Performance Assessment of Urban Geoexchange Projects in the Greater Toronto Area

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NOTICE

PUBLICATION INFORMATION

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THE SUSTAINABLE TECHNOLOGIES EVALUATION PROGRAM

The Sustainable Technologies Evaluation Program (STEP) is a multi-agency program, led by the Toronto and Region Conservation Authority (TRCA). The program helps to provide the data and analytical tools necessary to support broader implementation of sustainable technologies and practices within a Canadian context. The main program objectives are to:

- monitor and evaluate clean water, air and energy technologies;
- assess barriers and opportunities to implementing technologies;
- develop tools, guidelines and policies, and
- promote broader use of effective technologies through research, education and advocacy.

Technologies evaluated under STEP are not limited to physical products or devices; they may also include preventative measures, alternative urban site designs, and other innovative practices that help create more sustainable and livable communities.

ACKNOWLEDGEMENTS

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We also thank the following organizations and individuals for allowing STEP to study their geoexchange installations and for their help with data collection.

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EXECUTIVE SUMMARY

Geoexchange is an environmentally sustainable alternative to conventional heating and cooling systems that uses the stable temperatures, found below the surface of the ground, to heat and cool a building. Geoexchange systems typically require 30 to 70 percent less energy for heating and 20 to 95 percent less energy for cooling than conventional systems.[1] The Canadian Geoexchange Coalition has predicted that a 16% penetration of Ontario's residential market by geoexchange would result in a savings of 1,485,742 tons of eCO_2, or the equivalent of removing 442,185 cars from the road.[2] In Toronto, heating a single-family residence using a geoexchange system rather than a conventional natural gas furnace can, in many cases, yield annual greenhouse gas emissions reductions comparable to taking an average car off the road for an entire year.[3]

Within the last decade, Canada's geoexchange industry has rapidly expanded. Between 2005 and 2010, annual growth of the industry exceeded 40%, and there are currently over 100,000 geoexchange systems installed in Canada.[4] Despite these successes, geoexchange technology has not yet achieved mainstream status, and widespread adoption continues to be limited by the persistence of several key market barriers, including:

- the cost of electricity compared with natural gas;
- high up-front costs;
- lack of consumer awareness and confidence in geoexchange technology, and
- lack of policymaker and regulator awareness and confidence in geoexchange technology.

To address these barriers, there is a clear need for improved demonstration and documentation of the performance and benefits of geoexchange systems. This study analyzed the performance of several geoexchange projects in the Greater Toronto Area, using data collected over the period of approximately one year. The lessons learned within this study are relevant to a broad audience, including current or prospective system owners, policy-makers, designers, installers and operators. The aims were to:

- evaluate geoexchange system performance to determine whether the systems were performing according to expectations;
- identify areas of improvement for systems that did not meet expectations;

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[1] Natural Resources Canada, 2002. Commercial Earth Energy Systems: A Buyer's Guide. Online document: http://publications.gc.ca/collections/Collection/M92-251-2002E.pdf (Accessed December 12, 2013)

[2] Canadian Geoexchange Coalition, 2010. Comparative Analysis of Greenhouse Gas Emissions of Various Residential Heating Systems in the Canadian Provinces. Online document: http://www.geo-exchange.ca/en/UserAttachments/article63_GES_Final_EN.pdf (Accessed February 11, 2013)

[3] Canadian Geoexchange Coalition, 2010.

[4] Canadian Geoexchange Coalition. 2012. Canadian Geoexchange Heat Pump Industry Technology Roadmap: Final Report. Online document: http://www.geo-exchange.ca/en/UserAttachments/article84_Roadmap_FINAL_E.pdf (Accessed January 14, 2013)

- identify system design attributes or control strategies that lead to exceptionally good performance in systems that exceeded expectations, and
- identify areas where performance monitoring may be improved.

In total, ten geoexchange systems were monitored (Table 1). They ranged in size from small-scale residential systems to large-scale commercial systems. Four of the systems were instrumented by the Sustainable Technology Evaluation Program (STEP). Five systems had an existing building automation system (BAS) or monitoring system collecting performance data, which system owners shared with STEP. On the remaining system, external consultants were hired by the system owner to a produce a monitoring report that was then shared with STEP.

Table 1. Monitored geoexchange installations used this study

Site	Location	Approx. Conditioned Area [ft^2]	Building Type	Geoexchange Rated Heating Capacity [Btu/hr per ft^2]	Loop Orientation	Instrumented By
Peel House A	Mississauga	1,750	Residential	28.6	Vertical (DX)	Existing
Peel House B	Mississauga	5,360	Residential	9.3	Vertical (DX)	Existing
Archetype Sustainable House, TRCA	Vaughan	3,770	Residential	12.1	Vertical & Horizontal	STEP
Greenlife Condominium	Milton	673 – 900 (estimated)	Multi-unit residential	7.1 – 10.6	Vertical	STEP
Earth Rangers Centre	Vaughan	60,000	Office	16.6	Vertical	Existing
Restoration Services Building, TRCA	Vaughan	12,000	Office	15.2	Horizontal	STEP
Downsview Park Office Building	Vaughan	23,000	Office	27.7	Vertical	STEP
Durham College	Oshawa	13,500	Institutional	26.7	Vertical	Existing
Ebenezer Community Hall	Brampton	2,000 (estimated)	Community centre	44.3	Vertical	Existing
Greater Toronto Airport Authority North Fire hall	Toronto	Not determined	Fire hall	16.8 tons heating but square footage not determined	Vertical	External consultant

This study focused on the ground loop side of the geoexchange system wherever possible, with an aim to limit the complexity of the analysis and the extent of the performance monitoring. At least three monitoring points are required to determine the quantity of heat delivered/removed by the system and the system's coefficient of performance (COP). They include:

- the entering and leaving fluid temperatures from the ground loop;
- the fluid flow rate through the ground loop, and
- the electrical power consumption of the heat pump compressor and ground loop circulator pump.

Not all of these monitoring points were available for all sites and, in such cases, a more limited analysis was conducted. Several performance metrics were calculated for each site. These include:

- average heat delivered or removed;
- COP;
- average cycle time;
- percentage of time in-use (PTIU);
- time-of-use electricity consumption;
- time-of-use electricity operating costs, and
- greenhouse gas (GHG) emissions savings compared to conventional heating.

Summary of Findings: Residential

A summary of the findings for residential buildings studied in this report is presented in Table 2. Several observations can be made:

1. Geoexchange systems were determined to be sized appropriately if they were on during most of a typical design heating day. Based on this metric, all systems were appropriately sized. System sizing for the condominium apartments was notably less than Peel House A but comparable to Peel House B when normalizing for square footage. Both of the Peel houses are group homes with multiple occupants so they are likely to have higher internal heat gains than a conventional detached home. Differences in the occupancy and usage profile may partly account for the differences in sizing.
2. The annual energy required by the geoexchange systems to heat and cool the condominium apartments was notably less than that for Peel House A and Peel House B when normalizing for square footage.[5] The energy-efficient Archetype House B geoexchange system consumed a comparable amount of electricity per unit conditioned floor area when compared with the condominium apartments.
3. The performance of Peel House A is notably worse than Peel House B. The primary observed difference between the two sites is that Peel House A has shorter cycle times. The reason for the difference in cycle times is not clear. Both systems appear to be appropriately sized for their loads. There may also be a difference in the occupancy or usage profile.
4. All buildings are heating dominant but where imbalances exist, it is due to more heat being rejected to the ground than is removed.
5. Buildings had an annual GHG savings of approximately 1000 kg eCO_2 per nominal ton heating capacity of the system. In other words, one ton of installed geoexchange system saved one ton of GHG emissions annually. This result is similar to the theoretical GHG savings calculated elsewhere.[6] Since this is a conservative estimate, the actual savings are likely much better.

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[5] Note that Peel House A and B both had back-up systems and this was not considered in the study. It should also be noted that the Greenlife Condominium numbers include the compressor box and distribution-side blower (the unit is water-to-air) but not the ground loop circulator.

[6] Canadian Geoexchange Coalition, 2010.

Table 2. Summary of residential geoexchange system performance metrics

	Peel House A	**Peel House B**	**GLC Unit 1**	**GLC Unit 2**	**GLC Unit 3**	**Archetype House B[7]**
System Sizing						
Building Type	Detached house	Detached house	Condo apt.	Condo apt.	Condo apt.	Semi-detached house
GSHP heating capacity [Btu/hr per ft^2]	28.6	9.3	10.6	7.1	7.1	12.1[8]
GSHP cooling capacity [Btu/hr per ft^2]	27.4	9.0	14.8	10.0	10.0	11.5
PTIU – design heating day	0.70	0.82	0.75	0.87	0.70	N/A
Maximum PTIU – heating month	0.55	0.68	0.55	0.45	0.73	N/A
PTIU – design cooling day	0.90	0.88	0.26	0.40	0.06	N/A
Maximum PTIU – cooling month	0.57	0.68	0.15	0.20	0.06	N/A
Total annual heat delivered [kWh per ft^2]	13.1	4.6	N/A	N/A	N/A	5.0
Total annual heat removed [kWh per ft^2]	9.1	4.0	N/A	N/A	N/A	0.66
Maximum average monthly heating mode cycle time [min]	11	27	13	18	81	N/A
Maximum average monthly cooling mode cycle time [min]	20	41	16	13	43	N/A
System Efficiency[9]						
Annual heating mode COP	2.8	3.5	N/A	N/A	N/A	3.110
Annual cooling mode EER	10.9	13	N/A	N/A	N/A	19.7
Ground Loop Sizing						
Loop orientation	Vertical	Vertical	Vertical	Vertical	Vertical	Horizontal & Vertical
Borehole length or horizontal loop length [ft per MBtu/hr rated heating capacity]	8	8	N/A	N/A	N/A	11.0 (Vertical)
Lowest average heating mode EST [ºC]	N/A	N/A	9	9	9	N/A
Highest average cooling mode EST [ºC]	N/A	N/A	18	18	18	N/A
Imbalance [kWh per ft borehole length]	15	12.5	N/A	N/A	N/A	N/A
System Electrical Energy Consumption[11]						
Total annual heating [kWh per ft^2]	4.8	1.3	N/A	N/A	N/A	1.6
Total annual cooling [kWh per ft^2]	2.9	1.1	N/A	N/A	N/A	0.1
Total annual [kWh per ft^2]	7.7	2.4	1.5	0.7	1.6	1.7
Emissions Savings						
Annual GHG savings [kg eCO_2 per rated heating ton]	990	1100	N/A	N/A	N/A	920

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[7] Safa, A., 2012. Performance analysis of a two-stage variable capacity air source heat pump and a horizontal loop coupled ground source heat pump. Master of Applied Science Thesis, Ryerson University.

[8] Net floor area in (Safa, A., 2012) is listed as 350 m^2 (3770 ft^2). This includes the basement.

[9] Includes the compressor box and ground loop circulator power consumption.

[10] See Table 22, pg. 100, in (Safa, A., 2012). Includes ground loop circulator and compressor unit.

[11] Includes the compressor box and ground loop circulator power consumption.

Summary of Findings: Non-Residential

A summary of the findings for non-residential buildings is given in Table 3. Several observations can be made:

1. The Downsview Park Office Building geoexchange system seems to be oversized. It has twice the capacity per square foot than the other two office buildings evaluated in this project. It is only operating approximately 50% of the time during approximate design heating days and cooling days. The reason for its oversizing is at least partly evident from the geoexchange electrical energy consumption per square foot. It likely has a much larger load per square footage because the geoexchange system is consuming two times more electricity per square foot than the other office buildings, both of which are built to LEED platinum standards.
2. The Earth Rangers site studied in this report demonstrated that free-exchange operation can **increase monthly cooling mode COPs by between 2 to 3 times compared with conventional heat pump operation.** Free exchange involves using the ground loop to directly cool a building without the use of a heat pump. This is especially relevant as air-source heat pumps gain in popularity because air-source heat pumps are not able to operate in free-exchange mode and therefore they are not capable of these exceptionally high cooling COPs. Free-exchange worked well in this application because the ground loop temperatures were exceptionally cool and the radiant-slab distribution system had a very large heat exchange surface area, allowing warmer fluid temperatures to be used for cooling. Further studies would be required to determine the effectiveness of free-exchange for other applications.
3. The constant flow operation of the circulator pumps at the Restoration Service Building **decreased the monthly COP by as much as 80% and increased annual operating costs by 50%**. The Earth Rangers Centre, Downsview Park Office Building and Durham College also showed evidence of suboptimal circulator pump operation.
4. The time-of-use energy consumption profiles of these sites suggest that there is the potential to shift the peak and mid-peak loads to an off-peak time-of-use bracket for an **electricity cost savings of between 20 and 25%.** This might involve the use of larger ground loops, greater thermal storage, predictive heat pump control and potentially other advanced design attributes.
5. Durham College appeared highly imbalanced with 6 times more heat rejected to the ground than removed. However, when the imbalance is normalized, the kWh imbalance per ft borehole length does not seem large compared with the imbalances seen in residential systems examined in this study. This is because it has about 3 times more borehole length per unit geoexchange system capacity when compared with other systems. The reason for this sizing is not clear.
6. Based on the criteria presented in Section 3.2.3, **there was no evidence to suggest that any of the ground loops were undersized. If anything, they tended towards optimized performance as opposed to optimized cost.**
7. **Short cycling was only observed in cooling mode at the Restoration Services Building.** This is because the system is sized to meet the heating load and is oversized for the cooling load. It is worth noting that other buildings had variable capacity or two-stage heat pumps while this building did not.

Table 3. Summary of findings for non-residential buildings in this study

	Earth Rangers Centre	**Downsview Park Office Building**	**Restoration Services Building**	**Ebenezer Community Hall**	**Durham College**	**GTAA North Fire hall[12]**
System Sizing						
Building Type	Office	Office	Office	Community Hall	College	Fire hall
GSHP heating capacity [Btu/hr per ft^2]	16.6	27.7	15.2	44.3	26.7	202[13] MBtu/hr
GSHP cooling capacity [Btu/hr per ft^2]	N/A	35.1	15.3	50.8	N/A	202 MBtu/hr
PTIU – design heating day	N/A	0.99/0.02	88	N/A	N/A	N/A
Maximum PTIU – heating month	94	0.93/0.16	68	N/A	N/A	N/A
PTIU – design cooling day	N/A	0.53/0.56	36	N/A	N/A	N/A
Maximum PTIU – cooling month	42	0.39/0.31	16	47/31	N/A	N/A
Total annual heat delivered [kWh per ft^2]	3.9	N/A	N/A	N/A	N/A	N/A
Total annual heat removed [kWh per ft^2]	1.7	N/A	N/A	N/A	N/A	N/A
Maximum average monthly heating mode cycle time [min]	8460	160/25	55	N/A	N/A	N/A
Maximum average monthly cooling mode cycle time [min]	3060	168/95	14	41/21	N/A	N/A
System Efficiency						
Annual Heating mode COP	2.4	N/A	3.5[14]	N/A	N/A	2.6[15]
Annual Cooling mode EER	28	N/A	14.1	N/A	N/A	15.0
Ground Loop Sizing						
Loop orientation	Vertical	Vertical	Horizontal	Vertical	Vertical	Vertical
Borehole length [ft per MBtu/hr rated heating capacity]	17.7	12	N/A	13.5	53.3	N/A
Lowest average heating mode EST [°C]	6	9	1	5	12	N/A
Highest average cooling mode EST [°C]	13	20	20	22	17	N/A
Imbalance [kWh per ft borehole length]	-1.6	N/A	N/A	N/A	9.9	N/A
System Electrical Energy Consumption						
Total annual heating [kWh per ft^2]	1.6	N/A	2.8	N/A	N/A	N/A
Total annual cooling [kWh per ft^2]	0.2	N/A	0.3	N/A	N/A	N/A
Total annual [kWh per ft^2]	1.8	5.2	3.1	N/A	N/A	N/A
Emissions Savings						
Annual GHG savings [kg eCO$_2$ per rated heating ton]	0.5	N/A	N/A	N/A	N/A	N/A

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[12] AMEC, 2013. Greater Toronto Airports Authority North Fire Hall Ground Source Heat Pump Performance Monitoring Final Report. AMEC Project # TR1713018.

[13] Square footage not determined.

[14] This is not a seasonal average. It is artificially high because it is taken from one month of operation at the beginning of the heating season.

[15] The low heating mode COP may have been at least partly due to the incorrectly sized air-handler heat exchangers used in this building.

Recommendations: Performance

1. **Circulator pumps should be interlocked to the heat pumps unless there is a compelling reason to do otherwise.** The performance degradation associated with non-interlocked circulator pumps was quantified in two cases. Interlocking needs to be considered by geoexchange system designers, building automation control technicians and system installers. Ideally, checking that pumps are appropriately interlocked would be a part of a standardized commissioning procedure but this does not appear to be currently available.
2. Short cycling times, on the scale of 10 minutes, was associated with poor performance in at least one installation. **Effort should be taken by system designers and installers to avoid short cycle times where possible.** This could involve making adjustments to aquastat or thermostat settings, incorporating an appropriately-sized buffer tank or, in installations with multiple heat pumps, temporarily taking units offline during periods of low-load.
3. In systems with multiple heat pumps, it might be advisable to **develop controls that allow each heat pump do an even amount of work**. This would help to ensure a longer life for the system as a whole by not subjecting any one heat pump to more wear than others in the installation.
4. **Architects and geoexchange system designers should be aware of the ultra-efficient cooling mode operation that free-exchange provides**. Further research into free-exchange is warranted to determine at which applications/sites it is most suitable. A financial evaluation is also recommended as the payback may be notably affected if the system is capable of annual cooling mode EERs that surpass 28.0.
5. **TOU control of geoexchange systems should be further researched and developed.** This has the potential to reduce electricity fuel costs by between 20 and 25% (not including regulatory and distribution charges). It also would provide benefits to utilities in the form of peak-shaving. Future incentive schemes might consider the incorporation of TOU control to some degree because of these multiple benefits.
6. Tables 2 and 3 above offer experimental operational data that may be useful for modeling, sizing guideline development and benchmarking exercises.
7. The development of a standardized commissioning template may be useful to prevent the occurrences of short cycle times, un-interlocked circulator pumps and other issues that might potentially degrade performance.

Recommendations: Performance Monitoring

1. **If a BAS is to be used for performance monitoring then extra effort needs to be taken to configure it properly for this purpose.** Several geoexchange systems studied in this project were controlled and monitored by a BAS, however, the data obtained from this level of monitoring was often either incomplete for a performance analysis or not sufficiently accurate.
2. **Matched pair temperature sensors are necessary for accurate performance results but they are not necessarily standard on all energy meters**. A simple error analysis (Appendix B) would show that the greatest source of error when calculating the COP is the measurement which

determines the difference between the entering and leaving source (or load) temperatures of the heat pump. The difference is often small and it is difficult to determine with any level of accuracy unless matched pair temperature sensors are used.

3. Flow measurements may be difficult to obtain after the fact. **It is easier and more cost effective to install a flow monitoring apparatus while the geoexchange system is being installed**.
4. **Surface mounting temperature sensors is permissible but the sensors must be firmly attached to the pipe and sufficiently insulated.**
5. **Develop a monitoring plan with objectives clearly defined.** This is further discussed in Appendix A. To ensure the monitoring system will achieve the desired goals it is useful to clearly document those goals and develop/document a monitoring plan capable of achieving it.
6. **Assign a staff person to periodically inspect the data to ensure the monitoring system is functioning as intended, otherwise data may be lost.**
7. **Commission the monitoring system and document the commissioning for future use and knowledge transfer.** Errors are more likely to be caught early on if the monitoring system installation is followed by a commissioning procedure.
8. **It is important to check that the data are consistent and reasonable.** There are several methods of doing this discussed in Appendix A.

GLOSSARY OF TERMS

Term	Definition
BAS	Stands for “building automation system.”
borehole length	The depth of the boreholes multiplied by the number of boreholes yields a total "borehole length."
BOS	Stands for “balance of system.”
capacity	Capacity is the quantity of heat that the geoexchange system is delivering or removing given in units of power (energy per unit time).
COP	The coefficient of performance quantifies the efficiency of a heat pump. It is a unitless ratio of the heat delivered (or removed) over the electrical energy consumed.
dT	The difference between entering and leaving temperatures on either the source or load side of the heat pump.
DX	Stands for "direct exchange" and describes a ground loop through which a refrigerant is circulated rather than standard heat transfer fluid such as glycol.
EER	The "energy efficiency ratio" is normally used to quantify cooling mode efficiency. It is the cooling mode COP multiplied 3.41 to yield units of Btu/hr per W.
ELT	The entering fluid temperature on the load side of the heat pump.
EST	The entering fluid temperature on the source side of the heat pump.
GSHP	Stands for "ground source heat pump."
LLT	The leaving fluid temperature on the load side of the heat pump.
LST	The leaving fluid temperature on the source side of the heat pump.
PTIU	Stands for "percentage time in-use." The percentage of time in a given interval that the heat pump is on.
TOU	Stands for “time of-use.”

