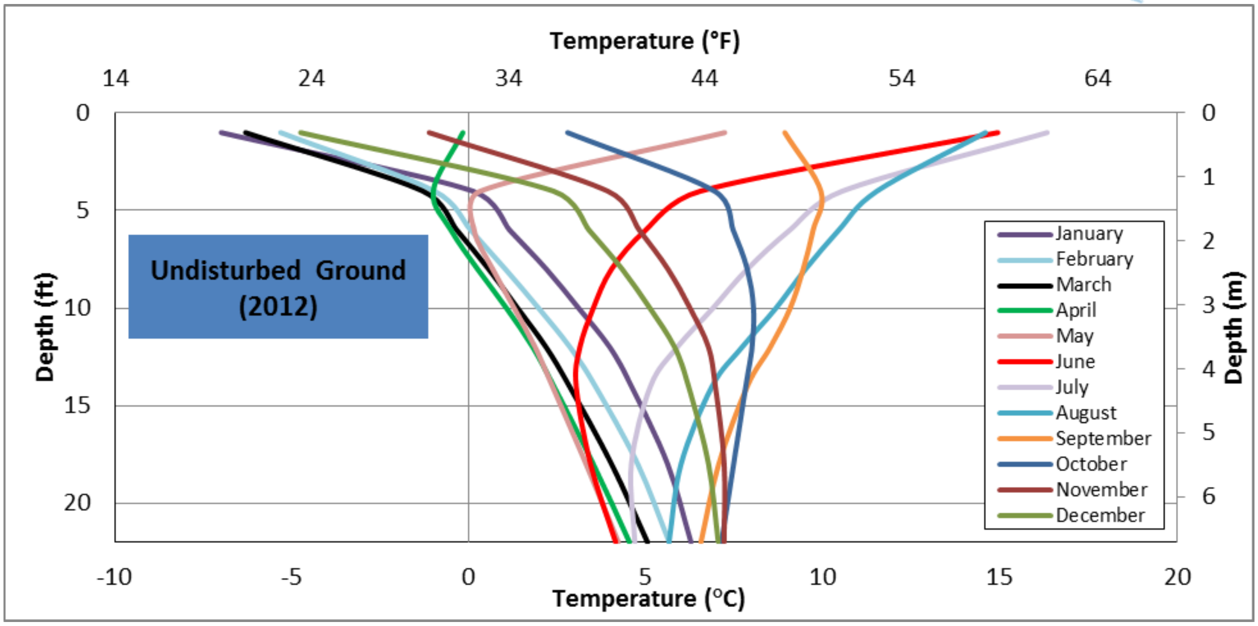

Figure 8. Soil temperatures outside of the ground loop influence, 2012. The depth of freeze in April was 7.5 feet below the surface.

Figure 9 shows the ground temperature within one of the slinky coils at 3.7m (12 ft.) depth. The ground temperatures measured in 2010 and early 2011 serve as a thermal regime baseline because they measure the period before the addition of the solar thermal system and prior to the proper functioning of the heat pump. The Fairbanks temperatures were generally colder in 2012 than 2011 and 2013. In 2012 there were 15,007 base 65°F heating degree days as compared to 13,588 and 13,532 in 2011 and 2013 respectively (Western Regional Climate Center, 2013 and Alaska Climate Research Center).

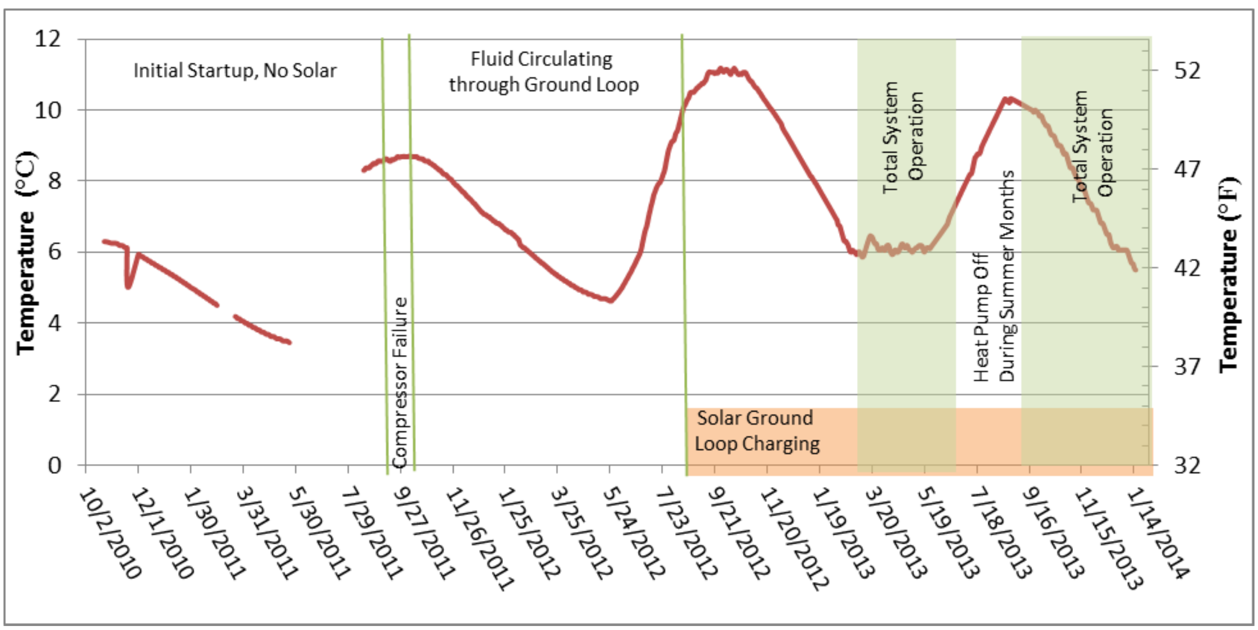

Figure 9. Ground temperatures over time. The temperatures in the center of the ground loop were recorded at 3.7m (12 ft.) of depth and were averaged on a daily basis.

Figure 10 shows the soil temperatures at 12 feet of depth in the center of the ground loop compared over 3 years. The January average temperature around the ground loops was about 1.6°C (2.8°F) greater in 2012 than it was the previous January without the addition of solar energy, possibly due to the circulation pump circulating fluid through the loops before the system was operational. The solar panels started adding heat to the ground in July 2012. The ground temperature starting in July 2012 is noticeably warmer than 2011, even though 2012 was a much colder year, with about 1,500 more heating degree days than normal.

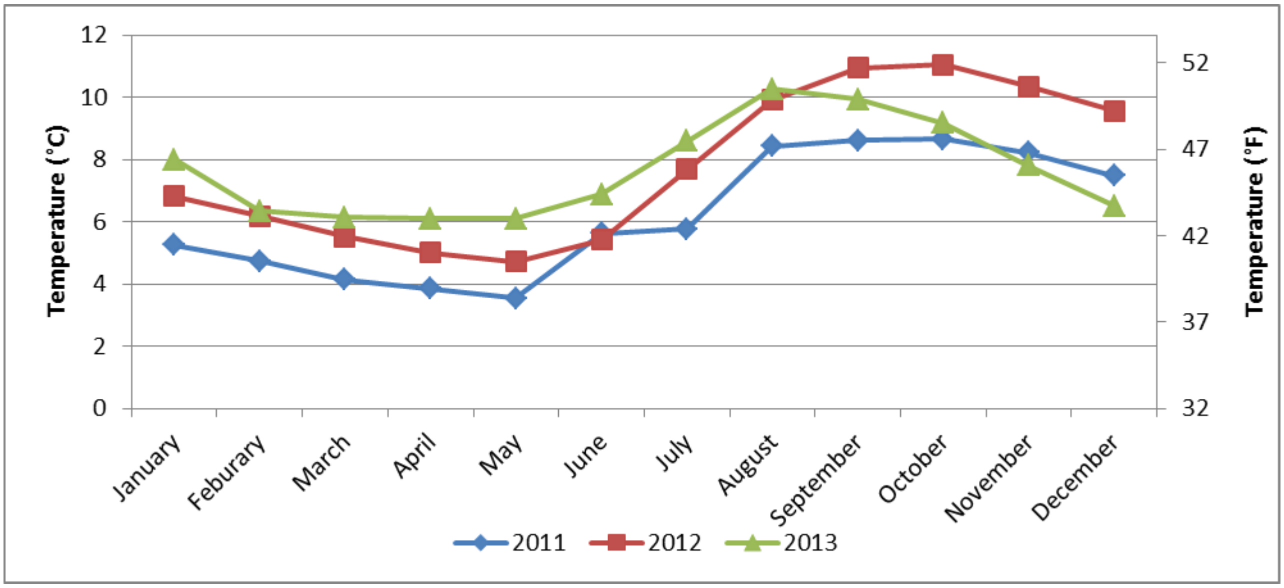

Figure 10. Soil temperature in the center of the ground loop. The soil temperature at 12 feet deep right at the level of the slinky coils.