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1.0 BACKGROUND

1.1 Geoexchange in Canada

In Canada, vast amounts of energy are used every year to maintain comfortable temperatures in the buildings where we live, work, and play. Between 1990 and 2010, 50% of the total energy consumed in the commercial and institutional sectors was devoted to space heating and cooling.[16] In the province of Ontario, 73% of commercial and institutional buildings are heated using natural gas and 20% using electricity.[17,18] Remaining buildings rely on other fuels such as heating oil, propane, and wood. Electricity is the predominant source of energy for space cooling, serving 83% of commercial and institutional buildings.[19]

Geoexchange systems are a sustainable space heating and cooling alternative that is gaining broader adoption across many sectors. A geoexchange system keeps a building warm in winter by using heat energy extracted from the ground. The process is reversed in summer when a building is kept cool by rejecting heat energy back into the ground. Heat transfer with the ground is made possible by a fluid circulating though buried pipes, referred to as a ground loop.[20] A geoexchange system is conventionally powered by electricity but since it moves heat energy rather than generating it, it is able to deliver more than three units of heat energy for every unit of electrical energy consumed.

Geoexchange systems typically require 30 to 70 percent less energy for heating and 20 to 95 percent less energy for cooling than conventional systems.[21] The Canadian Geoexchange Coalition has predicted that a 16% penetration of Ontario's residential market by geoexchange would result in a savings of 1,485,742 tons of eCO_2, or the equivalent of removing 442,185 cars from the road.[22] In Toronto, heating a single-family residence using a geoexchange system rather than a conventional natural gas furnace can, in many cases, yield annual greenhouse gas emissions reductions comparable to taking an average car off the road for an entire year.[23]

Within the last decade, Canada's geoexchange industry has rapidly expanded. Between 2005 and 2010, annual growth of the industry exceeded 40% due mainly to the federal ecoENERGY Retrofit program, financial assistance from provincial governments and utilities, as well as the development of a national

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[16] Natural Resources Canada. 2013. Energy Efficiency Trends in Canada 1990 to 2010, Chapter 4. Online document: http://oee.nrcan.gc.ca/publications/statistics/trends12/trends2010chapter4.pdf (Accessed March 4, 2014)

[17] In the Province of Ontario, the principal sources of electricity are nuclear, hydroelectricity, and natural gas.

[18] Natural Resources Canada. 2008. Commercial & Institutional Consumption of Energy Survey. Summary Report. Online document: http://oee.nrcan.gc.ca/publications/statistics/cices08/pdf/cices08.pdf (Accessed April 22, 2014)

[19] Natural Resources Canada, 2008.

[20] There also exists "water loops" and "ground water loops" that serve the same purpose but are not of relevance for this report.

[21] Natural Resources Canada, 2002.

[22] Canadian Geoexchange Coalition. 2010.

[23] Canadian Geoexchange Coalition. 2010. Note: Average car emissions in Canada cited to be 3,360 eq. CO_2/year within report.

training, accreditation, and certification program by the Canadian Geoexchange Coalition.[24] As of 2012, there were over 100,000 geoexchange systems installed in Canada.[25]

Despite these successes, geoexchange technology has not yet achieved mainstream status. Widespread adoption continues to be limited by the persistence of several key market barriers, including:

- the cost of electricity compared with natural gas;
- high up-front costs;
- lack of consumer awareness and confidence in geoexchange technology, and
- lack of policymaker and regulator awareness and confidence in geoexchange technology.

To address these barriers, there is a clear need for improved demonstration and documentation of the performance and benefits of geoexchange systems. Towards this end, this study documents the results from performance monitoring of several urban geoexchange systems in the Greater Toronto Area that range in size from small-scale residential systems to large commercial systems.

1.2 Geoexchange Systems

A geoexchange system is composed of three parts: (i) a ground loop, (ii) a heat pump and (iii) a distribution system. In heating mode, fluid flows through the ground loop and absorbs heat energy from the ground. The heat pump uses that heat energy to create a warmer fluid that is suitable for space heating and the distribution system distributes the heat energy throughout the building. In cooling mode this process is reversed, with the distribution system absorbing the building’s heat energy and the ground loop rejecting it back to the ground.

1.2.1 Ground loop

There are many ways to classify the ground loop. It can be open or closed, vertical or horizontal, direct exchange or conventional. An open ground loop sucks up water from one location in some volume water, like a lake, well or underground reservoir, and deposits it in another, while a closed loop constantly circulates the same volume of fluid, with heat exchange occurring through the surface area of the ground loop piping. Closed loops are much more common in Canada.

A vertical loop extends into the earth to depths that may approach several hundred feet while a horizontal loop extends over a large surface area at relatively shallow depth, on the scale of several feet. Vertical loops are more expensive to implement because they require specialized equipment but they can be sized to be physically smaller than a comparable horizontal loop because of the more stable ground temperatures available at greater depth. Vertical loops are often the only option in space-constrained urban settings and have the potential to perform better because of the more ideal ground temperatures available at greater depths. Figure 1.1 illustrates a horizontal and vertical ground loop.

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[24] Canadian Geoexchange Coalition. 2012.

[25] Canadian Geoexchange Coalition, 2012.

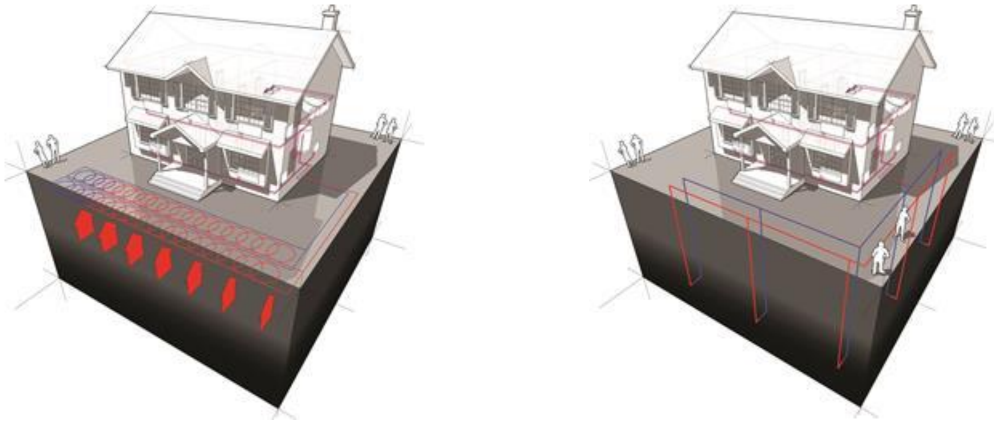

Figure 1.1: (Left) A slinky-style horizontal ground loop extends over a large surface area several feet below the ground. (Right) A vertical ground loop is composed of boreholes extending up to several hundred feet into the ground.

A conventional ground loop circulates glycol, or a similar antifreeze solution, through a closed loop that is interfaced with the heat pump's refrigeration cycle via a heat exchanger. In contrast, with a direct-exchange ground loop, the refrigerant flows through the ground loop and the loop itself acts as the refrigeration cycle's evaporator or condenser depending on whether it is in heating or cooling mode.

1.2.2 Ground Source Heat Pump

The core technology of a ground source heat pump (GSHP) is a reversible vapor-compression cycle. It is the same basic technology as a refrigerator or air conditioner except that it can "pump" heat in either direction depending on whether space heating or space cooling is required. One important attribute of a heat pump is that it can make heat flow from a cooler object to warmer object, the opposite of what might be expected. In this way, it can use the heat energy from the relatively cool ground to heat a building at room temperature. There are "water-to-water" GSHPs that heat and cool water and "water-to-air" GSHPs that heat and cool air. Larger commercial systems may use a water-cooled chiller in their geoexchange installation. A chiller serves the same function as a heat pump except that it is not reversible. However, this functionality can be regained through the use of external valves.

A simplified water-to-water geoexchange system is illustrated in Figure 1.2:

1. a hot refrigerant gas is discharged from the compressor;
2. the gas gives up its energy at the condenser and condenses into a liquid;
3. an expansion valve restricts refrigerant flow and drops the pressure, rapidly cooling the refrigerant;
4. the cool liquid refrigerant gains energy at the evaporator and evaporates in the process;
5. the cool low-pressure refrigerant gas enters the compressor, increases in pressure and temperature, and is discharged out the compressor at 1;

6. the ground loop circulator circulates a glycol solution through the ground loop and it enters the compressor box;
7. the glycol solution gives up its energy at the evaporator and exits the compressor box;
8. the ground warms the glycol solution up again;
9. warm water returns from the building's distribution system, and
10. the water gains the heat energy given up by the refrigerant in 2 and is recirculated through the distribution system.

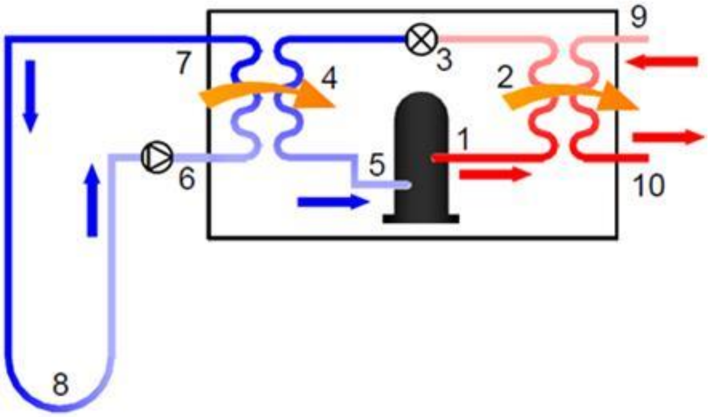

Figure 1.2: Schematic representation of a water-to-water geoexchange system that uses a conventional heat transfer fluid in the ground loop (i.e. it is not DX). The heat pump compressor box also has a reversing valve (not shown) that allows it to "pump" heat energy in the other direction so that it can also operate in cooling mode.

1.2.3 Distribution System

Two common ways to distribute heat throughout a building are radiant in-floor/slab and forced-air. Radiant in-floor/slab heating is accomplished by circulating the hot supply water coming from the heat pump through a network of piping inside the floor or through an equivalently large thermal mass within the building. Heat is slowly transferred from the water to the slab and then from the slab to the conditioned area of the building.

Forced-air heating uses a blower to force air across a heating coil. A hot fluid flows through the coil and transfers its heat energy to the air. The heated air is transported through the building via a network of air ducts. A hydronic coil has water flowing through it while a direct-exchange (DX) coil has refrigerant flowing through it. Cooling is typically accomplished using forced-air because of condensation issues that arise with radiant cooling but this can be avoided with appropriate dew point control.

Another common component of some geoexchange systems is a buffer tank. The buffer tank is typically heated or cooled by the heat pump directly. The piping for forced-air or radiant slab heating or cooling then uses the buffer tank, rather than a direct connection to the heat pump, to heat or cool the building.

Distribution systems can be simple or complex. The complexity varies with the size of the building, the type of building and the number of HVAC components in the system.

2.0 STUDY OBJECTIVES

This study analyzes the performance of several geoexchange projects in the Greater Toronto Area, using data collected over the period of one year, with an aim to:

- evaluate geoexchange system performance to determine whether the systems were performing according to expectations;
- identify areas of improvement for systems that did not meet expectations;
- identify system design attributes or control strategies that lead to exceptionally good performance in systems that exceeded expectations, and
- identify areas where performance monitoring may be improved.

The lessons learned within this study are useful to a broad audience, including current or prospective system owners, policy makers, designers, installers and operators.

3.0 STUDY APPROACH

3.1 Study Sites

In total, ten geoexchange systems were studied. Shown in Table 3.1, they ranged in size from small-scale residential systems to large-scale commercial systems. Four of the systems were instrumented by STEP. Five of the systems had an existing building automation system (BAS) or monitoring system collecting performance data, which the system owners shared with STEP. Performance monitoring from the remaining system was completed by an external consultant and shared with STEP. It is included here for the sake of completeness.

Table 3.1: Monitored geoexchange installations used this study

Site	Location	Approx. Conditioned Area [ft^2]	Building Type	Geoexchange Rated Heating Capacity [Btu/hr per ft^2]	Loop Orientation	Instrumented By
Peel House A	Mississauga	1,750	Residential	28.6	Vertical (DX)	Existing
Peel House B	Mississauga	5,360	Residential	20	Vertical (DX)	Existing
Archetype Sustainable House, TRCA	Vaughan	3,770	Residential	14	Vertical & Horizontal	STEP
Greenlife Condominium	Milton	673 – 900 (estimated)	Multi-unit residential	7.1 – 10.6	Vertical	STEP
Earth Rangers Centre	Vaughan	60,000	Office	16.6	Vertical	Existing
Restoration Services Building, TRCA	Vaughan	12,000	Office	15.2	Horizontal	STEP
Downsview Park Office Building	Vaughan	23,000	Office	48.6	Vertical	STEP
Durham College	Oshawa	13,500	Institutional	26.7	Vertical	Existing
Ebenezer Community Hall	Brampton	2,000 (estimated)	Community hall	44.3	Vertical	Existing
Greater Toronto Airport Authority North Fire hall	Toronto	Not determined	Fire hall	16.8 tons heating but square footage not determined	Vertical	External consultant

This study focused on the ground loop side of the geoexchange system wherever possible with an aim to limit the complexity of the analysis and the extent of the performance monitoring. At least three monitoring points were required to determine the quantity of heat delivered/removed by the system and the system's coefficient of performance (COP). They include:

- the entering and leaving fluid temperatures from the ground loop;
- the fluid flow rate through the ground loop, and
- the electrical power consumption of the heat pump compressor and ground loop circulator pump.

Not all of these monitoring points were available for all sites and, in such cases, a more limited analysis was conducted. Several performance metrics were calculated for each site. These include:

- average monthly heat delivered or removed;
- COP;
- average cycle time;
- percentage of time in-use (PTIU);
- time-of-use (TOU) electricity consumption;
- TOU electricity operating costs, and
- greenhouse gas (GHG) emissions savings compared to conventional systems.

3.2 Geoexchange System Performance Metrics

3.2.1 Capacity

The quantity of heat energy that a geoexchange system delivers or removes from a building per unit time is called the capacity. It is typically given in units of Btu/hr (or MBtu/hr)[26] but could also be given in units kW. Also, it is common to talk of heat pump capacity in terms of "tons," a unit that is equivalent to 12,000 Btu/hr.

In heating mode, the instantaneous capacity can be calculated using the entering and leaving source temperatures (EST and LST),[27] the fluid flow rate through the ground loop and the compressor power consumption. The EST and LST are labeled on the schematic in Figure 3.1. The heating mode and cooling mode capacities are calculated using Equation 3.1 and 3.2. The heating mode capacity is equal to the ground loop fluid density (ρ_G) multiplied by the ground loop fluid flow rate (Q_G), specific heat capacity (C_p) and temperature difference between EST and LST, all added to the compressor power draw (P_{Comp}). The cooling mode capacity is similarly calculated except that the compressor power draw is subtracted rather than added. The compressor power term is necessary because the compressor does work on the

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[26] In HVAC terminology, "Btuh" or "MBtuh" is intended to mean Btu/hr or MBtu/hr. Also, the prefix "M" is intended to mean thousands in the same way "k" is normally used (ie. 1 km is 1000 m). In this report, "Btu/hr" is used instead of Btuh and "MBtu/hr" is used to denote 1000 Btu/hr.

[27] This convention is different than that used in the ASHRAE geoexchange design document that is referenced throughout this report (Kavanaugh, S. and Rafferty, K., 2014). In that document, "ELT" is intended to mean entering liquid temperature on the source side of the heat pump and "LLT" is intended to mean leaving liquid temperature on the source side of the heat pump. That convention is used because that document is concerned mainly with air-to-water heat pumps where there is less need to specify leaving and entering temperatures on the load side of the heat pump.

refrigerant, ultimately causing it to gain heat energy. In heating mode that heat energy contributes to heating the building but in cooling mode it is just waste energy that is rejected to the ground loop.

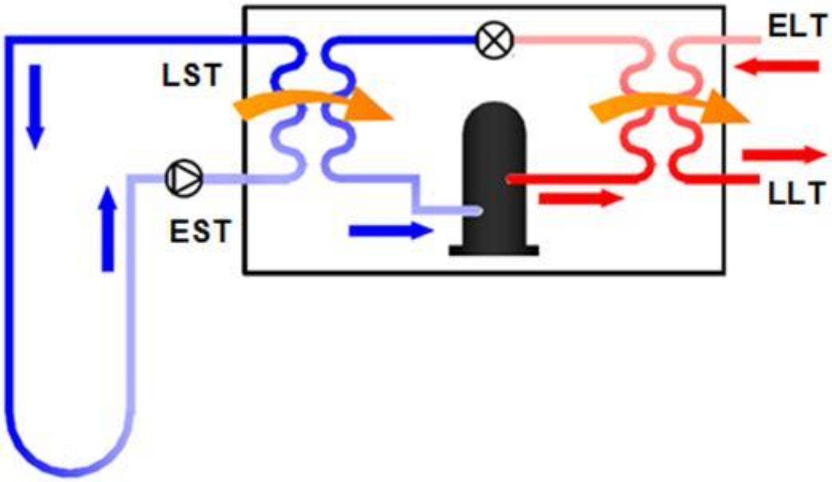

Figure 3.1: Entering/leaving source/load temperatures are shown schematically

$$Cap_H = \rho_G Q_G C_G (EST - LST) + P_{Comp} \tag{3.1}$$

$$Cap_C = \rho_G Q_G C_G (LST - EST) - P_{Comp} \tag{3.2}$$

It is also possible to measure the heat delivered to or removed from that building directly by using the entering load temperature (ELT), leaving load temperature (LLT) and distribution system flow rate, using Equations 3.3 and 3.4. Note that the subscript “D” is meant to represent “distribution.” The benefit of measuring on the ground loop side rather than the distribution side is that the ground loop temperature measurements contain useful information about the ground loop performance. However, it should be noted that with DX ground loops it often makes sense to measure on the distribution side because of the difficulties associated with instrumenting and analyzing a refrigerant circuit that is changing phase. If possible, it is beneficial to measure on both sides of the heat pump to ensure that the results are correct and the energy balances between source and load.

$$Cap_H = \rho_D Q_D C_D (LLT - ELT) \tag{3.3}$$

$$Cap_C = \rho_D Q_D C_D (ELT - LLT) \tag{3.4}$$

If the following is assumed:

1. a specific heat of water of 4.186 kJ / (kg ^{o}C);
2. a density of water of 1000 kg / m^3;
3. a specific heat of 20% propylene glycol of 4.018 kJ / (kg ^{o}C);
4. a density of 20% propylene glycol of 1017 kg /m^3;

5. the ground loop contains 20% propylene glycol, and
6. the distribution system contains water.

Then, Equations 3.1 to 3.4 simplify to Equations 3.5 to 3.8 where temperatures are expressed in units of [^{0}C], "GPM" is the flow rate in units [GPM] and power is in units of [kW]. Capacity is expressed in units [kW].

$$Cap_H = GPM \cdot 0.258 \cdot (EST - LST) + P_{Comp} \tag{3.5}$$

$$Cap_C = GPM \cdot 0.258 \cdot (LST - EST) - P_{Comp} \tag{3.6}$$

$$Cap_H = GPM \cdot 0.264 \cdot (LLT - ELT) \tag{3.7}$$

$$Cap_C = GPM \cdot 0.264 \cdot (ELT - LLT) \tag{3.8}$$

The total heat delivered to or removed a building over a period of time can be expressed in units Btu or kWh. It is the sum of the instantaneous capacities determined from monitoring multiplied by the monitoring timescale. For example, if the monitoring interval (Δt) is one hour and the instantaneous heating capacity for the given interval is 5 kW then the total heat delivered is 5 kWh. The total heat delivered over a greater period of time is then just the sum of the heat delivered in each of the smaller intervals.

$$Heat\ Energy\ Delivered = \sum^{Total\ Time} Cap_H \cdot \Delta t \tag{3.9}$$

$$Heat\ Energy\ Removed = \sum^{Total\ Time} Cap_C \cdot \Delta t \tag{3.10}$$

3.2.2 COP and EER

The primary metric for heat pump performance is the coefficient of performance (COP). It is a unitless ratio, shown in Equation 3.11, of the heat energy delivered or removed by the geoexchange system divided by the electricity energy consumed.

$$COP = \frac{Heat\ Energy\ Delivered\ or\ Removed\ [kWh]}{Electrical\ Energy\ Consumed\ [kWh]} \tag{3.11}$$

Cooling is often expressed as an energy efficiency ratio (EER) rather than a COP (Equation 3.12).

$$EER = \frac{Heat\ Energy\ Removed\ [MBtu]}{Electrical\ Energy\ Consumed\ [kWh]} \tag{3.12}$$

COP and EER values on a manufacturer specification sheet have a very specific meaning. This is laid out in the following standards: AHSRAE/ANSI/AHRI/ISO 13256-2 for water-to-water heat pumps, AHSRAE/ANSI/AHRI/ISO 13256-1 for water-to- air heat pumps and ANSI/AHRI 870 for direct-exchange heat pumps. [28] However, informally, COP and EER are often used to denote the experimentally-determined as-installed performance of geoexchange systems as is the case with this report. Important considerations, relevant to this report are given below (this list is not exhaustive):

- In AHSRAE/ANSI/AHRI/ISO 13256-2, the EST/ELT for heating mode and cooling mode testing is 0°C/40°C and 25°C/12°C, respectively. Heat pump performance depends heavily on the EST and ELT and actual operational conditions will vary. However, the temperatures used in AHSRAE/ANSI/AHRI/ISO 13256-2 are somewhat conservative. In many cases, the actual operational temperatures would be better for performance.
- AHSRAE/ANSI/AHRI/ISO 13256-2 considers the electrical power consumed by the compressor unit and a correction factor is calculated for the pump power required to overcome the resistance of the outdoor-side heat exchanger. Pumping power for ground loops or distribution systems is not included. Nor is there any consideration for power consumption of air handlers.
- None of the standards account for losses that may result from frequent compressor cycling. There may be limited information regarding the extent to which these cycling losses affect overall performance.
- ANSI/AHRI 870 rating calculations apply a correction factor to take into account air handler power consumption. Installations may not actually incorporate an air handler. This would cause the standardized COP/EER to be lower than an experimental COP/EER calculation that only included the compressor unit power consumption.
- In large installations, a chiller with a water-cooled condenser is sometimes used in the place of heat pump. It will function in a similar way but it is not rated according to COP and EER in the same way as with a heat pump.

In order to compare both DX and conventional systems, the experimental COPs and EERs are calculated in this report to include the ground loop circulator and compressor box but not the distribution system. Where appropriate, these values have also been calculated without including ground loop circulators.

3.2.3 Average Entering Source Temperature

The entering source temperature is useful to some extent when analyzing the ground loop sizing. Ground loop sizing guidelines are available here.[29] The basis of ground loop design optimization calculations is the steady-state heat transfer equation shown in Equation 3.13 (note that this is a simplified version of the design equations used for illustrative purposes). In this equation, L_{bore} is the borehole length, q is the heat transfer rate, R_{ov} is the thermal resistance of the borehole, t_g is the

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[28] Note that standardized performance testing is not compulsory. Specification sheets will indicate if a given heat pump has undergone standardized third-party testing.

[29] Kavanaugh, S. and Rafferty, K., 2014. Geothermal Heating and Cooling: Design of Ground-Source Heat Pump Systems. ASHRAE Document, 2014.

undisturbed ground temperature and t_w is average temperature in the ground loop liquid when the heat pump is operating. R_{ov}, q and t_g are all constants that are dictated by the constraints of the building and the ground. In the design process, a value of t_w is chosen and the required borehole length is calculated. Implicit in this equation is that t_w is colder than t_g in heating mode and higher than t_w in cooling mode.

$$L_{bore} = \frac{q \times R_{ov}}{(t_g - t_w)} \tag{3.13}$$

The value of t_w must be optimized to take into account both cost and performance. This is because the heat pump COP is strongly affected by the difference in source and load temperatures, termed the "lift." A warmer source temperature in heating mode will result in a lower lift and a better COP. Similarly, a cooler source temperature in cooling mode will lead to lower lift and a better COP. However, in both cases, a longer borehole length is needed to achieve a lower lift and this will increase cost.

Best practice design documents state that the optimal balance point between cost and performance occurs when the ground loop is sized such that the heating mode EST is 5 to 8 ^{o}C below t_g and the cooling mode EST is 11 to 17 ^{o}C above t_g.[30] Since t_g is a constant, it follows that the difference between the steady-state heating mode design EST and the steady-state cooling mode design EST is expected to be between 16 ^{o}C to 25 ^{o}C if the system has been optimally designed for cost and efficiency. If the difference is lower, then the balance is towards better performance and if higher, towards lower cost. In this report, the annual fluctuation in average entering source temperature will be evaluated against this guideline in order to gain insight into the ground loop sizing. It should be noted that this method is imprecise, in part because t_w is a steady-state value and, as section 3.2.4 will show, steady-state may not be quickly realized relative to the cycle time of the system. This approach should therefore be considered as a "ball-park" check on ground-loop sizing rather than a definitive analysis.

3.2.4 Cycle Time

The amount of time that a heat pump spends in an on state is termed here as a "cycle." A single-stage heat pump is generally expected to perform better if it is operated with longer less-frequent cycles as opposed to shorter more frequent cycles. This is because there are losses associated with starting the compressor. The average cycle time for any period of time is shown in Equation 3.14. It is the total time that the heat pump is on during that time period divided by the total number of cycles in that time period. Short cycle times also increase the wear on the heat pump components. Variable capacity heat pumps are likely to operate with longer cycle times than single-stage "on/off" heat pumps. Short cycle times may indicate that the heat pump is oversized for the load or that the system is not operating with optimal thermostat or aquastat settings.

$$Average\ Cycle\ Time = \frac{Total\ Time\ Heat\ Pump\ is\ On}{Total\ Number\ of\ Cycles} \tag{3.14}$$

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[30] Kavanaugh, S. and Rafferty, K., 2014.

It is interesting to note that longer cycle times may be associated with performance degradation in those cases where the heat transfer between the GSHP and ground loop fluid is larger in magnitude than that between the ground loop fluid and the ground. Figure 3.2 shows average temperatures during a cooling mode cycle at the TRCA's Archetype House B. This site has both a vertical and horizontal ground loop for testing purposes but that is unimportant here. Note that the vertical loop EST increases as the cycle continues. This indicates that ground loop fluid has a net heat gain. An increasing EST in cooling mode will result in a decreasing COP. It follows that this system likely has an optimum cycle time that is neither too long nor too short. Equation 3.13 assumes steady-state operation but it is clear from this example that steady-state begins to appear near the end of the cycle. Unfortunately, for now this is just an interesting aside as this phenomenon has not yet been sufficiently explored to determine if any of the sites in this study operate with cycle times that are prohibitively long.

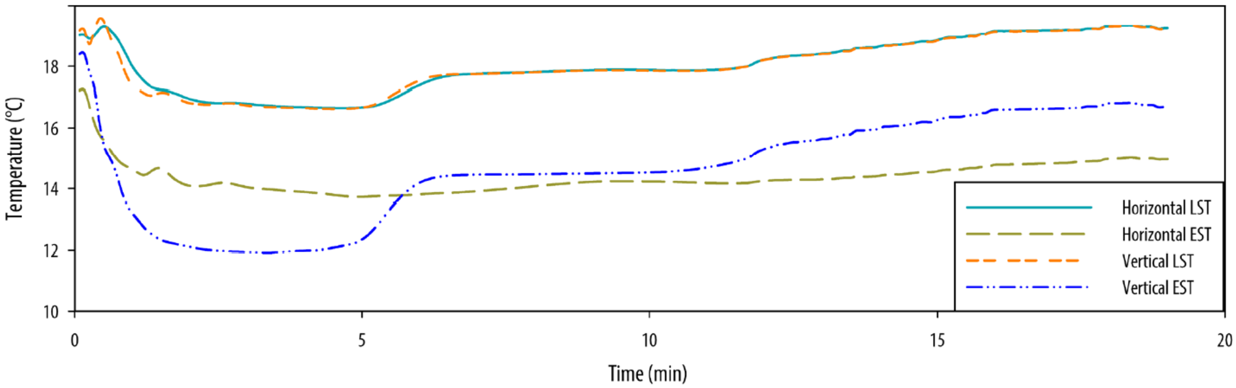

Figure 3.2: Geoexchange entering and leaving source temperature during an average cooling mode cycle at the Archetype House B

Best practice design guidelines[31] do not address performance degradation due to short cycling and there appears to be no definitive answer as to what the minimum cycle time ought to be. From the perspective of performance, it is clear from Figure 3.2 that, at minimum, the cycle time should likely be longer than a few minutes because it takes that much time for the system to reach full capacity. However, the heat pump is not operating at maximum efficiency during those first few minutes and ideally, the total cycle time is much longer so that initial period of poor performance does not notably affect the overall COP of the cycle. Qualitatively, it would seem that 10 minutes may still be considered short while approaching or exceeding 20 minutes may be more ideal. Unfortunately, a greater degree of precision would require further work that is beyond the scope of this study.

3.2.5 Balancing of heating and cooling loads

In heating mode, the geoexchange system removes heat from the ground and in cooling mode, the system rejects heat to the ground. Ideally, the quantity of heat removed equals that rejected and the ground experiences no net heat gain or loss. This would be called a "balanced" system. If a system was

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[31] Kavanaugh, S. and Rafferty, K., 2014.

imbalanced, it might create a long-term temperature change in the ground. Depending on the extent of the imbalance with respect to the size of the ground loop, this could affect system performance. Best practice design guidelines[32] suggest taking balancing into account by calculating a temperature penalty that represents the average change in ground temperature over a 10 or 20-year period and ensuring that is below a reasonable limit (eg. less than 5 °F). However, ground temperature change is very difficult to calculate accurately based on a steady-state conduction heat transfer model that does not take many important things into account (for example, moisture changes in the soil).

The constraints of this study limit the monitoring period to approximately one-year and as a result, system balancing cannot be evaluated using long-term ground temperature measurements. Where possible, the annual net heat gain or loss of the ground is calculated and expressed as a ratio in terms of the borehole length because the system's sensitivity to imbalance is likely to be strongly dependent on the ground loop sizing. The question of whether or not a measured imbalance would result in prohibitively large long-term ground temperature changes is a question that is beyond the scope of this analysis. It would have to be answered using the experimental data and ground loop modeling.

3.2.6 Temperature difference between EST and LST

At very low flow rates, heat exchange between the ground loop and the heat pump will be poor. This is because the condenser heats up and loses a greater portion of its heat energy to the surrounding environment. The temperature difference between EST and LST will be large because any given volume of water will spend a longer time in the heat exchanger. This will lead to a poorer COP. In contrast, very high flow rates will result in good heat exchange and a low temperature difference but this is at the cost of more electrical energy invested in the circulator pump. This may also lead to a poorer COP.

It is clear that there is an ideal flow rate for optimal COP. Towards this end, manufacturers typically specify a flow rate range. They may also specify expected temperature differences between EST and LST. This is likely to be on the scale of a few degrees Celsius. The difference between EST and LST is also useful for understanding the overall error of the COP and capacity calculation, as discussed in Appendix B.

3.2.7 Percentage of Time In-Use

The PTIU is the quantity of time that the heat pump spends actually running expressed as a fraction of the total time in a given monitoring interval. This provides information on how well the geoexchange system is sized for the load.

A process for sizing geoexchange systems is explained in detail in best practice design documents.[33] During the sizing process, the heat loss and heat gain of a building are estimated for a given design heating (or cooling) outdoor temperature. A heating mode "design day" would be a day that has an average outdoor air temperature equal to the design heating temperature. Design temperatures are

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[32] Kavanaugh, S. and Rafferty, K., 2014.
[33] Kavanaugh, S. and Rafferty, K., 2014.

standardized by geographical area and a given area's design heating temperature is the lowest temperature that occurs at least 1% of the time during a typical year. In Toronto, for example, the design heating temperature is -17ºC.[34] The designer is required to make informed estimates on heat energy losses through the building's envelope and ventilation, and heat energy gains through occupancy, solar gain, electrical equipment, etc.

Design sizing procedures are such that the heating system's capacity should be sufficient to maintain indoor air temperature set-points on a design day by delivering a quantity of heat energy equal to the building's net heat energy losses. A heating system that was not able to deliver this quantity of heat would be considered undersized. It would be running all the time on a design day, unable to satisfy the heating call, and it would not be able to maintain optimal thermal comfort. This is, of course, not desirable.

The label "oversized" is more difficult to apply because the nature of estimating heat gains and losses is such that a properly designed system ought to have more capacity than is actually needed, by at least some small margin, to account for uncertainties. With this in mind, a system that was slightly oversized would not be a bad thing. Oversizing further than this is an issue because it increases the capital cost of the system unnecessarily and such a system might be prone to short-cycling which could then degrade efficiency and increase component wear. The capital cost penalties of oversizing a system are comparatively larger for a geoxchange system than a conventional system because the cost of geoexchange systems is more proportional with system capacity than in conventional systems.[35] It follows that any unneeded capacity results in a proportional increase in the capital cost of the system. Design guidelines do not explicitly state a precise limit past which oversizing is prohibitively bad. Such a limit would be difficult to calculate because it involves both a cost optimization component but also a risk component in that, if some margin of extra capacity is not included in the sizing then there is more risk that the system will be undersized.

In this report, the PTIU on an approximate design day will be used to analyze system sizing because the sizing procedure is based on design day outdoor temperatures. In this regard, the phrase "approximate design day" is taken in this report to mean one of the coldest/hottest days of the heating/cooling season. Different days were chosen for this depending on the monitoring interval. They include[36]:

- January 23rd, 2013: Min: -18.1ºC; Max: -9.1ºC
- Feb 17th, 2103: Min: -14.2ºC; Max: -7.5ºC
- July 17th, 2013: Min: 24.7 ºC; Max 35.4ºC

If the design day percentage time in-use is 100% then there is evidence that the system is undersized. If the sizing procedures and best practices have been followed and the heat gain/loss estimates are accurate then the system should be on the large majority of the time and a high design day PTIU should

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[34] ANSI, 2011. Manual J Residential Load Calculation: Outdoor Design Conditions, 8th Ed. Ver. 2.

[35] Kavanaugh, S. and Rafferty, K., 2014.

[36] TWN, 2014. The Weather Network Historical Weather for Toronto. http://www.theweathernetwork.com/weather/historical-weather/caon0696 (Accessed Dec. 12/2014)

be expected (for example, 70, 80 or 90%). Data from back-up heating systems were not considered in the analysis. If a given geoexchange system had back-up heating and the geoexchange system was observed to be on infrequently during a design day then this could actually be a case of underutilization rather than oversizing. It may be feasible to increase the fraction of heat delivered by the geoexchange system by adjusting system settings. These cases are noted in the analysis.

3.2.8 Electrical Consumption

This performance metric allows for the calculation of heat pump operating fuel costs. It can be further broken down into time-of-use electrical consumption to potentially identify more cost effective modes of operation. Figure 3.3[37] shows the time of use electricity rates in Ontario effective May 1st, 2014. For simplicity, these were the rates used in the analysis and additional costs, such as distribution or regulatory charges, over and above the per unit rate were not considered.

Figure 3.3: Time-of-use electricity rates used in this analysis

3.2.9 Greenhouse Gas Emissions Analysis

GHG emissions reduction is calculated for the case of a GSHP versus that of a baseline natural gas heating appliance. To simplify the analysis the heating distribution system is considered to be the same in both cases and only heating mode is considered. The analysis is based on the total amount of heat energy delivered by the GSHP. The baseline case considers that same amount of heat energy but instead delivered by: (i) a natural gas heating appliance such as a furnace or (ii) electric resistance heating. As has been suggested elsewhere[38], three different rated natural gas heating efficiencies are considered to cover the spectrum of low to high efficiency.

The assumptions used in this analysis are listed below:

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[37] Hydro One, 2014. Online document: http://www.hydroone.com/TOU/Pages/Default.aspx (Accessed Oct 1st/2014)

[38] Canadian Geoexchange Coalition Report, 2010.

- the greenhouse gas emissions resulting from electrical power consumption is 0.11 kg eCO_2/kWh;[39]
- one cubic meter natural gas contains 0.0373 GJ of energy;[40]
- the greenhouse gas emissions resulting from natural gas combustion is 1.891 kg eCO_2 per m^3 of natural gas,[41] and
- an average car emits 3,360 kg of eCO_2 annually.[42]

Two major limitations of these assumptions are that: (i) leakage of natural gas, during mining or distribution, is not considered[43] and (ii) the emission factor of natural gas is calculated assuming a fuel combustion efficiency of 99.5% wherein the analysis explicitly assumes worse combustion efficiencies. If properly taken account both of these factors would serve to increase the emission factor associated with natural gas heating but this is beyond the scope of this analysis.

A third limitation is that the analysis only considers heating mode operation. There would be additional GHG savings if cooling mode operation was considered because a GSHP ought to function more efficiently than a conventional air conditioner. Cooling mode operation was not considered due to lack of experimental baseline data for a conventional air conditioner. For example, an Energystar rated air-conditioner will have a SEER that is better than 13.0 but this is a laboratory value. It was observed that the laboratory ratings of the ground source heat pump were higher than the actual performance. It would not be fair to compare the actual in-use performance data of one technology with the ideal laboratory value of another. The results are then a highly conservative estimate of GHG savings, with the actual savings being likely being much better.

3.3 Other Considerations

3.3.1 Accounting for Missing Data

Certain sites had intervals of time during the monitoring period in which data was not available. To account for this, performance metrics were calculated as averages or totals on a monthly basis. For example, if the month of February had only 10 days in which monitoring data was available, then the total heat delivered for the month of February would be calculated by determining the average daily heat delivered using the available data and then multiplying that value by the total number of days in February (i.e. 28) to determine the total heat delivered for the month. If no data was available at all for a given month, then no performance metrics were calculated that month.

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[39] Environment Canada, 2013. National Inventory Report 1990-2011: Greenhouse Gas Sources and Sinks in Canada.

[40] Natural Resources Canada, 2014. Online document: http://www.nrcan.gc.ca/energy/natural-gas/5641 (Accessed Dec. 20/2014)

[41] Environment Canada, 2008. National Inventory Report 1990-2008: Greenhouse Gas Sources and Sinks in Canada.

[42] Canadian Geoexchange Coalition Report, 2010.

[43] Recent research is suggesting that natural gas leakage may actually be much worse than initially estimated. See: R. Brandt et. al. Methane Leaks from North American Natural Gas Systems. Science, Vol. 343, p. 733, 2014.

3.3.2 Square Footage Estimates

It is useful to normalize certain performance metrics to the building square footage for the purposes of comparison between different systems. A rigorous analysis would demand that square footage be determined in the same way for each site. For residential system systems studied in this report, the square footages have been reported by the building owner or operator (unless otherwise noted) and can be thought of as the total conditioned floor area (more specifically, the building footprint multiplied by the number of levels in the building including the basement). Since the square footage values were reported and not directly verified with building schematics it is possible that there are margins of error in these values.

The square footages of non-residential buildings included in this report are also based on reported values from system owners or operators. It was a challenge in terms of data-collection to determine square footage in a standardized way so there is again an element of error that may exist in not having directly verified square footages with building schematics. Relevant considerations in terms of square footage estimates are treated on a case-by-case basis.

4.0 STUDY FINDINGS

This section presents findings from each site. Where possible, each site is documented with pictures as well as building, geoexchange system and monitoring system information. The level of detail offered for each site is commensurate with limitations and scope of the study and, as such, highly detailed information about building design or control strategies was not collected.

For each site, a number of performance plots are presented based on the metrics discussed in Section 3.2. Error analysis has been performed on the metrics that were most sensitive to errors, namely, the capacity and COP/EER calculations. A discussion on error analysis is presented in Appendix B.

The "Summary" section for each site will attempt to answer the following questions:

- Is the ground loop sized appropriately?
- Is the geoexchange system sized appropriately?
- How efficiently is the system operating?
- Were there any major performance-related issues, good or bad, identified?

Comments on ground loop and system sizing are based on best practice documents and procedures as has been discussed in Section 3.2. The methods employed to evaluate system sizing are necessarily based on a limited amount of data and are intended more as a "quick check" then an in-depth evaluation. However, the approach used should be sufficient to identify any obvious cases of under or oversizing of systems. Comparisons of system efficiencies with manufacturer ratings involve several important considerations that have been discussed already in Section 3.2.