The operation of the heat pump in conjunction with the solar thermal panels from February 6 to May 23, 2013 produced very steady temperatures in the soil around the ground slinky loops (Figure 9). The system appears to be near steady-state for this period with the solar panels inputting enough energy to make up for the heat pump extraction until the solar input eventually became greater than the building demand. The steady soil temperatures are not evident in late 2013; however, data collection ended in January before the full winter’s data was available. The temperature in the ground loop dropped slightly after the heat pump came online in early 2013: the temperature at 12 feet in December 2013 was almost 1°C (1.8°F) colder than in 2011 and was 3°C (5.4°F) colder than 2012.

Figure 11 shows the temperatures in the center of the ground loop in 2011 before the heat pump was fully functional. The heat pump was installed in September 2011 and started moving fluid through the ground loop, but the heat pump was not functioning during this period. However, the ground circulation pump continued circulating fluid to the ground for the winter months, possibly adding minute amounts of energy to the ground loop by transferring heat from the piping located in conditioned space through the slinky coils and into the ground.

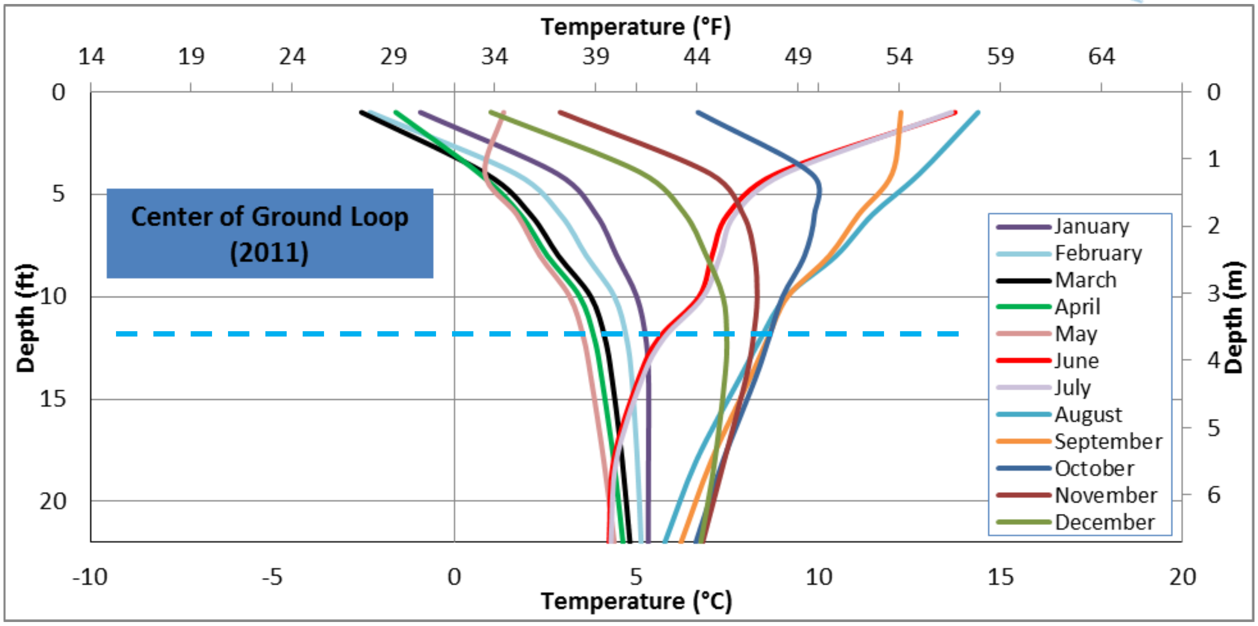

Figure 11. Center-of-ground-loop soil temperatures for 2011. This plot shows the temperatures of the soil following the installation the ground loop but prior to the hybrid heat pump system adding energy to or extracting energy from the ground. The blue dashed line shows the approximate location of the ground loop.

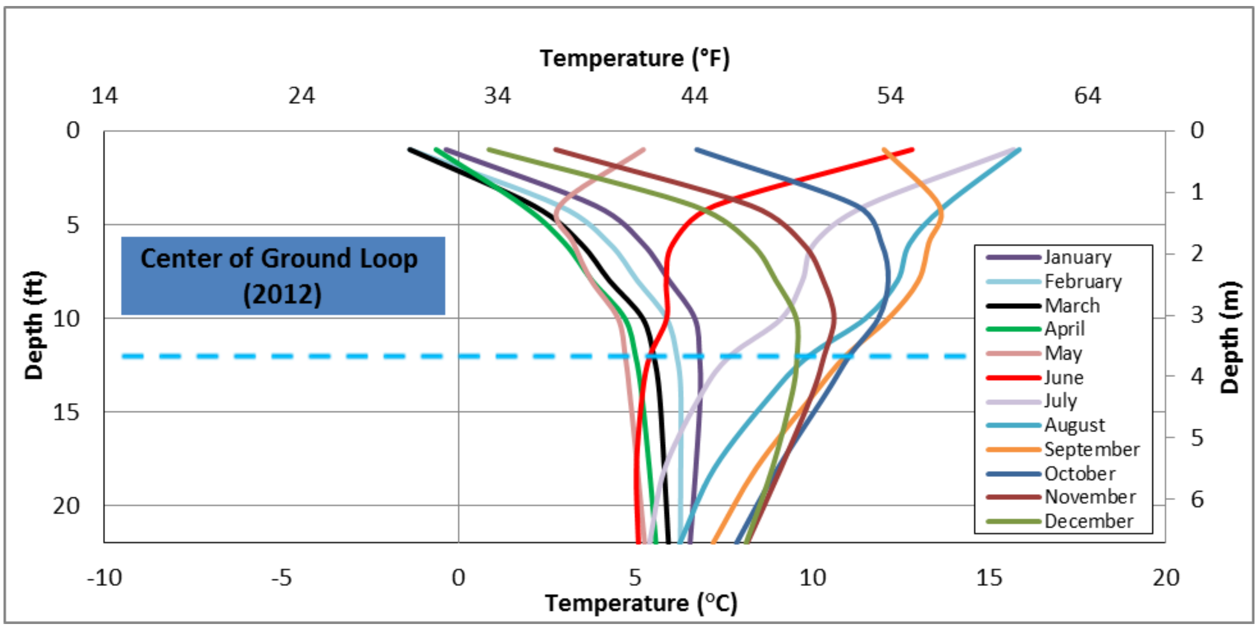

Figure 12. Soil temperatures in the center of the ground loop, 2012. Solar heat was injected into the ground starting in July. The blue dashed line shows the approximate location of the ground loop.