Where possible, metrics are normalized with respect to building square footage, borehole length, etc., to allow for comparison between the different sites.

The "Operational Lessons Learned and Recommendations" sections may have some overlap with previous sections but is intended to more specifically identify factors such as:

- potential adjustments to system design or control that could improve efficiency of the current system under study;
- potential adjustments to system design or control that could improve efficiency of future installations;
- monitoring-related issues that need to be rectified before a more thorough performance analysis could be completed;
- items, such as guidelines or best practice documents, that may be of use to the geoexchange industry but currently do not appear available (for example, standardized commissioning templates), and
- specific results that need to be communicated to other industry stakeholders (eg. architects).

Findings related to two of the study sites, Archetype House B and GTAA North Fire hall are not presented in this section because they have already been presented in detail in separate reports.[44] However, the findings from these sites are discussed alongside other sites in Section 5.0.

4.1 Peel House A

4.1.1 Geoexchange System Overview

The retrofit geoexchange system at Peel House A, was commissioned in 2009. It is used as the primary heating and cooling system for a multi-resident home operated by the Region of Peel. The system uses an SCW-048-1B Earthlinked compressor unit with 4 Tons nominal heating capacity. The ground-loop is direct exchange (DX) with four vertical boreholes extending 100 ft into the ground. Heating and cooling is accomplished via forced-air hydronic coils housed in a pair of air handlers, one of which is multi-zoned. Heated or chilled water is circulated through the coils from a buffer tank which is charged by the ground-source heat pump system. A gas-fired water heater is used for back-up heating. An overview of the house and geoexchange system is given in Table 4.1.

Figure 4.1: (Left) Street view of Peel House A. (Top right) A resistance temperature detector (RTD), used for temperature monitoring, installed in a thermal well. (Bottom right) The heat pump compressor box.

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[44] See (Safa, A., 2012) and (AMEC, 2013)

Table 4.1: Building and geoexchange system overview for Peel House A

Building	
Square footage	1750 ft^2
Usage	Residential group home
Geoexchange System	
GSHP Unit[45]	Earthlinked model SCW-048-1B 50 MBtu/hr rated heating capacity 28.6 Btu/hr per ft^2 heating capacity 48 MBtu/hr rated cooling capacity 27.4 Btu/hr per ft^2 cooling capacity 3.5 rated COP 15.0 rated EER Commissioned 2009
Ground-loop	Vertical loop 4 Boreholes, 100 ft deep 8 ft of borehole length per MBtu/hr rated heating capacity Direct exchange
Distribution	Multi-zone air handler with hydronic forced-air heating and cooling from buffer tank. The aquastat setpoint as chosen by the installer is 40 to 42 °C in heating mode and 6 to 8 °C in cooling mode.

4.1.2 Monitoring Overview

Since the system is DX it has been instrumented on the distribution-side of the heat pump. This is shown schematically in Figure 4.2. The monitoring system is summarized in Table 4.2.

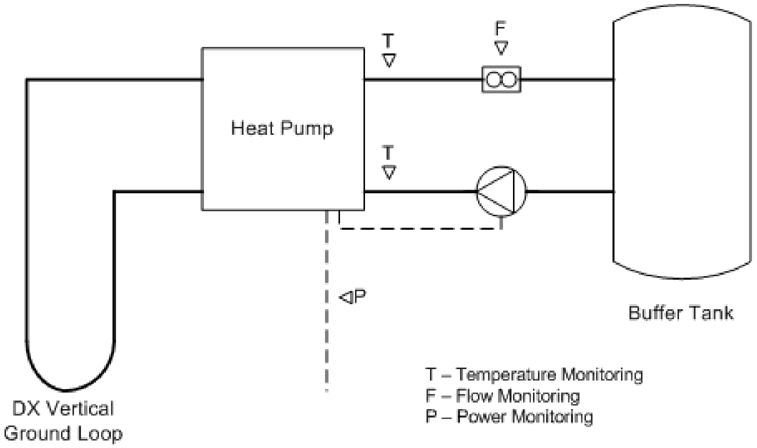

Figure 4.2: Schematic of Peel House A geoexchange system showing monitoring points

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[45] Earthlinked, 2008. Earthlinked Heating and Cooling System: Installation Operation and Maintenance Manual.

Table 4.2: Monitoring Overview for Peel House A

Flow	
Badger Series 380 Btu Meter	Accuracy: ±2% of reading Range: 2.70 to 40.48 GPM
Temperature	
RTD IEC 751 Class B probes in (i) thermal well and (ii) compression fitting integrated into Badger meter chasis. Probes monitor ELT and LLT.	Individual sensor accuracy is ±(0.3+0.005|T|) but a calibration has been applied with an estimated error in (LST-EST) of ±0.5^{o}C. Range: 4 to 125 ^{o}C
Power	
Power measurement device was not determined. Power measurements include both compressor unit and distribution side circulator pump. COP calculations have been adjusted to remove the distribution circulator pump. There is no ground loop circulator since it is DX.	Accuracy is not determined because measurement device is not known. Power measurements can be done accurately with inexpensive devices. Analysis will assume accuracy is ±0.5% of reading.
Acquisition	
Obvious Aquisuite A8812 with GSM Modem	
Monitoring Period	
February 2013 – January 2014	
Data Logging Interval	
Instantaneous data is being logged every one minute.	See Appendix B for a discussion on the error associated with instantaneous logging.

4.1.3 Findings: Performance Plots

1. **The total seasonal heating and cooling COPs are 2.8±0.5 and 3.2±0.6 (10.9±2 EER) respectively.** The COP has been adjusted to exclude the distribution circulator pump power. Monthly COP is shown in Figure 4.3. In the initial months of the cooling season, with low load and cool ground temperatures, the COPs are high. However, as the ground warms and the load increases, the COP decreases notably. The AHRI certified testing results for this heat pump model state that it has a heating COP of 3.5 and an EER of 15.0 (cooling COP of 4.4). The measured results are notably worse than the manufacturer ratings. It should be noted that there are reasons why the experimental as-installed COP should disagree somewhat with the manufacturer rating. This is discussed in Section 3.2.2.
2. **The heating capacity of the geoexchange system appears to fall short of rated capacity during some months.** The nominal rated heating capacity with a source temperature of 0 ^{o}C is 50 MBtu/hr for this unit. The nominal rated cooling capacity, with a source temperature of 25 ^{o}C, is 48 MBtu/hr for this unit. The actual operational ground temperatures for this unit are not known. Figure 4.4 shows that the average instantaneous heating and cooling capacity falls short of the rated capacity during some months. The seasonal trends show decreases in capacity as both seasons progress. This is likely due to ground temperature variations discussed in Finding 1.

3. **The heating load of the building is 50% larger than the cooling load but approximately 40% more heat is rejected to the ground than is removed.** This is possible because in heating mode, the compressor heat helps to heat the building (reducing the amount of heat removed from the ground) while in cooling mode, the compressor heat is rejected to ground (increasing the total heat rejected to the ground). The total heating and cooling loads for the year were 23,000±4,000 and 16,000±3000 kWh respectively. The total heat delivered and removed from the ground were 21,000±3000 and 15,000±4000 kWh respectively. Figure 4.5 breaks the heating and cooling loads down by month. An imbalanced system may show an average ground temperature warming or cooling trend from season to season that may affect long-term performance. This is discussed in Section 3.2.5. Modeling would need to be used to determine if the imbalance in this system is prohibitively large.
4. **Heating and cooling mode cycle times are on the scale of 10 minutes and 20 minutes respectively.** Figure 4.6 breaks the cycle times down by month. Short cycle times can degrade COP due to the losses associated with starting the compressor and cause increased wear on components. The cycle time is affected by the heat pump capacity, the buffer tank size, load profile and aquastat settings. These cycle times are the shortest amongst all heat pumps studied.
5. **The heat pump sizing is sufficient for the loads without being oversized.** Figure 4.7 shows that in peak heating and cooling months the geoexchange system is operating 55% of the time. The system was operating for 70% of the time on a day that approached design heating conditions (February 17th, 2013, see Section 3.2.7). Whether or not the back-up was operating on this day was not evaluated. The system was operating 90% of the time on a day that approached design cooling conditions (July 17th, 2013, see Section 3.2.7). The system is operating the large majority of the time on days that approach design heating and cooling conditions and it is therefore considered to be properly sized.
6. The total electricity consumption for one year was 13,500 kWh. Figure 4.8 shows the monthly electrical consumption broken down into time-of-use bracket. Error bars are not shown because the error in is estimated to be very small (<0.5%). Predictive control algorithms, greater storage and increased ground loop sizing may make it possible to shift the usage profile. For example, **20% of electricity fuel costs could be saved by shifting on-peak and mid-peak energy usage to off-peak**. This would need to be weighed against the increased system cost and complexity and the potential benefit of this approach would need to be further examined in future work.
7. **The distribution-side circulator pump is sized appropriately.** The average distribution-side flow rate is 18 GPM. A rule of thumb is approximately 3 GPM per ton of capacity,[46] which in this case would be 12 GPM. The flow rate may be a little more than is necessary but the penalty is not large since additional power to run the circulator is small. The average difference between ELT and LLT when the system is in-use in heating and cooling distribution modes are 3.3 and 2.1 ^{o}C respectively. The Earthlinked installation manual suggests that the temperature difference should be approximately 5 ^{o}F[47] (2.8 ^{o}C) but does not specify an optimal range.

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[46] Kavanaugh, S. and Rafferty, K., 2014.

[47] Earthlinked, 2008.

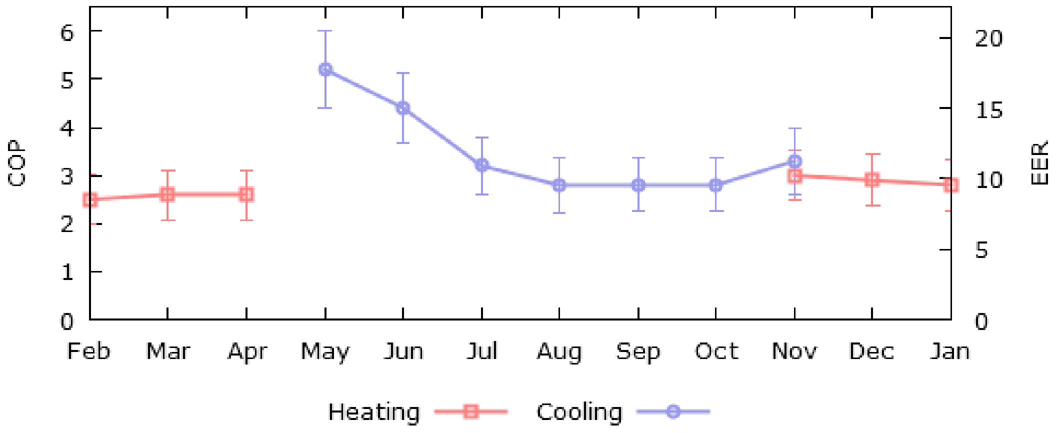

Figure 4.3: The cooling mode COP has a notable decline as the cooling season progresses due to increases in load and local ground temperatures

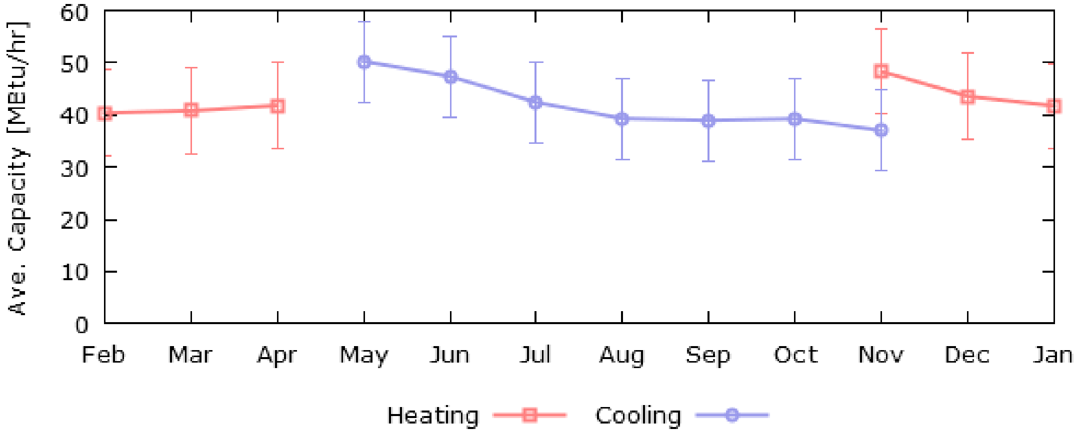

Figure 4.4: The operating capacity of the heat pump is typically highest at the beginning of a heating or cooling season

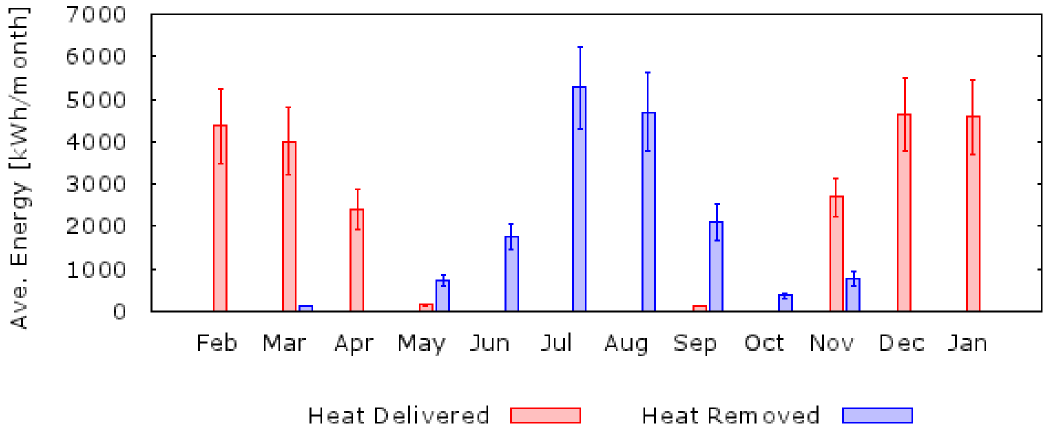

Figure 4.5: The heat delivered and removed by the system fluctuates seasonally as expected

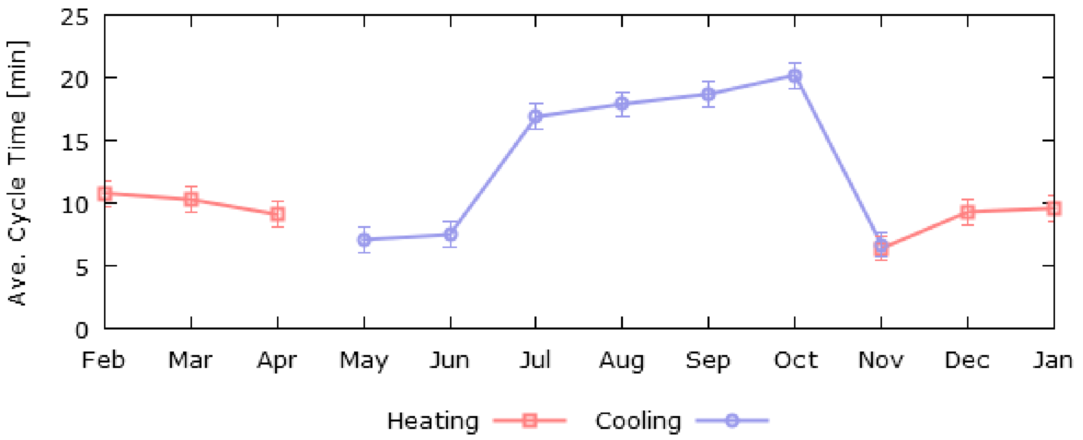

Figure 4.6: Heating and cooling mode cycle times are 10 min and 20 min respectively. Cycles are short in part because the heat pump is single stage and must be either off, or on at full capacity.

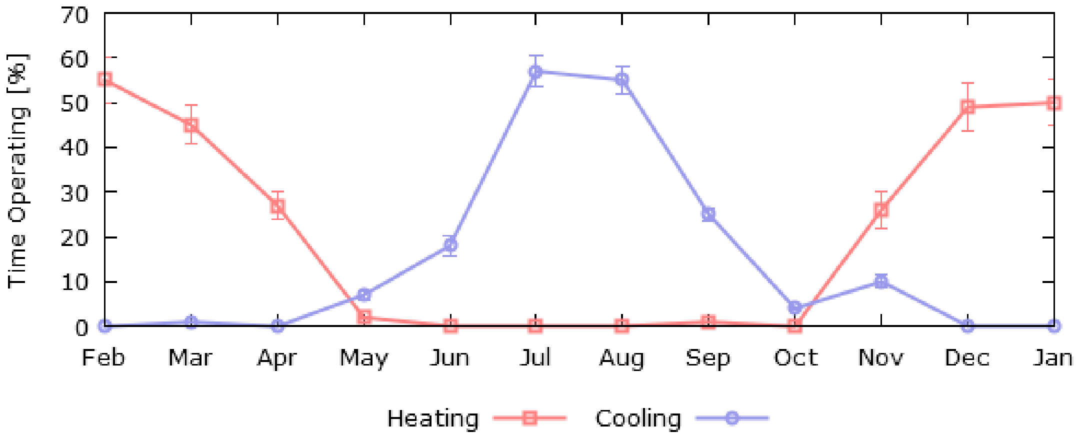

Figure 4.7: The heat pump is on 55% of the time during peak heating and cooling months

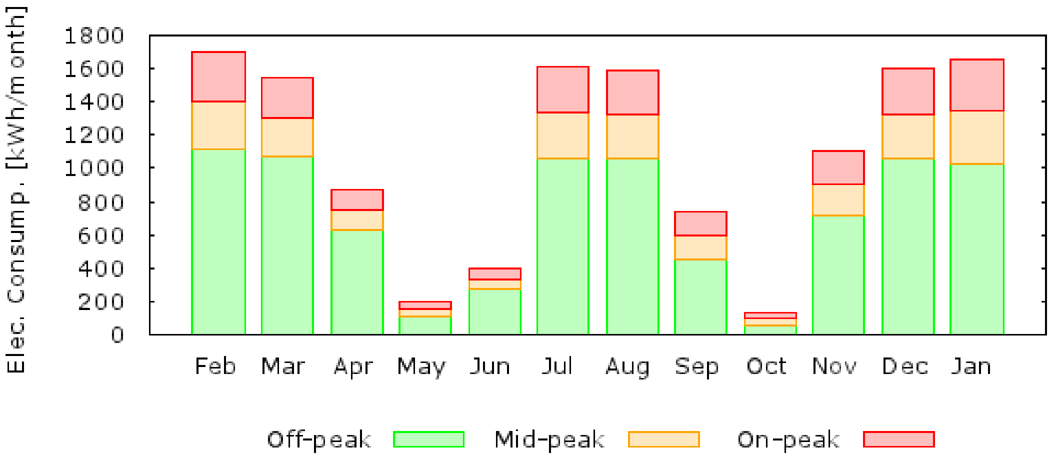

Figure 4.8: The majority of electrical consumption is off-peak

4.1.4 Findings: GHG Emissions Analysis

Emissions analysis results are shown in Table 4.3. Section 3.2.9 explains the methodology for this analysis. Error is not considered because there are many important factors not taken into account that have already been discussed qualitatively in Section 3.2.9. This simplified analysis suggests that the reduction in GHG emissions by opting to heat a residence using a single GSHP is comparable to or better than taking an average car off the road for an entire year. Based on the assumptions used in the analysis, this is a likely a highly conservative estimate. Actual savings are likely much better.

Table 4.3: GHG reduction analysis for Peel House A

Heating Scenario	Efficiency	Heat Delivered [MWh]	Electricity Consumed [MWh]	Eq. CO_2 Emissions from Electricity [103 kg eCO_2]	Natural Gas Used [m^3]	Eq. CO_2 Emissions Natural Gas [103 kg eCO_2]	GHG Emission Reduction Achieved by Using Heat Pump [103 kg eCO_2]	Equivalent number of cars off the road [cars/year]
Heat Pump	2.8	23.0	8.2	0.9	0	0	N/A	N/A
Natural Gas Heating	0.75	23.0	0.0	0.0	2960	5.6	4.7	1.4
Natural Gas Heating	0.84	23.0	0.0	0.0	2643	5.0	4.1	1.2
Natural Gas Heating	0.95	23.0	0.0	0.0	2337	4.4	3.5	1.0
Electric Resistance	1	23.0	23.0	2.5	0	0.0	1.6	0.5

4.1.5 Findings: Summary

Table 4.4 summarizes the system metrics. The COP for this system is low. This is likely related to the fact that average instantaneous capacity is also low. In some months the instantaneous capacity is 80% of its rating. This installation has no ground loop instrumentation so a major determinant of the performance is not known. The low performance may be related to the short cycle times, which are some of the shortest seen in this study. However, the low cycle time does not appear to be due to system oversizing as the system PTIU appears to be in an acceptable range for approximate design heating and cooling days. The low cycling time could be related to the aquastat settings that determine at which temperature the heat pump turns on and off. There are large decreases in system COP/EER as the heating of cooling season progresses. For example, the June EER is 60% greater than the August COP. This is also likely related to the seasonal changes in ground loop temperature in the vicinity of the borehole.

Table 4.4: Peel House A geoexchange performance metrics

System Sizing	
PTIU – design heating day	0.70
Maximum PTIU – heating month	0.55
PTIU – design cooling day	0.90
Maximum PTIU – cooling month	0.57
Total annual heat delivered [kWh per ft^2]	13.1
Total annual heat removed [kWh per ft^2]	9.1
Maximum average monthly heating mode cycle time [min]	11
Maximum average monthly cooling mode cycle time [min]	20
System Efficiency	
Annual heating mode COP	2.8
Annual cooling mode EER	10.9
Ground Loop Sizing	
Lowest heating mode EST [^oC]	N/A
Highest cooling mode EST [^oC]	N/A
Imbalance [kWh per ft borehole length]	+15
System Electrical Energy Consumption	
Total annual heating [kWh per ft^2]	4.8
Total annual cooling [kWh per ft^2]	2.9
Total annual [kWh per ft^2]	7.7
Emissions Savings	
Annual GHG savings [kg eCO_2 per rated heating ton]	990

4.1.6 Operational Lessons Learned and Recommendations

1. Achieving optimal heat pump performance extends beyond system design. Settings of balance of system (BOS) components, such as an aquastat, may have a large impact on system performance and this may be easy to overlook. For this system, setting the aquastat to have a wider deadband between the turn-on and turn-off setpoints may be beneficial. **In general, cycling time guidelines should be established and integrated into system commissioning procedures.**
2. There is the potential for a large uncertainty in heat pump capacity and COP calculations. This stems largely from the uncertainty in determining the difference between leaving and entering temperatures. This is discussed in Appendix B. **Matched-pair temperature sensors should always be used in geoexchange monitoring systems to reduce this uncertainty.**
3. The average instantaneous heating and cooling capacities are lower than expected, as is the COP and EER. A low cycling time was identified to be at least partly responsible. The ground loop was not instrumented in this study but ground loop temperatures are a major determinant of system performance. **For a full analysis, it is recommended that instrumentation be installed on both the building and ground loop side of the heat pump.**
4. This system was imbalanced such that the annual net heat gain of the ground was +15 kWh per ft of borehole length. **Ground loop modeling is recommended if the system owners desire to determine if this imbalance is prohibitively large.**

5. A time-of-use analysis shows that this system is operating primarily in an off-peak bracket which is reasonable since it is a residential building. However, if the mid-peak and on-peak usage was shifted to an off-peak time-of-use, it could represent an electricity fuel-cost savings of 20% (not including regulatory and distribution charges). This could also benefit utilities by shaving peak demand. **The relative merits and costs of implementing time-of-use control should be further examined for potential application in future sites.**
6. This system appears to have been sized sufficiently well to meet design heating and cooling loads. The heat pump is sized at 28.6 Btu/hr heating capacity per ft^2 of building. The total annual heating and cooling loads are 13.1 kWh/ft^2 and 9.1 kWh/ft^2. The GHG savings were calculated to be 990 kg eCO_2 per rated heating ton. This information may be useful for benchmarking exercises.

4.2 Peel House B

4.2.1 Geoexchange System Overview

The retrofit geoexchange system in Peel House B was commissioned in 2009. It is used as the primary heating and cooling system for a multi-resident group home operated by the Region of Peel. The system uses an SCW-048-1B Earthlinked compressor unit with 4 Tons nominal heating capacity. The ground-loop is direct exchange (DX) with four vertical boreholes extending 100 ft into the ground. Heating and cooling is accomplished via forced-air hydronic coils housed in 5 air handlers located in separate mechanical closets throughout the building, creating a multi-zone system. Heated or chilled water is circulated through the coils from a storage tank which is charged by the geoexchange system. An electric water heater is used for back-up heating. An overview of the house and geoexchange system is given in Table 4.5.

Figure 4.9: (Left) Street view of Peel House B. (Top right) Compressor box of ground source heat pump. (Bottom right) Air handler with hydronic coil.

Table 4.5: Building and geoexchange system overview for Peel House B

Building	
Square footage	5,360 ft^2
Usage	Residential Group Home
Geoexchange System	
GSHP Unit	Earthlinked model SCW-048-1B 50 MBtu/hr rated heating capacity 9.3 Btu/hr per ft^2 rated heating capacity 48 MBtu/hr rated cooling capacity 9.0 Btu/hr per ft^2 rated cooling capacity 3.5 rated COP 15.0 rated EER Commissioned 2009
Ground-loop	Vertical loop 4 Boreholes, 100 ft deep 8 ft of borehole length per MBtu/hr rated heating capacity Direct exchange
Distribution	Multi-zone air handler with hydronic forced-air heating and cooling from buffer tank. The cooling mode buffer tank setpoint is between 6 and 8^{o}C. The heating mode buffer tank setpoint is 40^{o}C.

4.2.2 Monitoring Description

The monitoring system and building is described in Table 4.6 and Figure 4.10 shows a schematic of the system with monitoring points labeled.

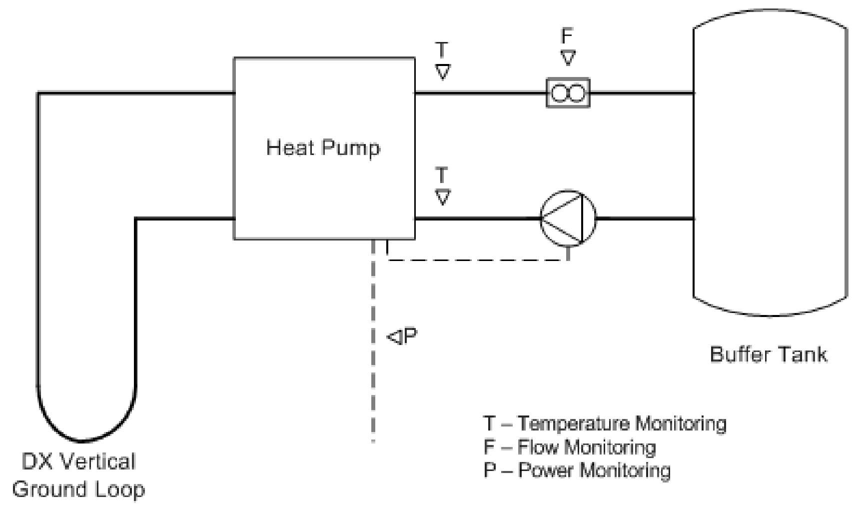

Figure 4.10: A schematic of the Peel House B geoexchange system showing monitoring points

Table 4.6: Monitoring overview for Peel House B

Flow	
Badger Series 380 Btu Meter	Accuracy: ±2% of reading Range: 2.70 to 40.48 GPM
Temperature	
RTD IEC 751 Class B probes in (i) thermal well and (ii) compression fitting integrated into Badger meter chasis. Probes monitor ELT and LLT.	Accuracy is $\pm(0.3+0.005|T|)$ ^{o}C Range: 4 to 125 ^{o}C
Power	
Power measurement device was not determined. Power measurements include both compressor unit and distribution side circulator pump. COP calculations have been adjusted to remove the distribution circulator pump. There is no ground loop circulator since it is DX.	Accuracy is not determined because measurement device is not known. Power measurements can be done accurately with inexpensive devices. Analysis will assume accuracy is ±0.5% of reading.
Acquisition	
Obvious Aquisuite A8812 with GSM Modem	
Monitoring Period	
January 2013 – December 2013	
Data Logging Interval	
Instantaneous data is being logged every one minute.	See Appendix B for a discussion on the error associated with instantaneous logging.

4.2.3 Findings: Performance Plots

1. **The total seasonal heating and cooling COPs are 3.5±0.8 and 3.8±0.6 (EER 13.0±2) respectively.** Monthly COP is shown in Figure 4.11. In the initial months of the cooling season, with low load and cool ground temperatures, the monthly COP reaches above 4.4, however, as the ground

warms and the load increases the monthly COP decreases notably down to as low as 3.2. The AHRI certified testing results for this heat pump model showed a COP of 3.5 and an EER of 15.0 (cooling COP of 4.4). The rated and experimental COP/EER agree to within the error bars of the analysis, however, it would be unreasonable to expect these numbers to agree entirely for several reasons. These have already been discussed in Section 3.2.2.

2. **The average monthly heating and cooling capacities are lower than rated values.** Figure 4.12 shows the average capacity of the geoexchange system when it is turned on in either heating or cooling mode with the average taken over the course of a month. The heating capacity is highest at the beginning of the heating season because the ground had previously been warmed during the cooling season, causing the lift to be low. The cooling capacity seems notably low. The reason for this is not yet clear. Since the EER seems unaffected by the low capacity this means that both the capacity and the power consumption is low.
3. **Not including the missing data in March, the heat and cooling loads of the building are comparable.** The total heating and cooling loads for the year were 24,000±6000 and 21,000±3000 kWh respectively. The total heat delivered to and removed from the ground were 26,000±3000 and 17,000±6000 kWh respectively. If March data were available the total heat removed from the ground would likely be closer to 19,000 kWh. These numbers are different then the heating and cooling load numbers because the compressor electrical power consumption helps to heat the home during the heating season and is rejected to the ground in the cooling season. Figure 4.13 breaks the heating and cooling loads down by month. If a system is imbalanced then the ground may show an average warming or cooling trend from season to season that may affect long-term performance.
4. **Heating mode cycle times are on the scale of 10 to 30 minutes while cooling mode cycle times are between 15 and 45 minutes.** Figure 4.14 breaks the cycle times down by month. Short cycle times can degrade COP due to the losses associated with starting the compressor. The cycle time is affected by the heat pump capacity, the buffer tank size, load and aquastat setting. Cooling mode cycle times may be longer because the cooling capacity is lower.
5. **The heat pump sizing is appropriately sized for the heating and cooling loads.** Figure 4.15 shows that in peak heating and cooling months the heat pump is operating 70% of the time. On a day that approached design day heating conditions, the system was operating for 82% of the time (Jan23rd, 2013, see Section 3.2.7) and on a day that approached design day cooling conditions (July 17th, 2013, see Section 3.2.7), the system was operating 88% of the time. Since the system is operating the large majority of the time on days that approach design condition, the system is deemed to be appropriately sized for the load.
6. Not including the missing data in March, the total electricity consumption for one year was 12,690 kWh. Figure 4.16 shows the monthly electrical consumption broken down into time-of-use bracket. The majority of the usage is off-peak since this is a residential building. **If it were possible to shift the peak and mid-peak loads to an off-peak bracket then 20% to 25% of electricity fuel costs (not including regulatory and distribution charges) could be saved.** This would require increased system sizing, complexity and control. The viability of this approach and the actual savings would need to be examined in future work.

7. **The distribution-side circulator pump is sized appropriately.** The average distribution-side flow rate is 15 GPM. A rule of thumb is approximately 3 GPM per ton of capacity,[48] which in this case would be 12 GPM. The average difference between the ELT and LLT is 2.8 and 2.6 ^{o}C respectively, both of which are reasonable given that the Earthlinked installation manual suggests it should be approximately 5^{o}F[49] (2.8^{o}C).

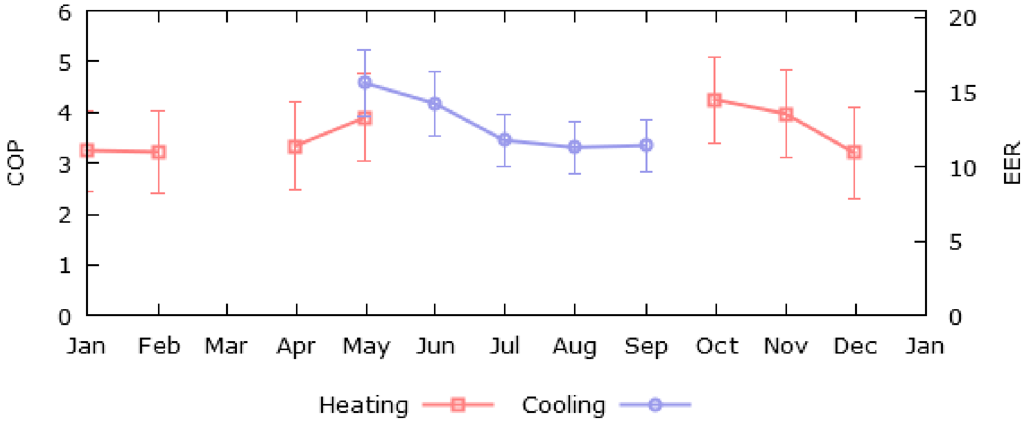

Figure 4.11: The seasonal heating mode COP is 3.5 and the seasonal cooling mode EER is 12.6 (cooling mode COP of 3.8).

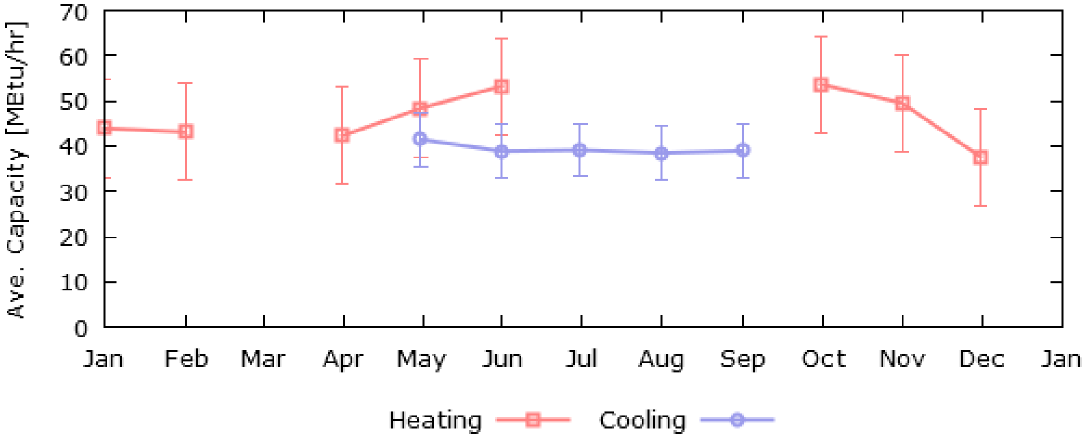

Figure 4.12: The heating capacity of the heat pump agrees with the rated value (50,000 MBtu/hr) while the cooling capacity is lower. Capacity is typically highest at the beginning of a heating or cooling season.

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[48] Kavanaugh, S. and Rafferty, K., 2014.

[49] Earthlinked, 2008.

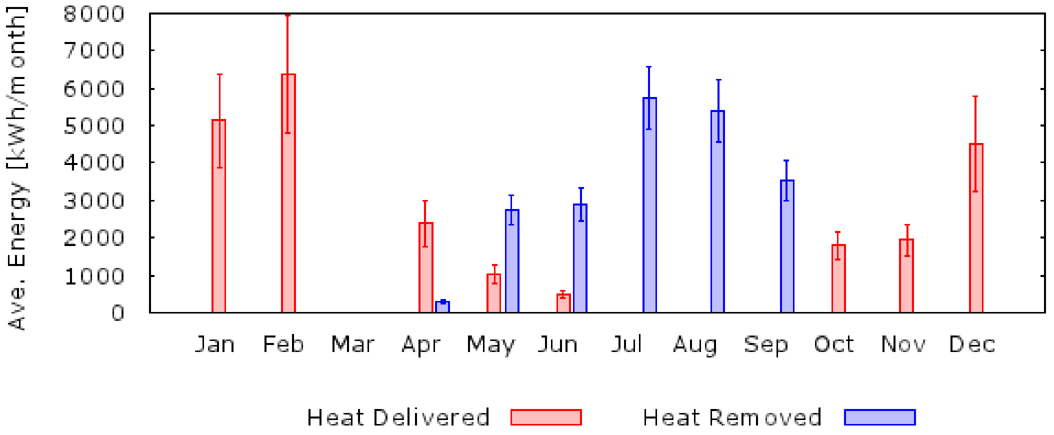

Figure 4.13: The heat delivered and removed by the system fluctuates seasonally as expected. Data was not available for March.

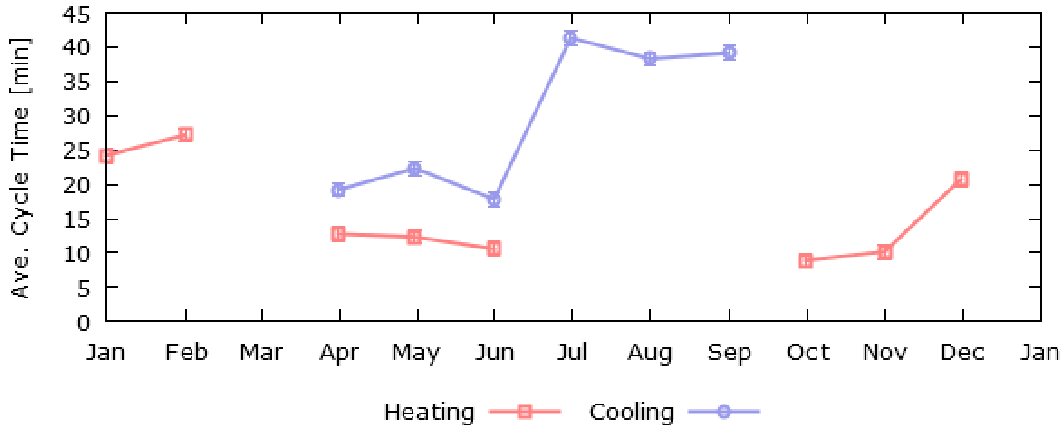

Figure 4.14: Heating and cooling mode cycle times are 25 min and 45 min respectively during peak heating and cooling months.

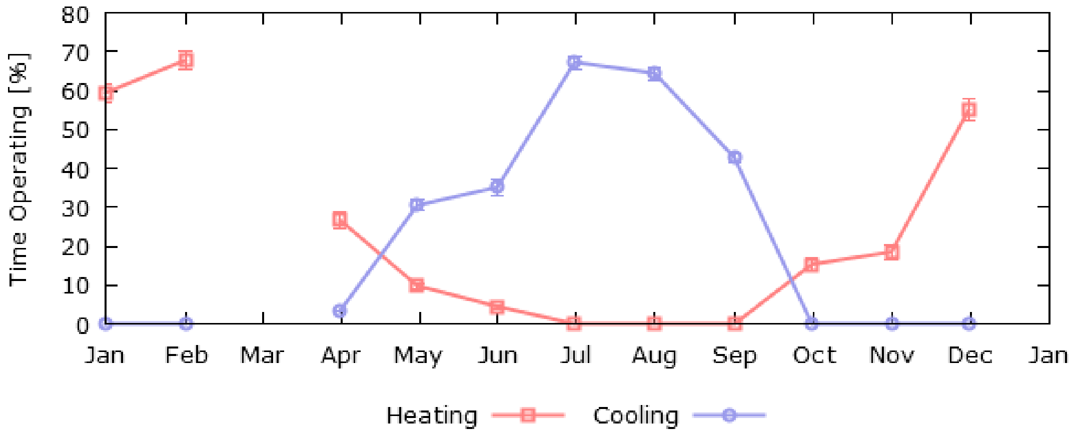

Figure 4.15: The heat pump is on 50% of the time during peak heating months and 70% during peak cooling months.