The solar panels began charging the ground on July 25, 2012. The temperatures in the ground loop field between 8 and 12 ft. (2.4 and 3.6m) deep were warmer from August into December 2012 (Figure 12) than the previous year (Figure 11) due to the solar recharge (2012 was a colder year based on heating degree days). The ground remained warmer into January and February 2013 (Figure 13) even though there was little solar recharge during those months. The slope of the whiplash curves in 2012 between 10 and 25 ft. are less steep than 2011 leaning toward warmer temperatures at 12 feet of depth. The active layer for the area above the ground loop moved from 3.25 ft. (1m) in 2011 to 2 ft. (0.6m) in 2013, which is assumed to be due to the influence of the solar thermal energy added to the system.

The ground temperatures in 2013 when the heat pump system and solar thermal panels were both operational provide insight into the behavior of the ground in response to the Weller heat pump (Figure 13). The heat pump was fully operational in February 2013 and ran until school closed for the summer at the end of May. Solar recharge ran during the summer while the heat pump was not operating. The heat pump was reengaged in August 2013. When compared to the temperatures from 2012 (Figure 12), the 2013 soil temperatures create a narrower trumpet curve. This indicates less yearly temperature fluctuations deeper in the soil. The solar thermal input and the heat pump extraction may be working to create a balance of heat flows in the soil. The solar heat injection into the soil during the summer creates warmer winter soil temperatures, but the heat extraction from the soil removes all the injected heat during operation (see “heat flow in the ground loop” section).

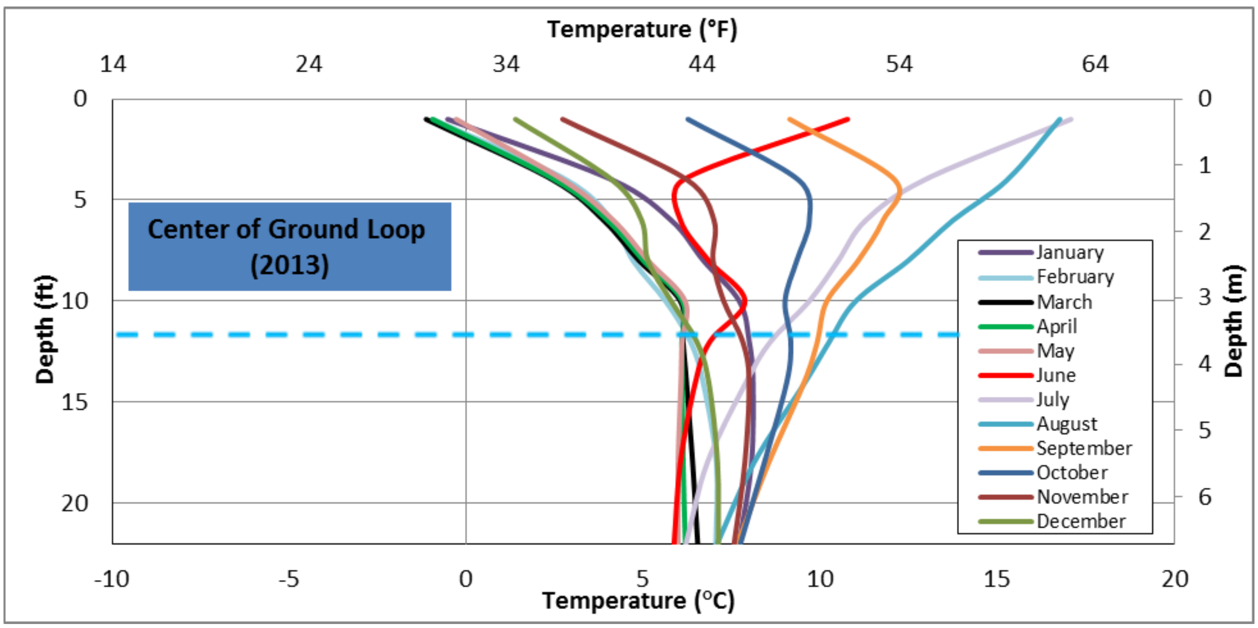

Figure 13.Soil temperatures in the center of the ground loop, 2013. The influence of the solar thermal heat injection and heat pump heat extraction is more apparent. The blue dashed line shows the approximate location of the ground loop.

There is a warming trend in the average monthly data over the course of the summers (Figure 14) especially when compared to soil outside of the ground loop (Figure 15). The solar thermal system started adding heat to the ground July 25, 2012; the bump in the August and July 2012 temperature at 10 feet is likely the result of the solar thermal heat. The smoother lines in July and August 2013 may be the result of the ground reaching a new balance at the end of a full season of solar thermal charging and half a winter of the heat pump extracting heat.

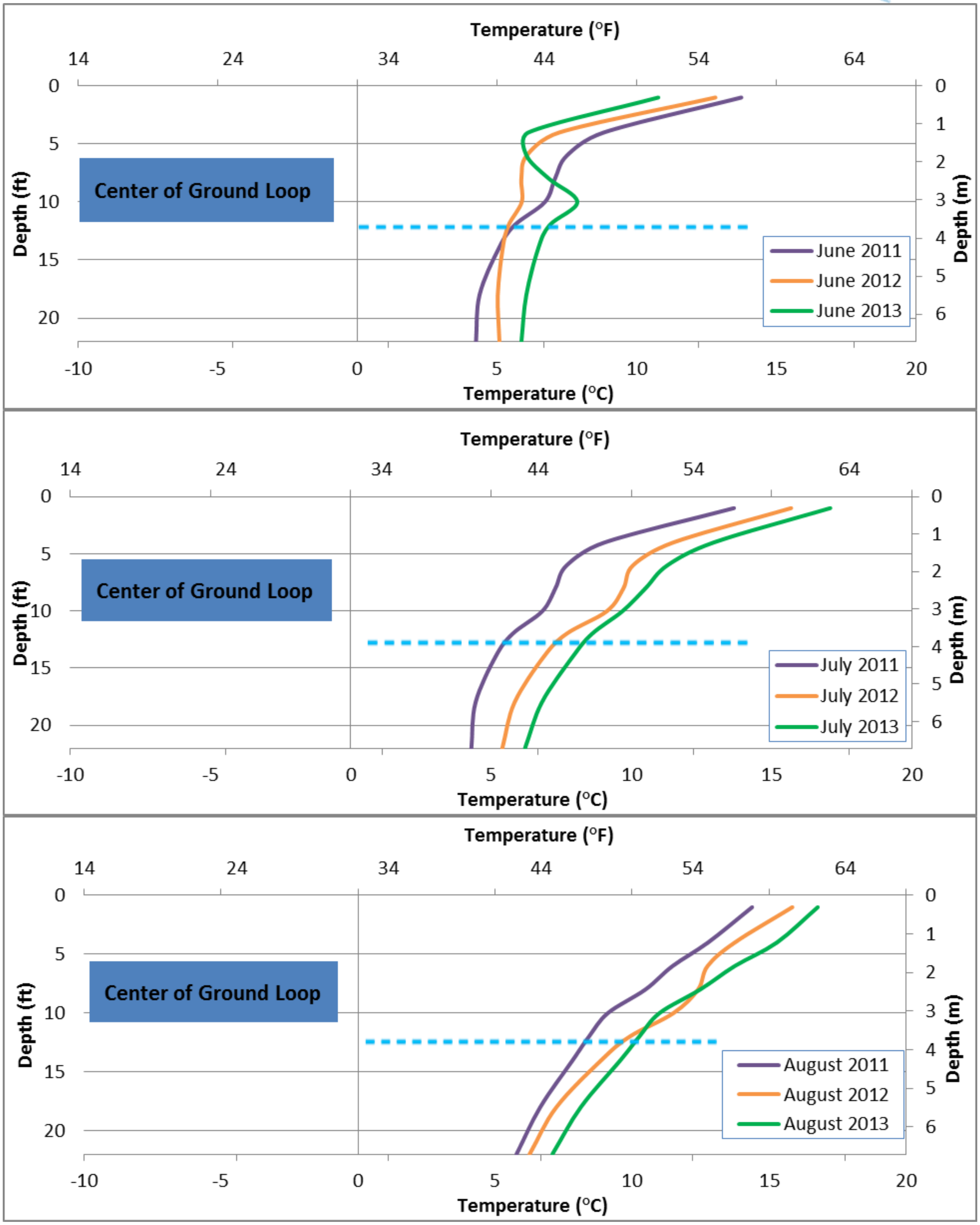

Figure 14. Average soil temperatures from the center of the ground loop for June, July, and August. The ground loop was installed in 2010. Solar recharge began in July 2012 and the heat pump began working in February 2013. The blue dashed line shows the approximate location of the ground loop.