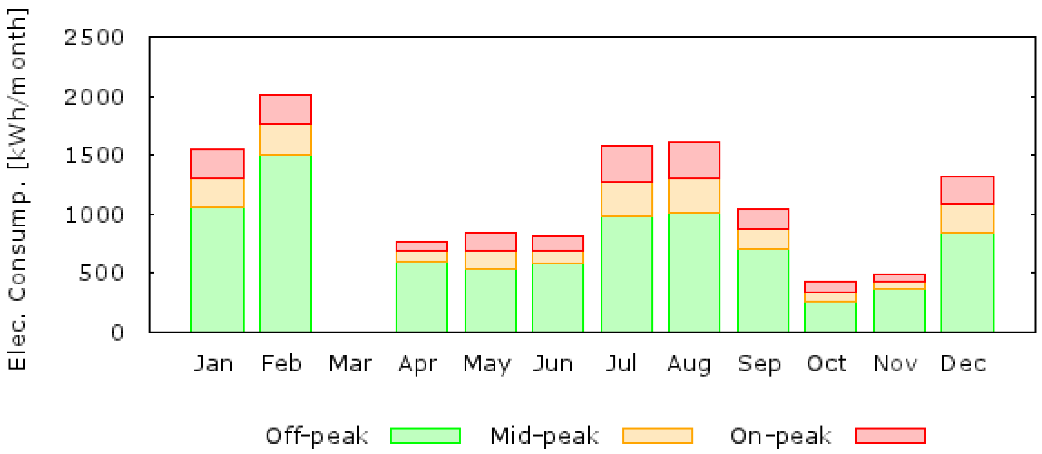

Figure 4.16: The majority of electrical consumption is off-peak

4.2.4 Findings: GHG Emissions Analysis

Emissions analysis results are shown in Table 4.7. Section 3.2.9 explains the methodology for this analysis. This simplified analysis suggests that the reduction in GHG emissions by opting to heat a residence using a single GSHP is comparable to or better than taking an average car off the road for an entire year. Based on the assumptions used in the analysis, this is likely a highly conservative estimate. Actual savings are likely much better.

Table 4.7: GHG reduction analysis for Peel House B

Heating Scenario	Efficiency	Heat Delivered [MWh]	Electricity Consumed [MWh]	Eq. CO2 Emissions from Electricity [103 kg eq. CO2]	Natural Gas Used [m3]	Eq. CO2 Emissions Natural Gas [103 kg eq. CO2]	GHG Emission Reduction Achieved by Using Heat Pump [103 kg eq. CO2]	Equivalent number of cars off the road [cars/year]
Heat Pump	3.5	24.0	6.9	0.8	0	0	N-A	N-A
Natural Gas Heating	0.75	24.0	0.0	0.0	3088	5.8	5.1	1.5
Natural Gas Heating	0.84	24.0	0.0	0.0	2758	5.2	4.5	1.3
Natural Gas Heating	0.95	24.0	0.0	0.0	2438	4.6	3.9	1.1
Electric Resistance	1	24.0	24.0	2.6	0	0.0	1.9	0.6

4.2.5 Findings: Summary

Table 4.8 summarizes important system metrics. The system was sized appropriately for the loads and operated near its rated efficiency values. The cooling capacity of the unit is lower than rated values but this did not affect EER notably, because it also operated with a lower power draw in cooling mode. The reason for the low cooling capacity is not clear.

Table 4.8: Peel House B geoexchange performance metrics

System Sizing	
PTIU – design heating day	0.82
Maximum PTIU – heating month	0.68
PTIU – design cooling day	0.88
Maximum PTIU – cooling month	0.68
Total annual heat delivered [kWh per ft^2]	4.6
Total annual heat removed [kWh per ft^2]	4.0
Maximum average monthly heating mode cycle time [min]	27
Maximum average monthly cooling mode cycle time [min]	41
System Efficiency	
Annual Heating mode COP	3.5
Annual Cooling mode EER	13.0
Ground Loop Sizing	
Lowest heating mode EST [^{o}C]	N/A
Highest cooling mode EST [^{o}C]	N/A
Imbalance [kWh per ft borehole length]	+12.5
System Electrical Energy Consumption	
Total annual heating [kWh per ft^2]	1.3
Total annual cooling [kWh per ft^2]	1.1
Total annual [kWh per ft^2]	2.4
Emissions Savings	
Annual GHG savings [kg eCO$_2$ per rated heating ton]	1100

4.2.6 Operational Lessons Learned and Recommendations

1. The error bars of the capacity and COP measurements are large. See Appendix B for a discussion on this topic. **Matched-pair sensors should always be used in geoexchange system performance analysis to limit the uncertainty of the results.**
2. The imbalance of this system is similar to the imbalance of House A. Ground loop modeling would need to be used to determine if this imbalance would cause an unacceptable increase in ground temperature. **Best practice documents[50] discuss modeling ground temperature loss/gain but it would be useful if acceptable ranges of system balancing, perhaps expressed in terms of kWh/ft, were developed to aid in the analysis of geoexchange systems.**
3. This system performed notably better than Peel House A. The obvious difference between the two systems is that Peel House A operated with shorter cycle times. However, specifically why it operates with shorter cycle times was not established**. A more in-depth analysis of these two systems might yield further information.** For example, the difference in performance may be associated with the load profile.
4. A time-of-use analysis suggests that between 20 and 25% of the electricity fuel costs (not included distribution and regulatory charges) could be saved by operating the system primarily

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[50] Kavanaugh, S. and Rafferty, K., 2014.

in an off-peak time-of-use bracket. This approach could also benefit utilities by peak shaving. **The viability of TOU control should be a topic of future work.**

5. **Future geoexchange studies should include ground loop instrumentation because this is an important component of system performance.**
6. This system was sized appropriately and performed well. Heat pump sizing and load information was presented and normalized to building square footage. **This information could be useful for benchmarking exercises.**

4.3 Greenlife Condominium

4.3.1 Geoexchange System Overview

The Greenlife Condominium in Milton, ON, is a net-zero condominium that was built in 2012 and the geoexchange system was incorporated as a part of the new build. The building is designed to be thermally efficient with a tight, highly insulated, building envelope. The ground loop of the geoexchange system is comprised of 68 vertical boreholes, each 400 feet deep. Each of the approximately 160 condo units has its own heat pump. The ground loop supplies the heat transfer fluid to each condo unit via vertical risers which connect up to 6 of the units in parallel. This monitoring study examined a single riser of 6 units. Attached to the riser are a single Climate Master TSV 012 (1 Ton nominal heating capacity) heat ground source pump (GSHP) and five TSV 006 GSHPs (0.5 Ton nominal heating capacity). The Climate Master heat pumps are water-to-air units that have an integrated air handler on the distribution side which allows for forced-air heating and cooling.

Figure 4.17: (Left) Front view of the Greenlife condominium. (Top right) Part of the ground loop manifold located in the basement parking garage. (Bottom right) Part of the solar photovoltaic system on Greenlife's roof.

Table 4.9: Building and geoexchange system overview of Greenlife Condominium

Building	
Square footage	Total condominium square footage is approximately 140,000 ft2 with 145 individual units ranging in size from 673 to 1470 ft2. There are 6 floors.51
Usage	Multi-residential condominium
Geoexchange System	
GSHP Unit52	Climate Master TSV 006/012 water-to-air heat pumps in each unit 4.8/9.5 MBtu/hr heating capacity 7.1/10.6 Btu/hr per ft2 heating capacity 6.7/12.4 MBtu/hr cooling cooling capacity 10.0/13.8 Btu/hr per ft2 cooling capacity 3.4/3.5 COP 18.5/18.1 EER Commissioned 2012
Ground-loop	Vertical loop 68 Boreholes, 400 ft deep Feeds 28 vertical risers, each riser connecting up to 6 heat pump units in parallel
Distribution	Forced-air

4.3.2 Monitoring Description

The monitoring system and building is described in Table 4.10 and a schematic diagram is shown in Figure 4.18 labeling the monitoring points. Only units 1, 3 and 5 are instrumented. This arrangement was chosen in an attempt to characterize the maximum amount of heat pumps for the minimum amount of instrumentation. The delivered or removed heat by a group of heat pumps can be collectively monitored by measuring the flow rate through a common supply and return and the temperature difference across it. Flow rate instrumentation is expensive and this arrangement allows for only a single flow rate measurement where otherwise six individual flow measurements would be required. By monitoring the power consumption of each heat pump in the riser, the COP could the also be calculated. Unfortunately, the power consumption was monitored for only half of the units in the riser. Unit 1 has the 1 ton heat pump while units 3 and 5 have half-ton heat pumps.

The COP was not determined because there was an issue with the flow measurement than was not identified until after the monitoring period. This issue might have been avoided if the monitoring system was more thoroughly commissioned. Appendix A presents a monitoring workflow which includes suggestions on commissioning. If followed, it ought to greatly reduce the risk of erroneous readings. A COP and heat energy analysis has been necessarily omitted for this site.

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[51] The TSV 006 heat pumps are installed in 1 bedroom + den units and the TSV 012 units are installed in 1 bedroom + den and 2 bedroom units. The estimated square footage of the units with a TSV 006 is 673 ft^2 and for the TSV 012, 900 ft^2.

[52] Climate Master, 2013. Tranquility 20 Single-Stage (TS) Series Submittal Data. Online document: http://www.climatemaster.com/downloads/EP007.pdf (Accessed Dec. 21st/2014)

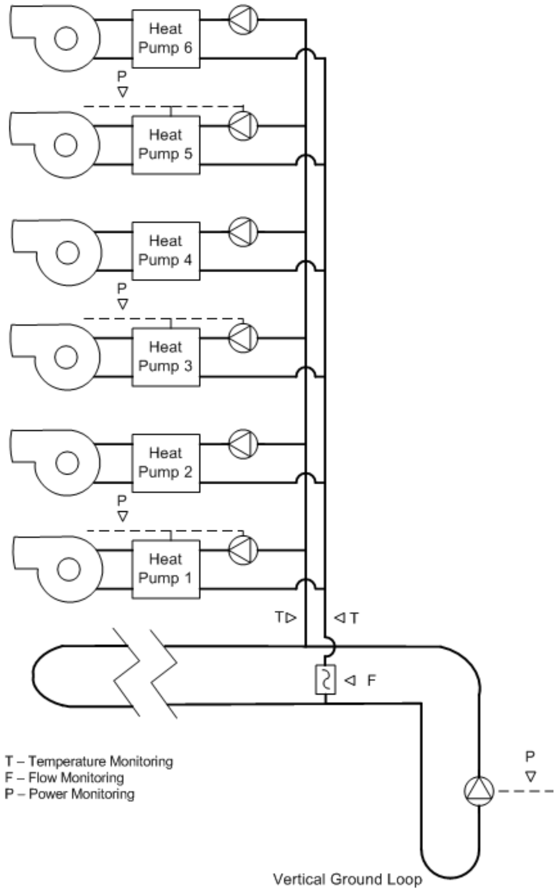

Figure 4.18: Schematic of Greenlife Condominium geoexchange system showing monitoring points

Table 4.10: Monitoring overview for Greenlife Condominium

Flow	
Dynasonics TFX Ultra Flow Meter (Ultrasonic)	Accuracy: ±1% of reading Range: >40 feet per sec velocity
Temperature	
Onset S-TMB-M002 Smart Temperature Probe (Surface Mounted)	Accuracy: ±0.2^{o}C Range: -40^{o}C to 100^{o}C
Power	
Wattnode WNB-3Y-208-P	Accuracy: 0.05% full scale + 0.45% reading Range dependent on current transducer (CT)
Acquisition	
Onset Hobo U30 **Data Logger**	
Monitoring Period	
November 2012 - October 2013	
Data Logging Interval	
Averaged data logged every 5 minutes	

4.3.3 Findings: Performance Plots

1. **The heat pumps are size appropriately for the load.** Figure 4.19 shows, on a monthly basis, the amount of time each heat pump operates. The heat pumps are on between 40 and 80% of the time during the peak heating months but on less than 20% of the time in peak cooling months. On a day that approached design heating conditions (Jan 23rd, 2013, see section 3.2.7) the PTIUs were 75%, 87% and 70% respectively for Units 1, 3 and 5. On a day that approached design cooling conditions (July 17th, 2013, see Section 3.2.7) the PTIUs were 26%, 40% and 6%.
2. **The cycle times of Units 1 and 3 are short, at around 10 minutes, while the cycle time for unit 5 reaches 80 minutes in heating mode and 40 minutes in cooling mode.** Monthly averaged cycle times are shown in Figure 4.20. Shorter cycle times may be associated with COP degradation and increased component wear. It is also worth noting that Unit 5 is on the largest percentage of time, suggesting it has a larger load. It is reasonable to expect that a longer cycle time would be associated with a larger load because for example, in heating mode, heat is being lost from the space as the heat pump is trying to heat it up. It would therefore take longer to reach the set-point temperature because the net heat gain of the space is smaller.
3. **The total <u>annual</u> electricity consumption required to heat and cool units 1, 3 and 5, were 1382 kWh, 458 kWh and 1070 kWh, respectively.** This is broken down on a monthly basis, and according to time-of-use, bracket in Figure 4.21. This is a small amount of energy relative to the area being conditioned, and it speaks to the energy efficient design of the condo.
4. **The total <u>annual</u> cost to heat and cool units 1, 3 and 5, taking into account time-of-use rates were $127, $42 and $95.** It should be noted that these numbers only take into account the per-kWh electricity fuel cost and not distribution or regulatory charges. The monthly breakdown is shown in Figure 4.22. These operating costs are extremely low. In general, the cost is split in half between off-peak and mid/on-peak usage. Approximately 20% of electricity costs could be saved if the entire load was shifted to an off-peak time-of-use bracket but, in this case, the consumption is so low that the savings may not justify the added system complexity.
5. **The EST varies between 9 °C and 17 °C over the course of the year.** Design guidelines suggest that the expected <u>difference</u> between heating and cooling season ESTs should be between 16 to 25°C (see Section 3.2.3) for a cost/performance optimized ground loop. The difference here is on the scale of 8°C so it is likely to tend towards the performance end of the spectrum rather than the cost optimized end. It should be noted that the temperature sensor is not able to distinguish when there is flowing fluid in the pipe. When there is no flowing fluid the pipe temperature will eventually equilibrate with the surroundings and this would show up as pronounced warming trend. This is likely the cause of the high entering source temperatures in April and May. This would be a period of low load and therefore the pumps may not have been circulating.

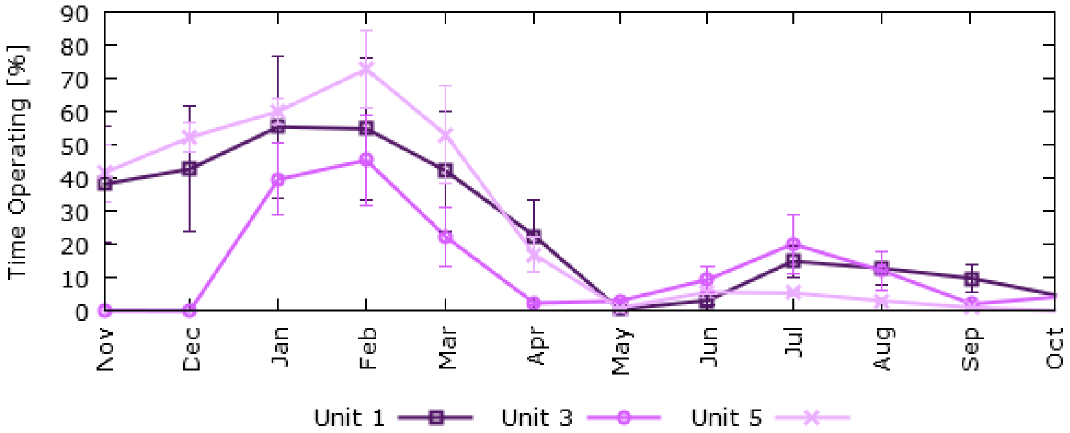

Figure 4.19: The heat pumps are on between 40 and 80% of the time in peak heating months and less than 20% of the time in peak cooling. The difference between the variation in the trends could be due to differences in thermostat settings, exterior wall area or similar. Data was not gathered on tenant temperature preferences so it is very possible that the unit 3 heat pump did not operate because the tenant was comfortable with cooler indoor temperatures. Error bars are wide due to the long logging interval.

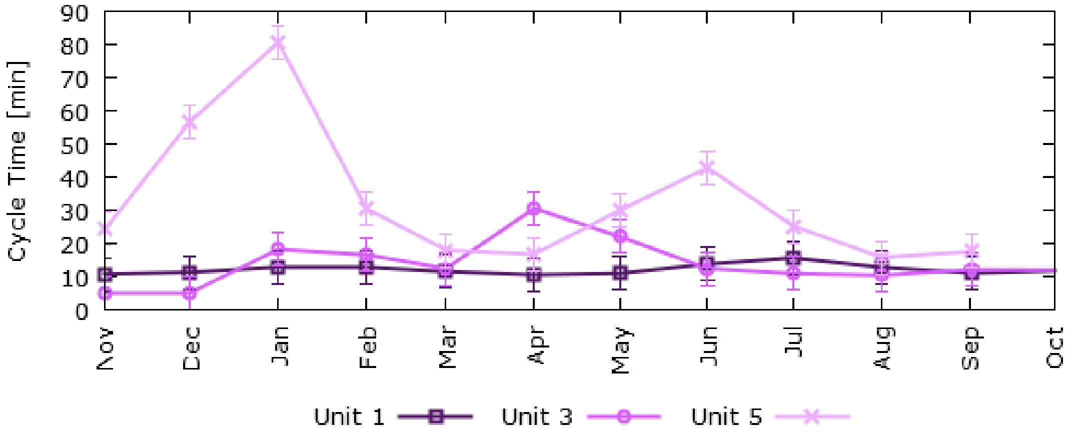

Figure 4.20: Unit 5 has longer cycle times, approaching 80 minutes during peak heating and 40 minutes during peak cooling. The other 2 units have cycles times on the scale of 10 minutes. The unit 5 heat pump is operating most frequently in heating mode so it is reasonable that the heating mode cycle times are the longest. Differences in the cycle times could be a result of thermostat settings. The unit 5 thermostat may settings may be such that the difference between the turn-on and turn-off temperature is larger than for the other units.

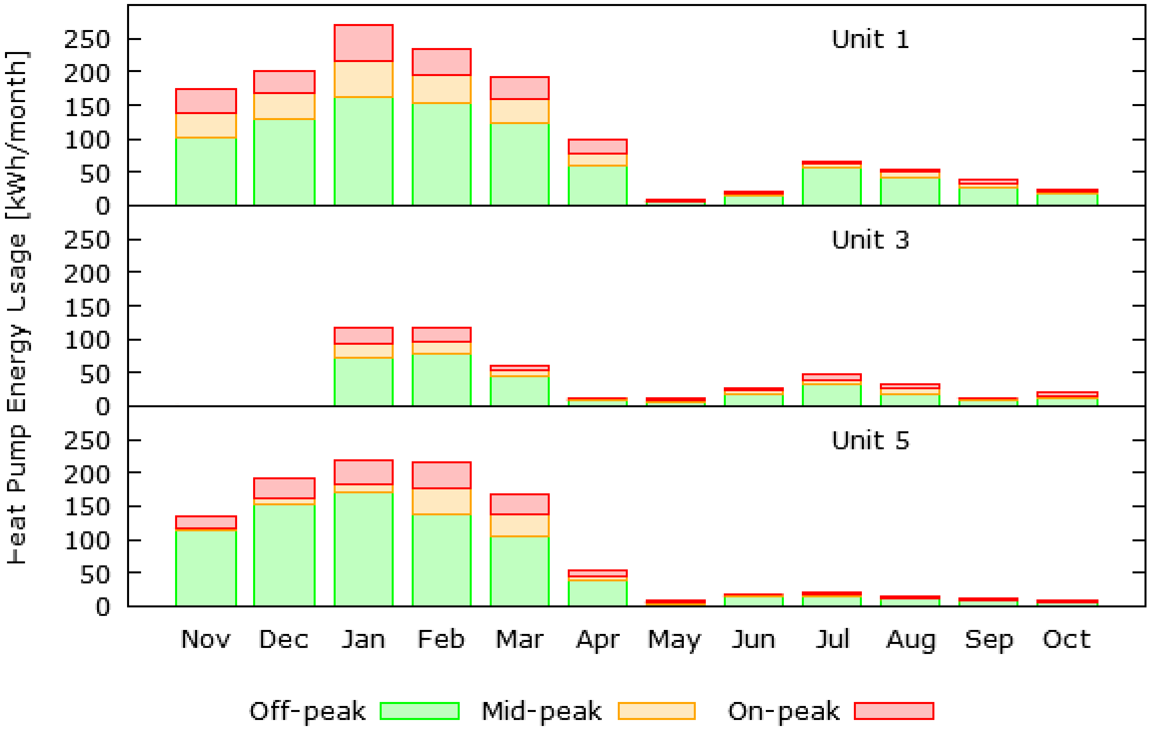

Figure 4.21: The monthly energy consumption is shown broken into time-of-use brackets.