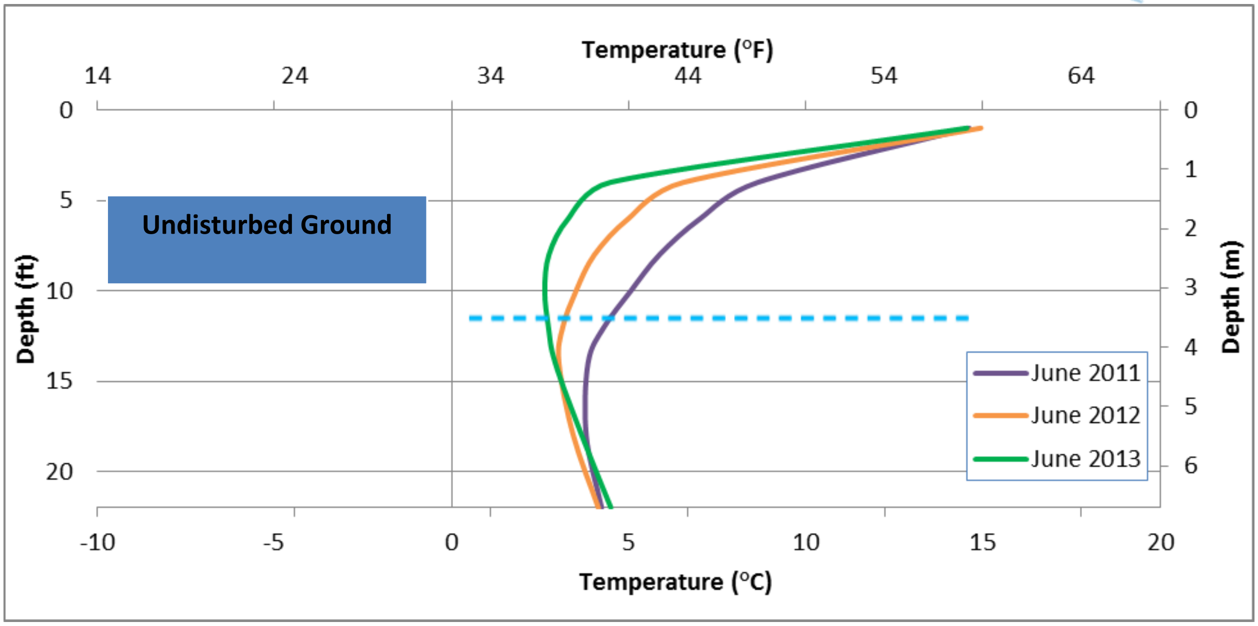

Figure 15. Average soil temperatures of undisturbed soil for June. The temperature in the undisturbed soil away from the ground loop was cooler in 2013 than in 2011. The blue dashed line shows the approximate location of the ground loop.

The plots in Figure 16 show a sample of the ground temperature data during winter months. The temperatures jumped from 2010 to 2011 possibly do to the circulation pump moving fluid through the system before the heat pump was engaged. While the temperatures near the surface tend to remain the same over these months, temperatures deeper and near the slinky coils tend to trend warmer in 2012 than in 2010 and 2011. At 10 ft. (3m) of depth the temperature in December jumps from 6°C in 2010 to 10°C in 2012 (42.8°F to 50°F). However, the effect of the heat pump heat extraction on the ground temperatures is very noticeable in 2013. The temperature from the surface down to the depth of the ground loops in December 2013 is the same as the temperature in 2010 before solar heat was added to the ground.

The thermal regime around the heat pump ground loop is greatly affected by the heat injection and extraction from the hybrid heat pump system. The injection of heat from the solar panels brought the average December temperature at 12 ft. (near the slinky loops) up by 2°C (3.7°F) relative to the soil temperatures prior to activation of the solar system. Extraction of heat with the heat pump brought the loop temperature back down to 6.5°C (43.7°F) by December 2013, about 1°C (1.7°F) lower than December 2011, before the solar thermal system started operating. This trend in colder soil temperatures with the heat pump running may continue or the ground loop may reach a steady state between the heat extraction and injection at some point in the future. Longer study of the ground temperature would provide a better understanding of this soil thermal regime.

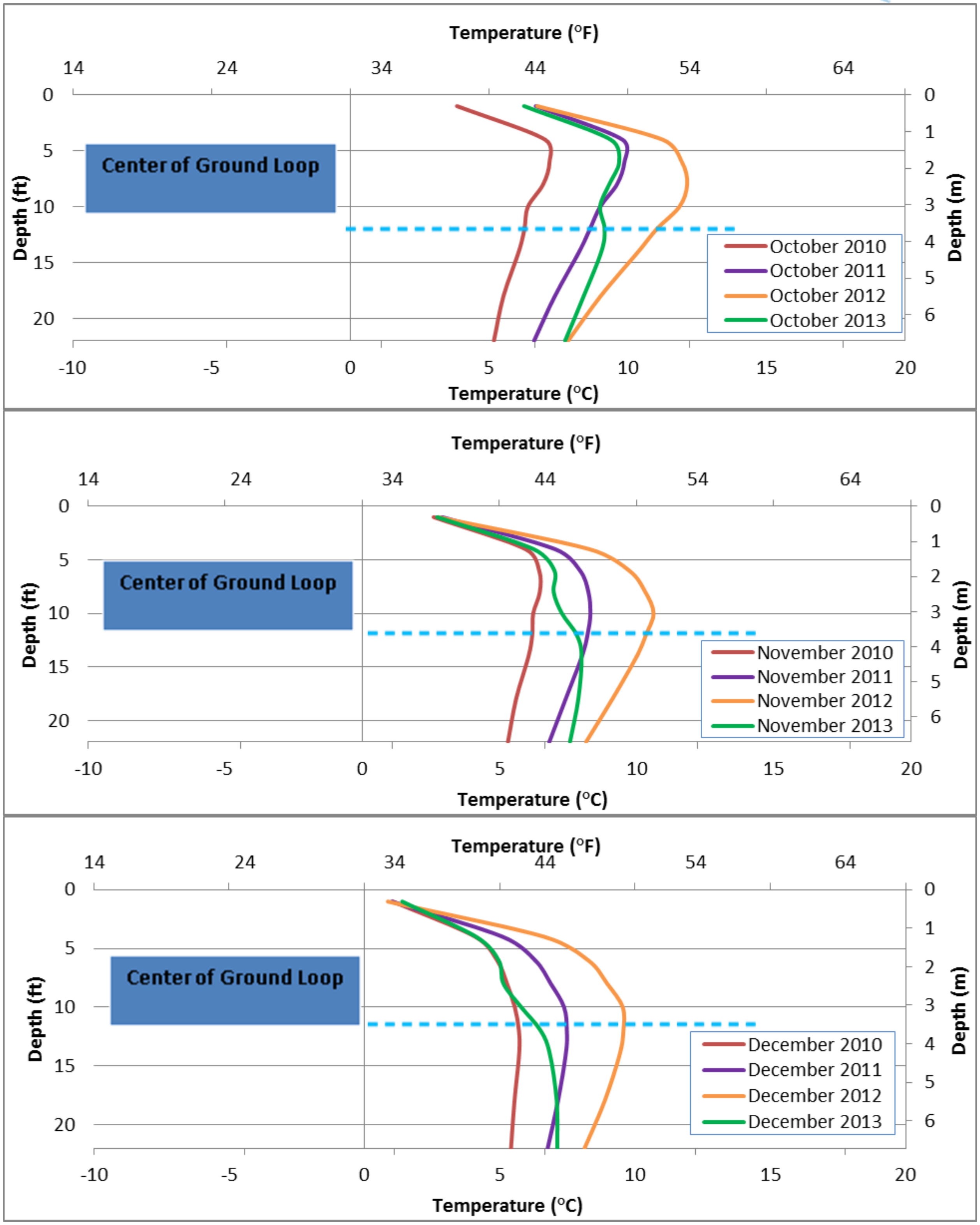

Figure 16.Average soil temperatures from the center of the ground loop for October, November, and December. The ground loop was installed in 2010. Solar recharge began in July 2012 and the heat pump began working in February 2013. The blue dashed line shows the approximate location of the ground loop.

The significance of the heat injection and extraction from the hybrid heat pump system operation is clearly visible in the changes of the trumpet curves during the monitoring period. Figure 17 shows the temperatures in the center of the ground loop from 2011 overlaid with 2012. The warming trend from the solar thermal recharge beginning in July 2012 is very apparent. Figure 18 overlays the ground temperatures from 2012 with 2013. The heat pump was running most of 2013, extracting heat from the ground resulting in cooler temperatures in 2013 when compared to 2012. This decline in ground temperatures is especially notable since 2012 was a colder year than 2013.

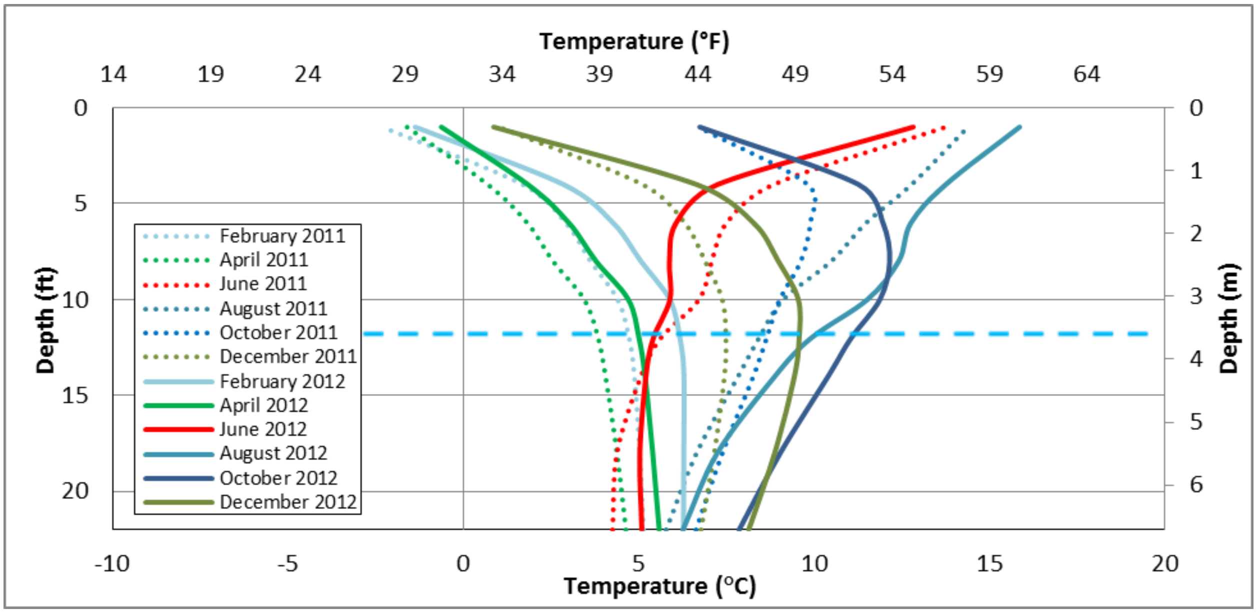

Figure 17. Changes due to solar panels - 2011-2012 trumpet curve. The dotted lines are data from 2011; the solid lines are from 2012. There is a warming trend in the monthly data. The horizontal blue dashed line shows the approximate location of the ground loops.

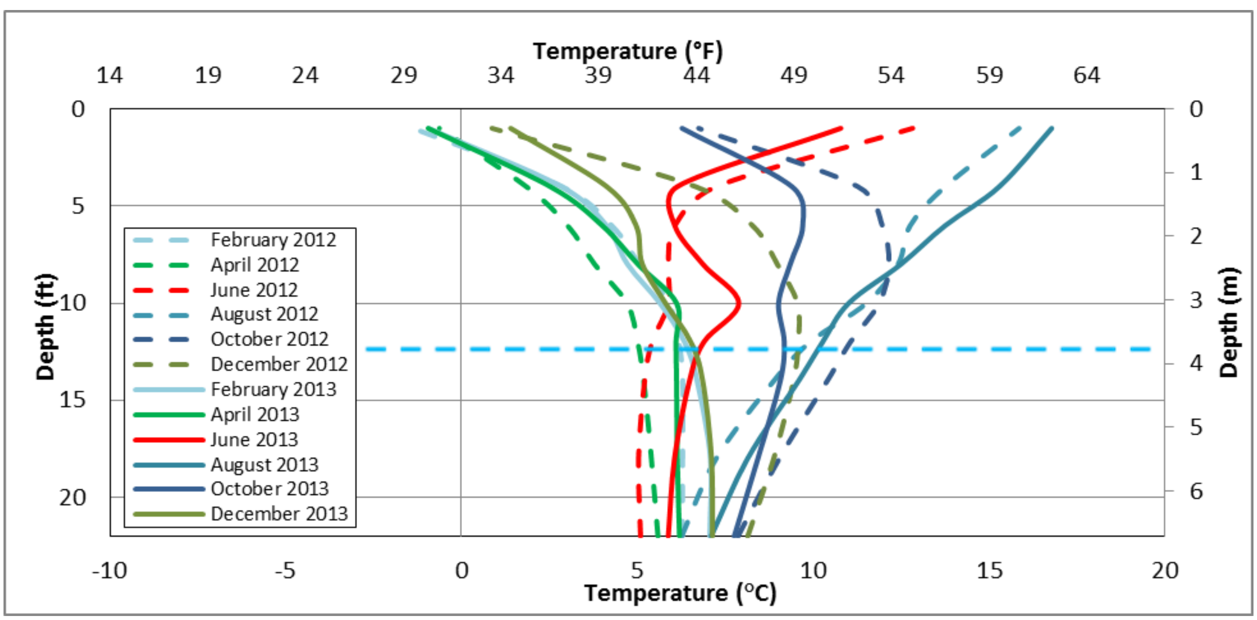

Figure 18. Changes due to the addition of the heat pump - 2012-2013 trumpet curve. The dotted lines are data from 2012 and the solid lines are from 2013. The horizontal blue dashed line shows the approximate location of the ground loops.

Heat Flow in the Ground Loop

The solar thermal panels were charged with fluid on July 25, 2012. They immediately began pumping heat into the ground loop soil, as can be seen by the rising temperatures in Figure 9. CCHRC calculated how much energy the solar panels put into the ground and how much energy the heat pump recovered from the ground. This data is presented in Table 3. The totals are based on the data collected. Gaps in the data (no more than 2 consecutive days at a time) over the collection period due to data logger connection problems are not accounted for in this analysis. Hourly averages were used to obtain the sums for July 2012 through March 2014. Because the heat pump was not running consistently, the heat recovered from the ground is zero from July 2012 to January 2013.

Table 3. Energy input to and recovered from the ground loop.

	Energy delivered to the ground (kWh)	Ground Energy extracted by the heat pump (kWh)
July 2012	1,289	0
August 2012	1,030	0
September 2012	815	0
October 2012	813	0
November 2012	841	0
December 2012	652	0
January 2013	41	0
February 2013	367	1,234
March 2013	1,387	1,098
April 2013	1,215	1,092
May 2013	1,854	1,550
June 2013	1,967	123
July 2013	1,413	24
August 2013	1,449	949
September 2013	580	1,413
October 2013	339	1,482
November 2013	120	1,355
December 2013	32	1,331
January 2014	116	1,621
February 2014	671	1,563
March 2014	1,804	1,246
Total	18,795	16,081

From the time the heat pump came online and the system was fully operational in February 2013 through March 2014, the heat pump has recovered 16,081 kWh while the solar thermal panels have added 13,314 kWh into the ground.