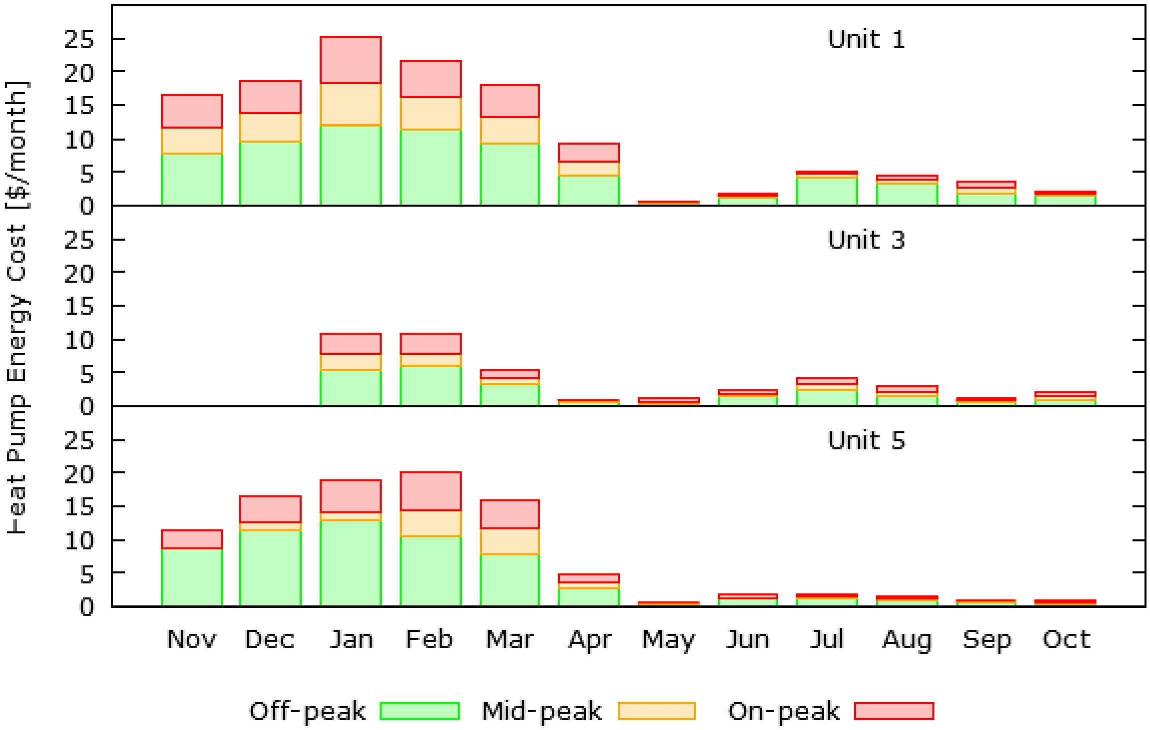

Figure 4.22: The monthly electricity costs are shown broken into time-of-use brackets

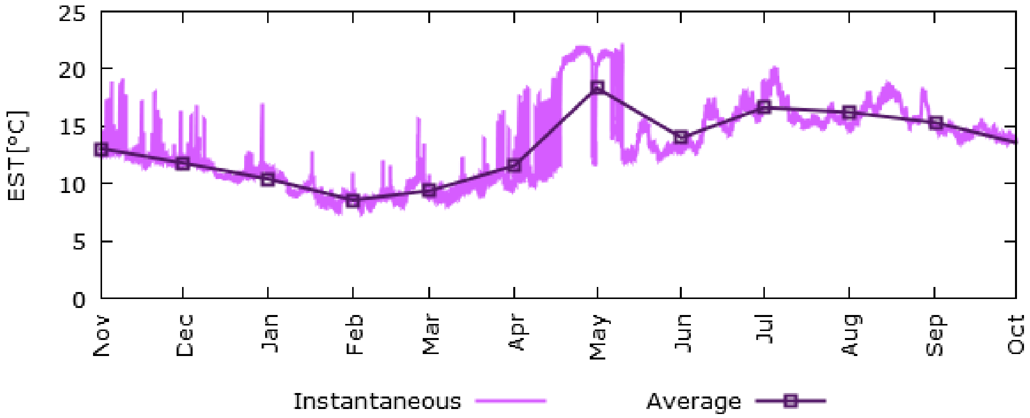

Figure 4.23: The seasonal variation in the entering source temperature is approximately 8 °C

4.3.4 Findings: Summary

Relevant system metrics are summarized in Table 4.11. PTIU values show that the building is heavily heating dominant and that the heat pumps are sized appropriately to meet the heating load, while operating infrequently in cooling mode. If this is the case throughout the building then it is likely that the system is imbalanced. However, it is worth noting that the compressor electrical power consumption will reduce the heat removed from the ground in heating mode and increase heat rejection to the ground in cooling mode. This would help mitigate the imbalance as would the apparently large ground loop sizing.

Table 4.11: Greenlife Condominium geoexchange performance metrics

	Unit 1	Unit 2	Unit 3
System Sizing			
PTIU – design heating day	0.75	0.87	0.70
Maximum PTIU – heating month	0.55	0.45	0.73
PTIU – design cooling day	0.26	0.40	0.06
Maximum PTIU – cooling month	0.15	0.20	0.06
Total annual heat delivered [kWh per ft^2]	N/A	N/A	N/A
Total annual heat removed [kWh per ft^2]	N/A	N/A	N/A
Maximum average monthly heating mode cycle time [min]	13	18	81
Maximum average monthly cooling mode cycle time [min]	16	13	43
System Efficiency			
Annual Heating mode COP	N/A	N/A	N/A
Annual Cooling mode EER	N/A	N/A	N/A
Ground Loop Sizing			
Lowest heating mode EST [°C]	9	9	9
Highest cooling mode EST [°C]	18	18	18
Imbalance [kWh per ft borehole length]	N/A	N/A	N/A
System Electrical Energy Consumption			
Total annual heating [kWh per ft^2]	N/A	N/A	N/A
Total annual cooling [kWh per ft^2]	N/A	N/A	N/A
Total annual [kWh per ft$^{2]}$	1.5	0.7	1.6
Emissions Savings			
Annual GHG savings [kg eCO$_2$ per rated heating ton]	N/A	N/A	N/A

4.3.5 Operational Lessons Learned and Recommendations

1. The COP of the heat pumps were not obtained due to issues encountered during the monitoring period. This could have been identified early on had the monitoring system undergone a more thorough commissioning procedure. **Appendix A offers a suggested workflow for implementing a monitoring program, including commissioning, and it is suggested that future monitoring efforts give consideration to this workflow.**
2. It was observed that the cycle time of Unit 5 was on average much longer than the other units. It appeared to have a somewhat larger relative load in that it was operating a larger percentage of the time but it also seems likely that this difference could have additionally been due to thermostat settings of the unit. If a thermostat is set to turn on at a lower temperature and off at a higher one, it will cause the heat pump to operate with longer cycle times. The cycle times of Units 1 and 3 where typically 10 to 20 minutes and this would likely be considered short. Heat pumps with shorter cycle times may wear out sooner and operate less efficiently. **It would be helpful if unit owners were made of aware of how cycling might affect the performance and lifetime of their heat pump and how thermostat settings are important in this regard.**
3. Best practice design guidelines suggest that an optimal variation (ie. the difference between the warmest EST in heating mode and coolest EST in heating mode) in EST in terms of both cost and performance may be in the range of 16 to 25 ^{o}C. The variation in EST at this site was 8^{o}C**.** This may suggest that the **heat pump sizing is optimized more for performance rather than for cost in that it may be larger than it needs to be. However, the larger ground loop will be better able to cope with the imbalances that are likely present at this site.**
4. The total annual electricity required to operate the Peel House A and B geoexchange systems was 7.7 and 2.4 kWh/ft^2 respectively. These units operate at 1.5, 0.7 and 1.6 kWh/ft^2. **This shows a geoexchange system in an energy efficient condo unit may consume much less electricity compared to a geoexchange system in a conventional detached residential building when adjusting for building square footage.** It should be noted that the Peel House A and B includes the energy required to circulate the fluid through the ground loop where the Greenlife Condominium units do not but the Greenlife power consumption data additionally includes the power to run the air handler. These factors may ultimately balance out.
5. **To properly asses the COP of the system a knowledgeable technician needs to service the monitoring system and additional instrumentation should be added to Units 2, 4 and 6.**
6. The monitoring timescale was 5 minutes but the cycle times are, in some cases, on the scale of 10 minutes. **A tighter monitoring timescale would be able to more accurately characterize the heat pumps performance.**

4.4 TRCA Restoration Services Building

4.4.1 Geoexchange System Overview

At approximately 12,000 ft^2 of conditioned area,[53] the Restoration Services Centre facility was constructed in 2007. It is a centre for the Toronto and Region Conservation Authority's (TRCA) resource management and environmental restoration projects while also acting as a showcase for sustainable building design. The ground loop of the Restoration Services Centre geoexchange system is composed of three horizontal slinky-style ground loops. This style of loop is cheaper to implement then vertical loops but requires less space than conventional horizontal loops. The system is powered by three Waterfurnace EW060 ground source heat pumps operating in parallel. The heat pump charges a buffer tank which is used for radiant in-floor heating and forced-air cooling. Radiant cooling is typically avoided due to condensation issues but, in this case, supplemental cooling is also provided by the in-floor loops. The heat pumps are controlled by the building's BAS. The distribution and ground loop pumps are not interlocked to the heat pump but rather, they are always on (termed here as "constant flow"). The effect of constant flow pump operation will be a main point of analysis for this site.

Figure 4.24: (Left) The Restoration Services Building exterior. (Top right) The three ground source heat pumps power the geoexchange system. (Bottom right) Ground loop pumps.

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[53] It was not clear from this site whether or not 12,000 ft^2 included the second level or the garage area that has a separate heating system so this square footage value should be treated as an estimate.

Table 4.12: Building and geoexchange system overview for the Restoration Services Building

Building	
Square footage	12,0000 ft2
Usage	Office Building; Primarily 8am – 5pm on weekdays
Geoexchange System	
GSHP Unit(s)54	Waterfurnace EW060 water-to-water heat pump 3 heat pumps 60.7 MBtu/hr heating capacity per heat pump 15.2 Btu/hr per ft2 heating capacity 61.1 MBtu/hr cooling capacity per heat pump 15.3 Btu/hr per ft2 cooling capacity 3.0 COP 13.5 EER Commissioned 2007
Ground-loop	Each heat pump has its own slinky-style horizontal loop. Loop length was not determined.
Distribution	Heat pump charges buffer tank used for radiant in-floor heating and forced-air cooling. Supplemental cooling achieved using in-floor loops.

4.4.2 Monitoring System

The geoexchange monitoring system is outlined in Table 4.13. The EST, LST and ground loop flow rate was monitored as well as the power consumption of the unit. However, an improperly installed temperature sensor prevented certain metrics, like COP or Capacity, from being used in the analysis for the majority of the monitoring period. The error was fixed in July 2014 and cooling performance data, including COP was available for July to September 2014. Three heat pumps were monitored but with an aim for conciseness, results are presented for only one of the heat pumps.

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[54] Water Furnace, 2008 . EW Installation Manual. Online document: http://www.waterfurnace.com/literature/eseries/IM1469.pdf (Accessed Dec. 21st/2014).

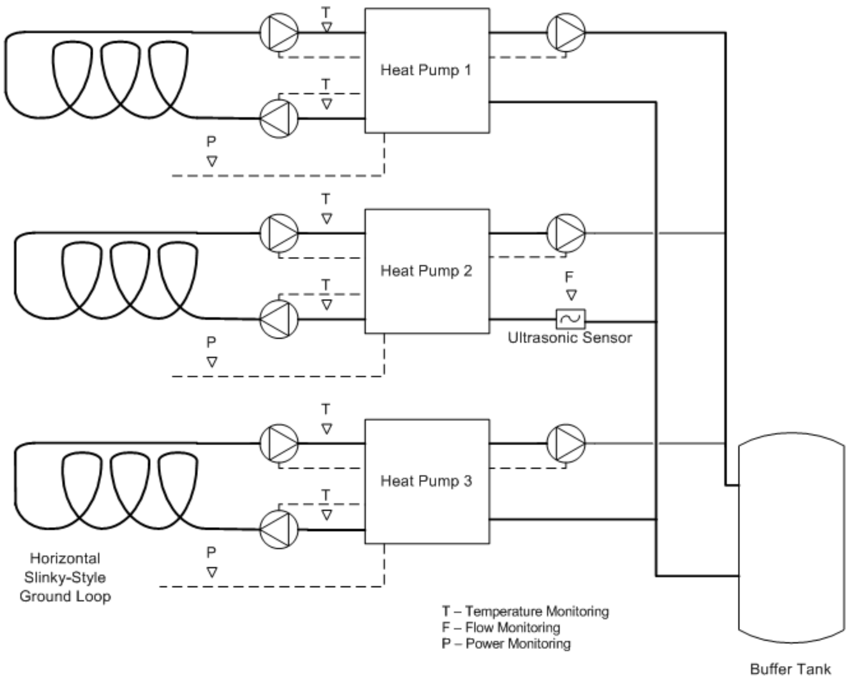

Figure 4.25: Schematic of Restoration Services Building geoexchange system showing monitoring points

Table 4.13: Monitoring overview for the Restoration Services Building

Flow	
Flow was not monitored continuously. An Eastech Flow Controls Vantage 3000 ultrasonic flow meter was used to determine the ground loop flow rate. Several measurements were taken over the course of day. The measurements ranged from 12.2 to 11.4 GPM, with an average of 11.8 GPM. This flow rate was assumed to apply across all points of time. This is a reasonable assumption given that the circulators are not variable speed. A flow measurement was only achieved on 1 of 3 heat pumps and this is the heat pump used in the analysis.	In-house testing calibration suggests an accuracy: ±10% of reading
Temperature	
Onset S-TMB-M002 Smart Temperature Probe (Surface Mounted)	Accuracy: ±0.2^{o}C Range: -40^{o}C to 100^{o}C
Power	
Wattnode WNB-3Y-208-P	Accuracy: 0.05% full scale and 0.45% reading Range dependent on current transducer (CT)
Acquisition	
Onset Hobo U30 Data Logger	
Monitoring Period	
February 2013 – July 2014	
Data Logging Interval	
Averaged data logged every 5 minutes. This interval was chosen instead of something shorter because the data needed to be collected manually from the site and the internal memory of the unit would fill up quicker with a shorter logging interval.	

4.4.3 Findings: Performance Plots

1. **The heat pump is appropriately sized for the heating load.** The heat pump is on for as much as 70% of the time in heating mode but not more than 15% of the time in cooling mode. Figure 4.26 shows, on a monthly basis, the percentage of time that the heat pump is on in heating or cooling mode. On a day approaching design heating conditions (Jan 23rd, 2013, see Section 3.2.7) the heat pump was on 88% of the time and on a day approaching design cooling conditions (July 17th, 2013, see Section 3.2.7), the heat pump was on 36% of the time. This suggests that the heat pump is appropriately sized for the heating load, but is more than needed for the cooling load.
2. **The average cooling mode cycle time is 10 minutes while that for heating mode is typically 30 to 60 minutes.** Figure 4.27 shows the average cycle time on a monthly basis. Short cycle times can degrade COP due to the losses associated with starting the compressor. The cycle time is affected by the heat pump capacity, the buffer tank size, the load and aquastat setting. The heating cycle time seems reasonable and is longer, in part, because the heating load is so much larger*, ie*. as the tank is being heated by the heat pump more of that heat is being taken away to heat the building and it takes longer to reach the set-point.
3. **Operating the pumps in constant flow operation causes up to 600 kWh per month to be consumed unnecessarily.** Ideally, the circulator pumps are interlocked to the heat pump, meaning that the circulator pumps would only be on when the heat pump is on but this is not the case with this installation. Operating the circulator pumps when the heat pump is off does not normally benefit the system but it does create an extra load. Here that load is on the scale of 0.9 kW (two ground loop circulators and one distribution circulator). The power draw is as much as 6 kW when the heat pump is on so this is not an insignificant amount of power. Figure 4.28 shows that this resulted in up to 600 kWh per month consumed with no benefit to the geoexchange system.
4. **Approximately a third of the total electricity cost for 2013 was spent to run the circulator pumps when the heat pump was not on, increasing operating costs by more than $500, from $1,110 to $1,630.** These figures do not include distribution and regulatory charges. Figure 4.29 breaks down the additional cost, on a monthly basis, of operating the circulator pumps when the heat pump is off. It is as much as 60$ for a given month. The cost of having an electrician properly interlock the circulator pumps would likely be recouped within a year and result in substantial savings over the long term.
5. **Operating the circulator pumps in constant flow operation decreased the COP by as much as 80%.** Figure 4.30 shows the effect of constant flow operation on the COP. For example, in August 2013, the geoexchange would have required 294 kWh to operate if the circulator pumps were interlocked. However, because of constant flow operation, the electricity consumption for the month was 906 kWh. Using 906 kWh as the electricity consumption instead of 294 kWh in the COP calculation would reduce the COP to 32% of its initial value (from 3.5 to 1.1 for example), or put differently, the COP degradation due to constant flow operation is 68%. This effect is largest for the months when the heat pump is on the least, specifically, the cooling months. The COP degradation is 10 to 20% in the heating months.

6. **Shifting peak and mid-peak loads to off-peak could reduce electricity costs by 20%.** The time-of-use energy and cost breakdowns are shown in Figures 4.31 and 4.32. The total operating cost for the monitoring period was $1992 when taking into account time-of-use rates (but not including regulatory and distribution charges), however, if all the energy was consumed at off-peak rates the cost would be $1,642.
7. **The EST varies between just above 0 °C in the heating season to 20 °C in the cooling season.** Figure 4.33 shows the monthly EST. Since this is a horizontal loop, the variation in entering source temperature is expected to be greater.
8. **Cooling mode EER was dropped from 11.4 to 9.5 from July to September 2014 when including the electrical power consumption of the ground loop circulator in the calculation. The drop was from 14.1 to 11.4 if only the compressor box power consumption was considered.** Table 4.14 shows the cooling mode performance results achieved once the sensor error had been fixed. It should be noted that these results are for the last half of the cooling season and it is expected that they will be poorer than the average COP (or EER) for the entire cooling season. The heating mode COP in September was either 3.5 or 3.9 depending on what is included in the calculation. This is higher than the rated COP because the ground temperature is at 17°C where the rated COP is for a ground temperature of 0°C. The product literature did not indicate that it received certified AHRI testing and this likely means that the reported COP and EER of 3.0 and 13.5 does not include ground loop circulator pump power consumption. If this is the case, then the measured COP and EER exceed ratings but this is in part because of the more optimum ground temperatures seen during the monitoring period.

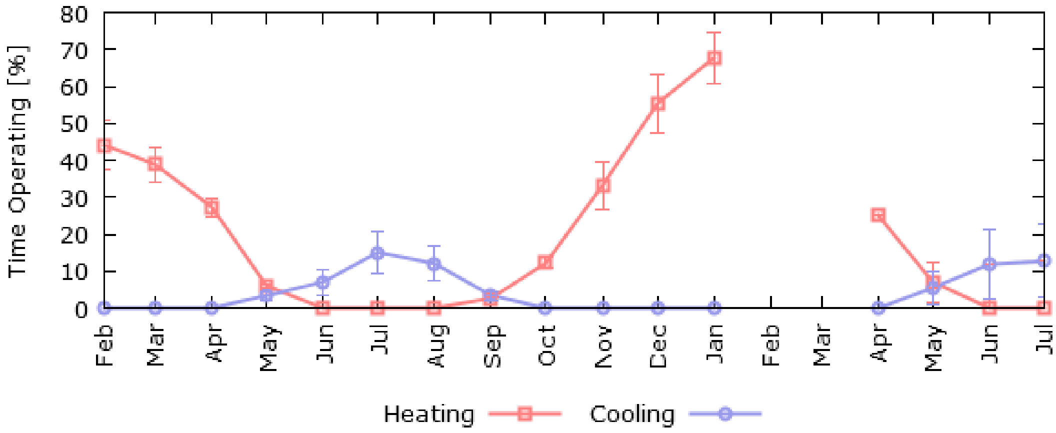

Figure 4.26: The heat pump is on for as much as 70% of the time during the heating season and 20% during cooling season.