To estimate how much of the energy extracted by the heat pump is attributable to the solar thermal panels, the time period when both systems were running was analyzed separately. During the period when the heat pump was active from February 2013 to March 2014 (with June, July and August removed), the heat pump extracted 14,985 kWh from the ground while the solar panels inputted 8,485 kWh into the ground. It can be estimated that 56% of the heat for the heat pump came directly from the solar, while the remainder came from other energy sources in the ground. However, the energy put into the ground before the heat pump came online was 5,481 kWh, which elevated the temperature in the ground loop so that the amount of energy recovered from the ground by the heat pump has not dropped the temperatures in the ground below the ground loops back to initial temperatures. This would tend to increase the estimate of the proportion of solar panel energy contribution because higher ground temperatures allow the heat pump to recover more heat from the ground.

Figure 19 shows the energy that has been put into the ground from the solar panels versus what has been recovered by the heat pump during the period of time both systems were running. The energy input from the solar panels generally follows the expected seasonal pattern of solar insolation, while the heat extraction from the heat pump while school is in session varies less and apparently does not directly match the building heat demand (e.g. the heat extracted in September 2013 is approximately the same as December 2013).

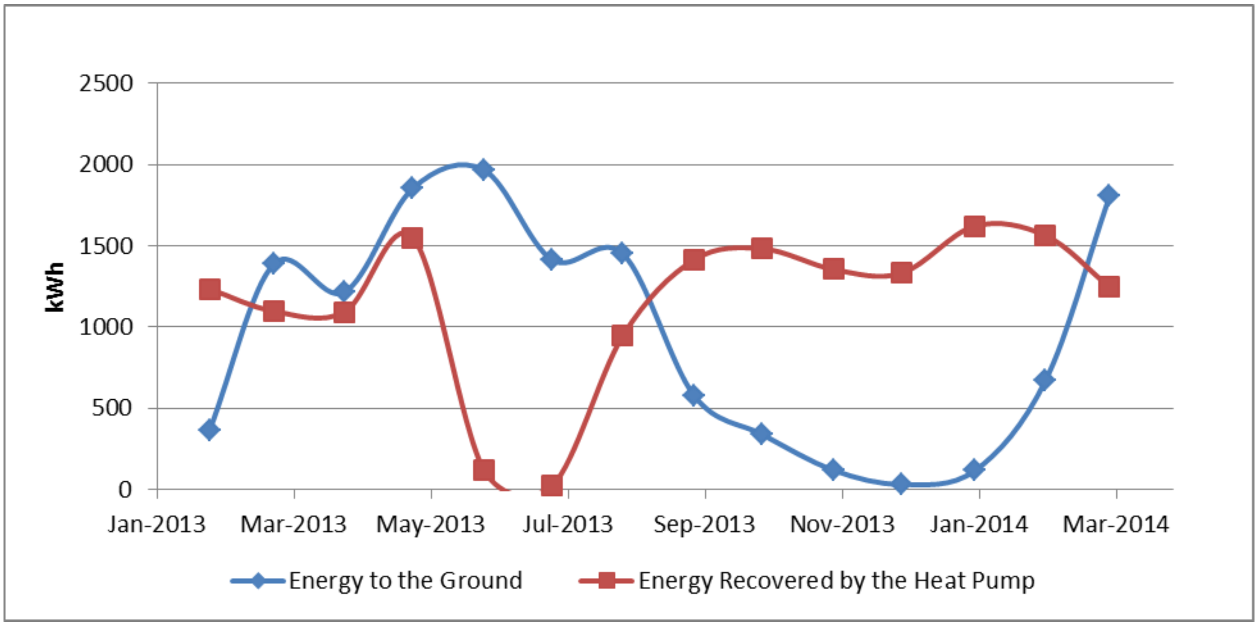

Figure 19. Energy input to and recovered from the ground loop (monthly summations). The heat pump and the solar panels can be running at the same time.

The difference between how much energy is stored in the ground and how much is utilized by the heat pump is influenced by the time of the year and school occupancy. During the summer months there are no occupants and the outside temperatures are warm enough that the building does not require heating. Injection of heat from the solar thermal panels without the heat pump running allows for thermal pre-charging of the soil. However, because the heat injected diffuses into the soil surrounding the ground loop, the amount of energy available to be recovered by the heat pump is less than when both systems are running. This effect occurs especially during winter months as shallow soils are exposed to the surface environment, increasing the transfer of subsurface heat. Soils at deeper depths are affected more slowly than those of shallower depths, as seen by the trumpet curves.

Heat Pump Analysis

The heat pump system has been a learning process for all involved. The technology is new to the school district and the participating engineers. The failure of the heat pump out of the box led to a protracted process of repair and a search for a local contractor who had the expertise and certifications to perform the repairs. This process has allowed the school district to develop a network of expertise on heat pumps for future projects.

Initial Start-up

The heat pump started for the first time on September 9, 2011 and ran until October 17, 2011, when the heat pump compressor failed. This initial startup of the heat pump allowed CCHRC to commission the data logging system. Commissioning found errors in the electrical data collection system, therefore there is no electrical data for this period of heat pump operation.

Analyzing the heat pump data in the absence of electrical data, it is uncertain whether the heat pump was functioning correctly from the outset. The average incoming ground fluid temperature was 10.7°C (51.2°F) when the circulation pump was running, whereas the exit average temperature from the heat pump back to the ground loop was 10.6°C (51.0°F). The difference between the incoming and the outgoing ground loop fluid temperature should be greater if the heat pump is removing heat from the ground loop. When the heat pump is working correctly the temperature drop in the ground loop fluid across the heat pump is 3.3°C to 4.4°C (6°F to 8°F).

Evaluation of the air flowing through the heat pump indicates that heat was being delivered to the building via the heat pump duct. Whether this heat was simply delivered from the pre-mixing damper or the heat pump itself is hard to ascertain without the electrical data. Temperature sensors are located in the ducts on either side of the heat pump. When the fan was not running the exit duct from the heat pump was typically 0.3°C to 0.9°C (0.5°F to 1.5°F) higher than the supply duct (most likely due to the location of the ducts in relation to the incoming air). When the heat pump was running the exit duct was 5.9°C (9.5°F) warmer than the supply duct. The performance data for the heat pump anticipates a temperature differential of 11.1°C to 16.7°C (20°F to 30°F).

Because this was the first operation of the heat pump, the errors remained unnoticed; however it is acknowledged that an error existed in the initial system from the start. This error could be attributed to the compressor malfunction, which was not recognized until a short in the electrical system related to the compressor failure caused the system operation to cease. This error could also be attributed to the condition of the heat pump refrigerant. If this fluid was not completely charged it could have superheated, causing the compressor to overheat (G. Free, personal communication December 6, 2012).

Second Start-up with a new compressor

The compressor in the heat pump was replaced February 10, 2012. After the system was restarted it continued to malfunction and was shut down February 13, 2012. The problems with the heat pump at this time were not studied until December 2012 when a heat pump contractor was able to analyze the system. The contractor found that the refrigerant was not charged to the proper level, leading to poor system performance. After providing the system with sufficient refrigerant levels a faulty pressure switch was discovered in the control system. A replacement was ordered and the system was out of commission until February 2013.

During the period of operation between February 10–13, 2012 the temperature difference in the ground loop across the heat pump ranged from 2.2°C to 3.3°C (4°F to 6°F) and the change in duct temperature across the heat pump ranged from 3.3°C to 7.8°C (6°F to 14°F). Based on these measurements it is apparent that the heat pump was not performing properly during this time and thus no efficiency was calculated for this period.

Final Commissioning

The fully commissioned heat pump came online February 6, 2013 and heated the ventilation make-up air from an average 14.4°C (58°F) to an average 27.8°C (82°F) for 40 minutes of every hour that the school was occupied. The incoming ventilation air is mixed with warm air from the fan room prior to entering the heat pump. Pre-mixing is necessary as the specified minimum entering air temperature for the heat pump is 7.2°C (45°F), well above Fairbanks winter air temperatures.

Based on Equation 1 and Equation 2 the heat pump has had an overall average COP of 3.73 since its operation commenced in February 2013. The average COP is lower than expected for this particular heat pump with an incoming ground fluid temperature of 9.2°C (48.6°F). The expected COP for this unit with this entering fluid temperature is 4.28; however, that is with an expected entering air temperature of 21.1°C (70°F) whereas the entering air temperature to the Weller heat pump is 14.4°C (58°F). This lower COP may also be due, in part, to the difficulty in getting good air flow reading from the duct sensors. The duct is shorter than the sensor recommends for achieving the laminar flow necessary for accurate readings. In addition, some error could be due to the large building fan, which also draws air through the heat pump and could affect the duct sensor readings. Figure 20 compares the COP and entering fluid temperature from the Weller heat pump to the manufacturer-specified COP and entering fluid temperature for the specific model. Based on all the data points the average monthly COPs from Weller correlate well with the manufacturer specified COPs.

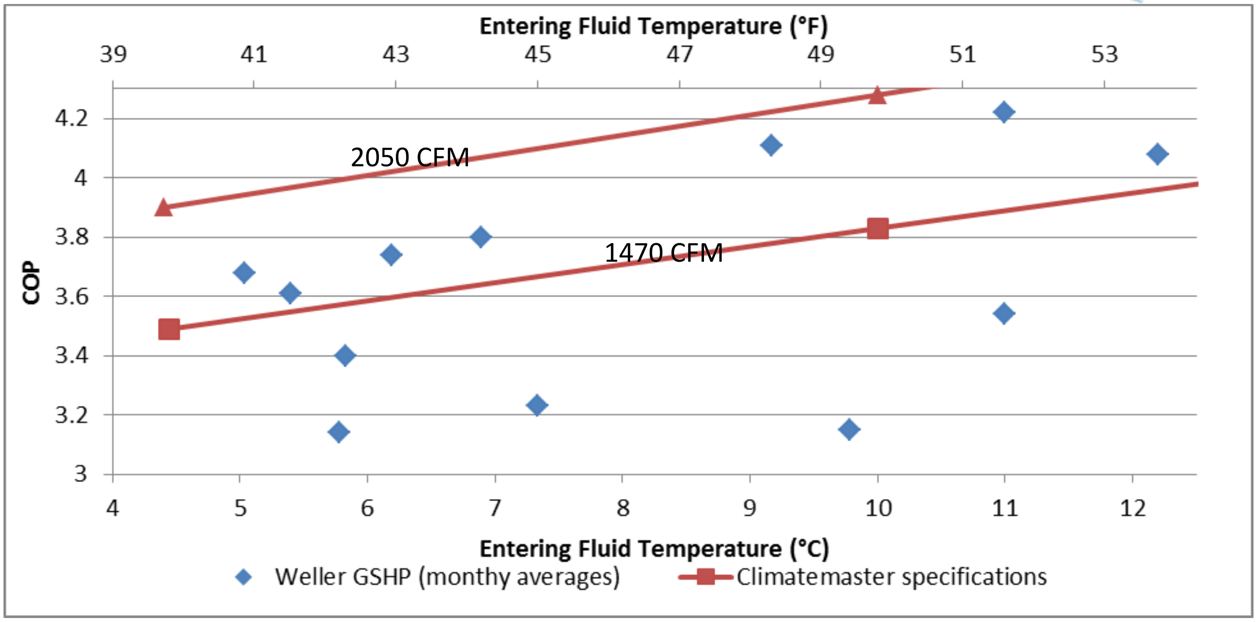

Figure 20.Weller COP and ClimateMaster specifications. The red lines interpolate the lab tested COP for the ClimateMaster unit that is installed at Weller. The upper red line with the triangles is for a heat pump running at 2050 CFM the lower red line is for 1470 CFM. The Weller heat pump ran at approximately 1505 CFM.

The average COP and entering fluid temperatures calculated for each month are listed in Table 4. As expected, the fluid temperatures and COP are highest in late summer when the entering fluid temperature is the highest. The COP fluctuates slightly over the darkest winter months, hitting a low of 3.3 in November and a high of 3.7 in January. The entering fluid temperature dropped steadily over the winter until the sun started adding heat to the system again in February.

Table 4. Calculated Coefficients of Performance

	COP	SCOP	Entering fluid temperature
May 2013	3.8	3.3	6.89°C (44.4°F)
***June 2013**	3.2	2.8	9.78°C (49.6°F)
***July 2013**	3.8	3.0	11.0°C (51.8°F)
August 2013	4.1	3.6	12.2°C (53.9°F)
September 2013	4.3	3.7	11.0°C (51.8°F)
October 2013	4.2	3.6	9.17°C (48.5°F)
November 2013	3.3	2.8	7.33°C (45.2°F)
December 2013	3.4	3.0	5.83°C (42.5°F)
January 2014	3.7	2.8	5.04°C (41.1°F)
February 2014	3.6	2.8	5.40°C (41.7°F)
March 2014	3.7	2.8	6.19°C (43.1°F)

*The heat pump ran for just a few days, probably as part of a maintenance test

School ended on May 24, 2013 and the heat pump was turned off for most of the summer. It came on three separate days in June and July leading to COP calculations for those months (these on-cycles are unexplained but may have been part of a system test run by the school district). Heat pump operation commenced August 14, 2013 with the start of the new school year.

When the circulation pumps and distribution fan are figured into the efficiency calculations using equation 3 the average SCOP is 3.11. This calculation includes the power to run the ground circulation pump and the solar panel pump. The monthly SCOPs are also summarized in Table 4. The two circulation pumps draw a combined 0.52 kW when both are running which is a small fraction of the 4.0 kW the heat pump draws when running. The combined circulation pumps make up about 11% of the electrical use of the entire system.

The Weller hybrid heat pump averaged a COP of 3.73 and a SCOP of 3.11. These efficiencies changed over the course of the winter due to changes in the incoming water temperature and variation in the inlet air temperature. Figure 21 shows the COP and SCOP variation over the course of the year.

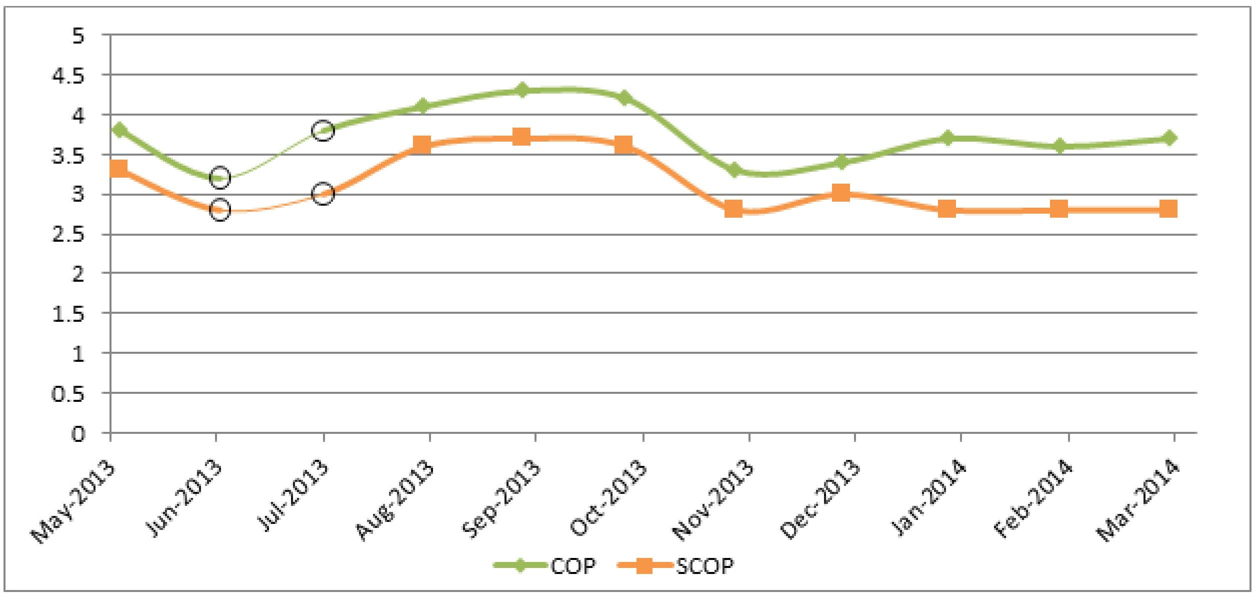

Figure 21. COP and SCOP for the Weller heat pump over the course of its first year of operation. Values for June and July are not realistic as the system only ran for testing a few times during those months.

Cost Estimates

While the Weller hybrid GSHP was an experiment in implementing new technology on a small scale, a rough estimate of cost savings can be calculated for the heat pump system relative to conventional heating methods. Information on the cost savings of the heat pump are presented in Table 5. Based on the school year of August through May, the annual operating cost for the heat pump was $1,271.25 versus an estimated equivalent cost of heat from an oil boiler of $2,179.83. This savings of about $900 is small when compared to the overall heating costs of the Weller school, which were $46,882 for the 2012-2013 school year. However, the cost of energy from the heat pump is approximately 40% less than the cost of energy from the oil boiler. Weller used 13,480 gallons of heating fuel during the 2012-2013 winter, and the heat pump offset about 600 gallons of heating fuel. While this barely registers in the whole building use, this result is not unexpected since it was a proof of concept system and only designed to pre-heat part of the incoming make-up air for the ventilation system.

Table 5. Calculated Estimate of Savings

	Thermal Energy to Building (kWh)	Gallons of oil offset**	Electrical Cost to run the heat pump ($0.21/kWh)	Savings (oil $3.67/gallon)
February 2013	1,168	36.10	$74.33*	$58.16*
March 2013	1,335	41.27	$84.97*	$66.48*
April 2013	1,132	35.00	$88.57	$39.89
May 2013	1,445	44.66	$100.28	$63.63
June 2013	174	5.39	$18.21	$1.58
July 2013	46	1.44	$7.29	-$2.01
August 2013	1,372	42.42	$76.89	$78.79
September 2013	1,931	59.69	$113.72	$105.36
October 2013	2,258	69.78	$132.91	$123.19
November 2013	1,536	47.49	$108.59	$65.70
December 2013	1,534	47.40	$110.39	$63.58
January 2014	1,919	59.32	$127.66	$90.05
February 2014	1,820	56.24	$123.74	$82.65
March 2014	1,545	47.75	$103.72	$71.53
Total	19,218	593.96	$1,271.25	$908.58

*Data estimated using the average SCOP of the system; electrical use is not available for this period.

** Heat content of oil is assumed to be 138,000 BTU/gal. Boiler efficiency is assumed to be 80%.

Recommendations

The Weller heat pump system is the first heat pump installed in a Fairbanks area school. The entire process of design and installation, as well as the operation of the system, has served as a learning opportunity for the FNSBSD. The early struggles to get the system running demonstrate the need to work with someone who has expertise with the technology. Heat pumps are so new to Fairbanks that there is only one certified installer in the area. The problem with low refrigerant charge in the heat pump itself required that the repair contractor hold an U.S. Environmental Protection Agency refrigerant technician certification, but that did not guarantee that the individual understood the proper refrigeration requirements of a ground source heat pump. Finding a person with the correct expertise led to the long commissioning process for this heat pump. Heat pump projects should involve a heat pump expert in the design, installation, and commissioning of the systems.

The heat pump has required little maintenance since commissioning. Reliability is a positive aspect of heat pumps for a school setting. However, if the school district were to install more GSHPs in local schools it would be worthwhile to have a technician on staff trained to work with heat pumps.

The Weller heat pump system is functional and is delivering heat to the school efficiently; however, the system could be better optimized. The heat pump has no controls beyond “run” for 40 minutes of every hour the school is occupied. This means that it runs whether heat is called for or not. There were times in May and August when heat was not necessary but the heat pump provided heat anyway. Adding a temperature set point to the incoming air would keep the heat pump from running when it is not required. It is also possible that if the solar recharge system is too large it could be putting more energy into the ground than the heat pump recovers. In this case it may be more efficient to use the solar thermal panels to heat the domestic hot water during the school year.

Conclusions

The hybrid heat pump experiment at Weller Elementary is the first implementation of a GSHP in the FNSBSD. While GSHPs are utilized in schools across the country for energy efficient heating and cooling, a GSHP in a Fairbanks school would operate in heating mode only. Heating-only devices can degrade in performance over time as the ground does not regain enough energy from passive recharge in the summer. For implementing a GSHP in Fairbanks, Alaska, it was unclear if this net cooling effect on the ground would reduce the heat pump efficiency or make heat pump operation impractical. Active solar thermal recharge was studied at the Weller installation as an option to improve performance of heating only systems and to investigate the effectiveness of this approach in a northern climate.

The Weller hybrid heat pump system strongly affects the thermal regime of the ground in the vicinity of the ground loop. During the period where the solar thermal system operated in isolation, a prominent warning trend was observed from the subsurface temperature monitoring network. This trend reversed upon start up of the heat pump, which appeared to be cooling the subsurface to temperatures measured around the ground loop immediately after the ground loop installation (before heat injection or extraction began). The extent to which the heat pump by itself changes the ground temperatures could not be determined in this study due to the nature of the hybrid GSHP system's commissioning. Another heat pump study at CCHRC is currently investigating the long-term efficiency of a GSHP, which includes consideration of the change in ground temperatures over time without active heat injection.

The performance of the hybrid GSHP was slightly less than anticipated based on the manufacturer's specifications. During the 13 months when both the heat pump and solar thermal system operated, the Weller system had a COP of 3.73 and a SCOP of 3.11. According to specifications from the manufacturer, the heat pump should have a COP of 4.28 for an average incoming water temperature of 9.2°C (48.6°F). This can be partially explained by lower entering air temperatures at Weller versus standard test conditions, and may also be partially attributable to experimental uncertainty in measuring air flow downstream of the heat pump.

While solar thermal recharge is effective at raising the ground temperature, which should help maintain higher operating efficiencies, a longer study is necessary to better understand the extent of solar recharge required to maintain the heat pump performance. It is difficult to discern how long solar energy needs to be directed into the ground in order to maintain the current COP. Approximately half of the energy for the heat pump in the winter comes from the solar thermal panels and the rest comes from energy stored in the ground. It is unknown if the heat pump and the solar thermal system will achieve some sort of balance in the soil or if one part of the system will tip the thermal regime of the soil one way or the other.

The Weller system was more expensive than a typical residential system due in part to its experimental focus and the retrofit nature of the installation. Overall cost of the system was approximately $70,000, including the heat pump system, solar thermal system, ground loop, and retrofit piping. Additional analysis of the costs of the heat pump system as part of the school's overall energy costs is recommended to further refine monetary savings estimates.

The hybrid GSHP system at Weller sheds light on the efficiency of heat pumps in cold soils and the potential of solar recharge to improve performance. While the study was unable to compare the efficiency of the system without the solar recharge to the system with solar recharge, the study shows solar thermal recharge can address one concern of the technology in cold climates – that they gradually degrade the temperature of the ground and thereby lower the efficiency. The study highlights further questions of how to best design a hybrid system in order to balance heat extraction and recharge. These include how to size the ground loop, optimal number of solar collectors, and whether to insulate the ground loop.

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