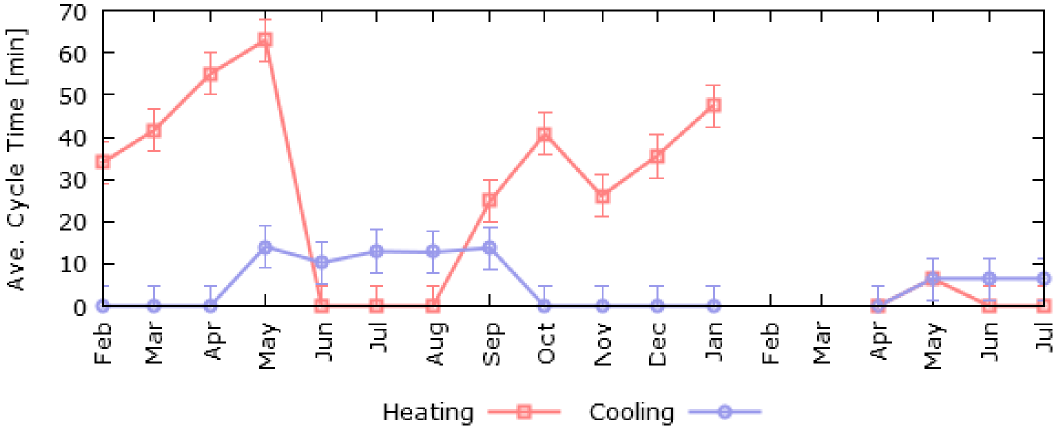

Figure 4.27: Heating mode cycle are typically 30 – 60 minutes while cooling mode cycles are shorter at 10 minutes. This is likely due to the larger heating load and smaller cooling load.

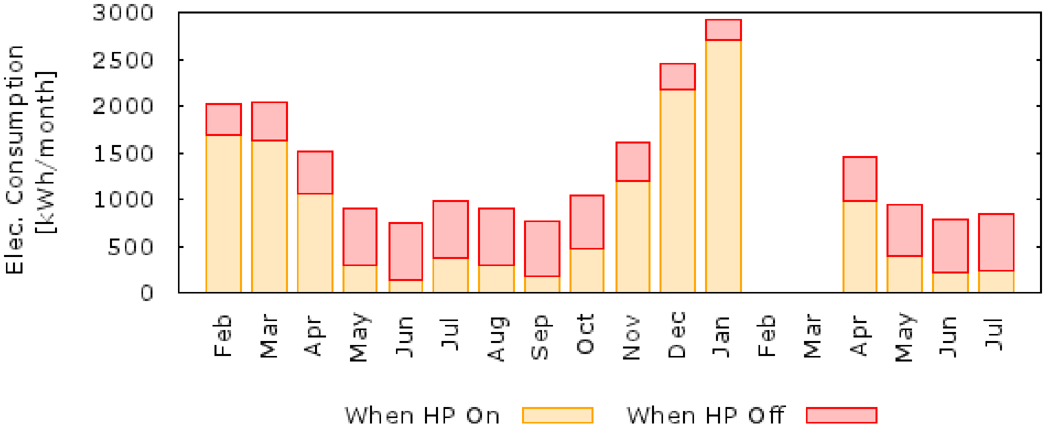

Figure 4.28: The electricity consumption shown in red is due to the circulator pumps functioning when the heat pump is off. This is a parasitic load that degrades performance.

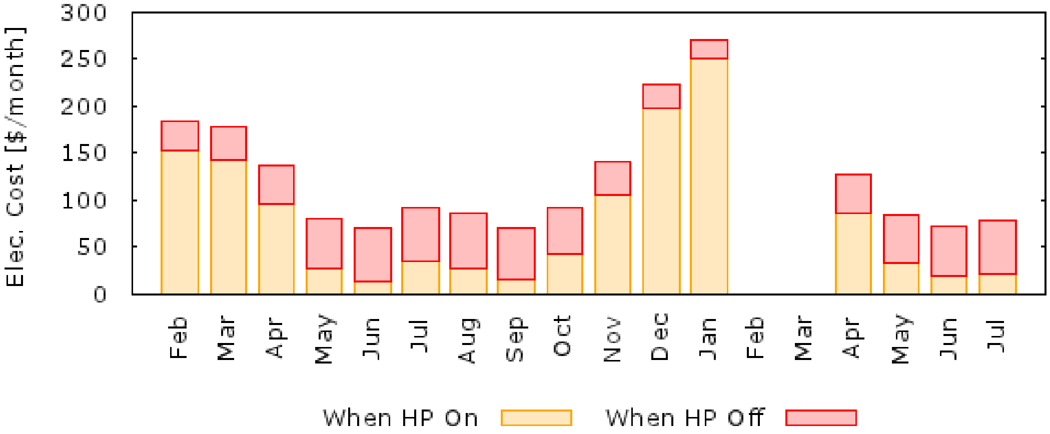

Figure 4.29: The electricity costs shown in red are due to the circulator pumps functioning when the heat pump is off.

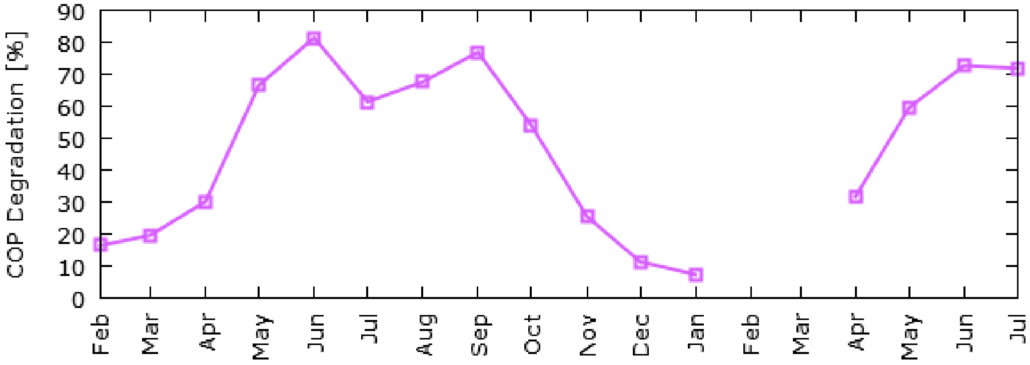

Figure 4.30: The COP degradation shows the extent to which the COP is reduced due to the constant flow operation of the circulator pumps. For example, in June the COP decreased by 80%, if it was 4.0 then constant flow operations reduced it to 0.8.

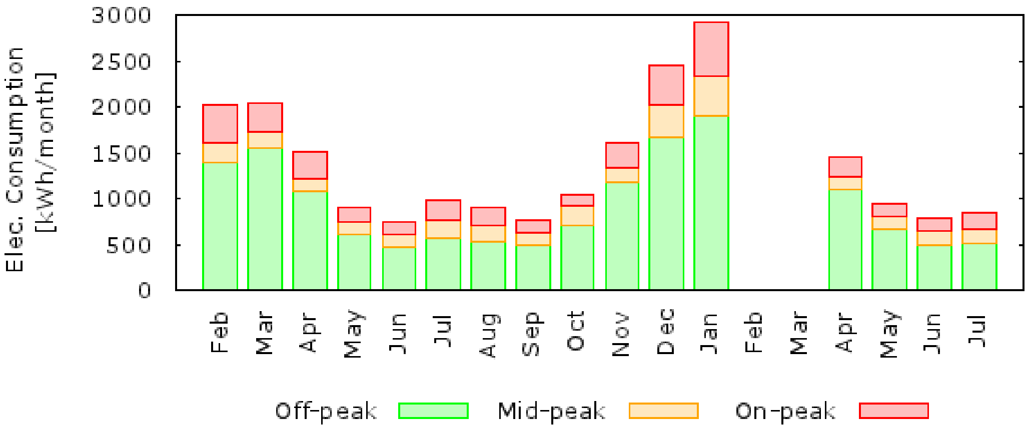

Figure 4.31: The time of use electrical consumption of the geoexchange system shows that the majority is off-peak which is interesting because this is an office building primarily used between 8am and 5pm.

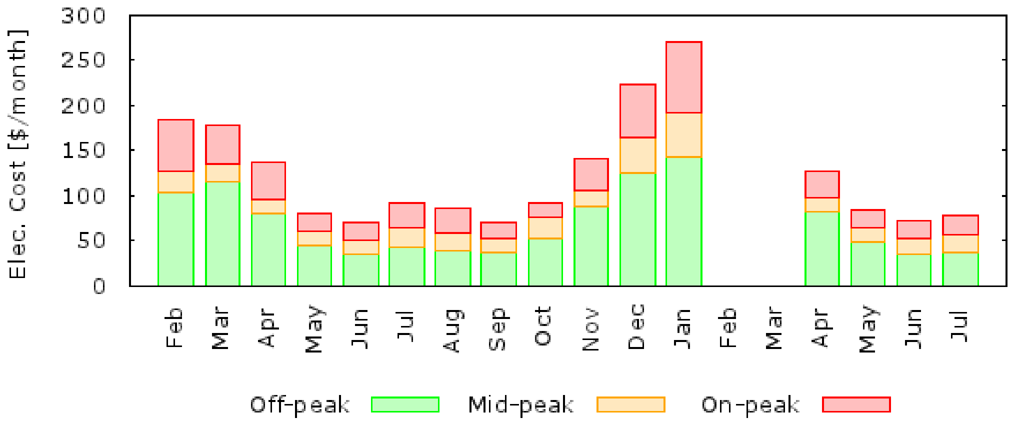

Figure 4.32: The time-of-use electrical costs. Peak and mid-peak costs approach half of the total electrical costs. If all peak and mid-peak loads were shifted to off-peak then it would result in a 20% savings.

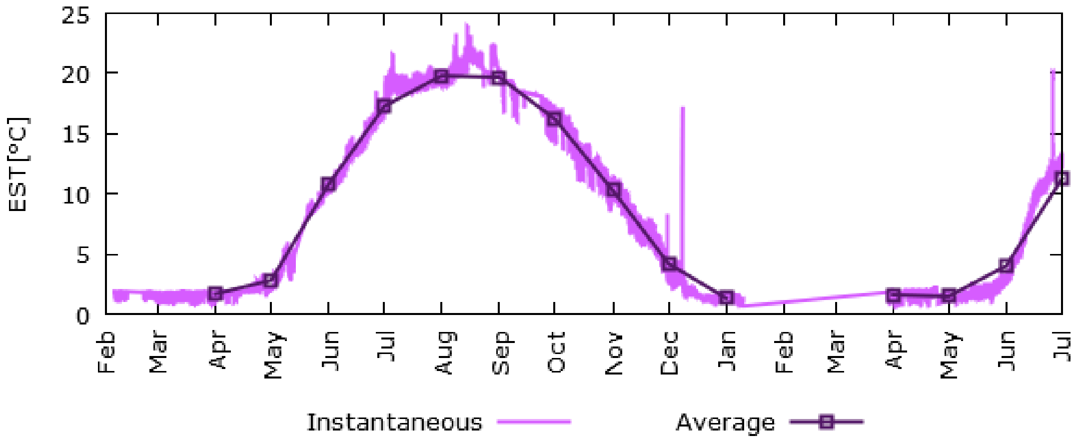

Figure 4.33: The entering source temperature varies between slightly more than 0 °C to approximately 20 °C.

Table 4.14: Restoration Services Building geoexchange system performance results from July to September 2014

Month	% Time On In Cooling Mode	Avg. Cycle Time [min]	Avg. EST [°C]	Avg. dT [°C]	Heat Removed [kWh]	Heat Delivered [kWh]	Cooling EER (incl. comp. & ground circ.)	Cooling EER (incl. compressor only)	Heating COP (incl. comp. & ground circ.)	Heating COP (incl. compressor only)
July	11%	12	14	3.7	720±120	-	11.4±1.9	14.1±1.9	-	-
Aug	9%	11	16	3.7	610±100	-	10.5±1.7	12.7±1.7	-	-
Sept	4%	13	17	3.8	280±50	390±40	9.5±1.7	11.4±1.7	3.5±0.4	3.9±0.4

4.4.4 Findings: Summary

Table 4.15 shows a summary of important system metrics. In general, the heat pump appears to be sized appropriately for the loads and if the constant flow operation of the circulators is ignored, the heat pump appears to be operating near manufacturer ratings.

Table 4.15: Restoration Services Building geoexchange performance metrics

System Sizing	
PTIU – design heating day	88
Maximum PTIU – heating month	68
PTIU – design cooling day	36
Maximum PTIU – cooling month	16
Total annual heat delivered [kWh per ft^2]	N/A
Total annual heat removed [kWh per ft^2]	N/A
Maximum average monthly heating mode cycle time [min]	55
Maximum average monthly cooling mode cycle time [min]	14
System Efficiency	
Annual Heating mode COP[1]	3.5
Annual Cooling mode EER[2]	14.1
Ground Loop Sizing	
Lowest heating mode EST [^{o}C]	1
Highest cooling mode EST [^{o}C]	20
Imbalance kWh per ft borehole length	N/A
System Electrical Energy Consumption	
Total annual heating kWh per ft^2 [3]	2.8
Total annual cooling kWh per ft^2 [3]	0.3
Total annual kWh per ft^2 [3]	3.1
Emissions Savings	
Annual GHG savings [kg eCO$_2$ per rated heating ton]	N/A

[1] Not an annual value

[2] Chosen from the monthly of July because it is likely to be near the total seasonal average EER

[3] This does not include the constant flow operation of the circulator pumps and assumes all heat pumps are delivering/removing the same amount of heat at the same efficiency

4.4.5 Operation Recommendations and lessons learned

1. The constant flow operation is severely limiting performance. A third of the electricity annual electricity costs are being incurred unnecessarily. The cost of fixing this issue will likely be recouped within only a year of operation. If it is not fixed, then it could result in tens of thousands of dollars in unnecessary expenses over the lifetime of the three heat pumps in the building. **It is recommended than an experienced technician or electrician interlock the circulator pumps to the heat pump unit according to the guidelines in the installation manual. This issue could have been perhaps been caught at the commissioning phase and in this regard, it would be helpful if standardized commissioning templates were available to installers that included verifying that circulator pumps are interlocked.**
2. The cooling mode cycle time is short because the load is lower. This may cause increased wear on system components. **It may be beneficial to adjust the BAS control algorithm to rotate control of the heat pumps such that only a single heat pump is operating at one time so that the load is better matched to the system capacity.**

3. The temperature sensor issue has been fixed and subsequent analysis will include COP and capacity for the upcoming 2014/2015 heating and cooling seasons. The error arose because a technician installed the sensor wrong due to inexperience. **It is suggested that the monitoring workflow presented in Appendix A be followed in the future to avoid such errors.** Even if the install had been done incorrectly, the issue could have perhaps been caught sooner if a more thorough commissioning was done.
4. **Future work might examine the viability of time-of-use geoexchange system control.** In this case, approximately 20% of the electricity fuel cost (not including distribution and regulatory charges) could be saved if the mid and on-peak loads were shifted to an off-peak time-of-use bracket.
5. This is a heating dominant system and the sizing was seen to be appropriate for the heating load. **The metrics outlined in Table 4.4.4 may be useful for benchmarking exercises.**

4.5 Downsview Park Office Building

4.5.1 Geoexchange System Overview

The office building is located in Downsview Park in Toronto, ON. The geoexchange system was installed as a part of more extensive energy upgrades. It uses a pair of two-stage Climate Master TMW 340 ground-source heat pumps operating in parallel. The heat pumps are attached to the ground loop comprised of 26 vertical boreholes going down to a depth of 300 ft. It is the primary heating and cooling for the building which is 23,000 ft^2.[55] The system is controlled by a BAS and does not use a buffer tank.

Figure 4.34: (Left) Street view of the Downsview Park Office Building. (Right) Two TMW 340 Climate Master heat pumps power the geoexchange system.

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[55] This is the gross floor area of the building including the basement, first floor and second floor.

Table 4.16: Building and geoexchange system overview for Downsview Park Office Building

Building	
Square footage	23,000 ft^2
Usage	Office Building; Primarily weekdays 8am – 5pm
Geoexchange System	
GSHP Unit(s)56	Climate Master TMW 340 two-stage heat pumps 2 heat pumps 316 MBtu/hr heating capacity per heat pump 27.7 Btu/hr per ft^2 heating capacity 399.6 MBtu/hr cooling capacity per heat pump 35.1 Btu/hr per ft^2 cooling capacity 3.4 COP 18.4 EER Commissioned 2007
Ground-loop	26 Vertical boreholes 300 ft deep 12 ft of borehole length per MBtu/hr rated heating capacity
Distribution	Forced-air heating and cooling.

4.5.2 Monitoring System

The geoexchange monitoring system is outlined in Table 4.17 and a schematic diagram of the system with monitoring points labeled is shown in Figure 4.35. The system is sufficiently complex that it requires continuous flow rate monitoring to determine COP and heat delivered/rejected by the system. The system has two heat pumps, each connected in parallel to the same ground loop and the same distribution circuit. Each heat pump has two stages. The ground loop is powered by two circulator pumps operating in parallel but independently controlled by the BAS and not directly interlocked to the heat pump. The monitoring plan for this system intended to save equipment cost and only measure the flow rate at single points in time, when one and both circulator pumps were operating. The flow measurement and the circulator pump power draw (to determine which pumps were on) could then be used to determine the flow, and subsequently, COP, across the whole monitoring period. This was not straightforward because the pumps cycled on and off often and also because there was a delay between when the pump started consuming full power and when it reached full flow. Because of these difficulties it was not possible to determine the COP for this system; it would require continuous flow monitoring.

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[56] Climate Master, 2013. Tranquility TMW Series Specifications. Online document: http://www.climatemaster.com/downloads/LC394.pdf (Accessed Dec. 21st/2014).

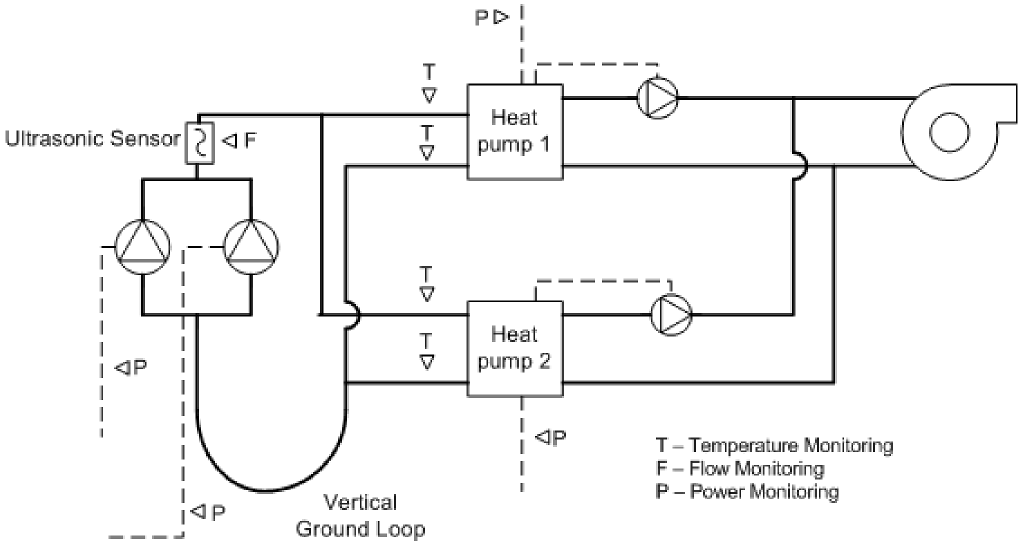

Figure 4.35 Schematic diagram of Downsview Park Office Building geoexchange system

Table 4.17: Monitoring Overview for Downsview Park Office Building

Flow	
Flow was not monitored continuously. An Eastech Flow Controls Vantage 3000 ultrasonic flow meter was used to determine the ground loop flow rate both when a single circulator and when both circulator pumps were operational. However, the circulator pumps were not interlocked to the heat pump, but rather controlled by the BAS. Because the circulator pumps were not interlocked, it was not straightforward to use the flow rate measurements to calculate capacity or COP from the data.	In-house testing calibration suggests an accuracy: ±10% of reading
Temperature	
Onset S-TMB-M002 Smart Temperature Probe (Surface Mounted)	Accuracy: ±0.2°C Range: -40°C to 100°C
Power	
Wattnode WNB-3Y-208-P	Accuracy: 0.05% full scale and 0.45% reading Range dependent on current transducer (CT)
Acquisition	
Onset Hobo U30 Data Logger	
Monitoring Period	
February 2013 - January 2014 (Missing April 2013)	
Data Logging Interval	
Averaged data logged every 5 minutes.	

4.5.3 Findings: Performance Plots

1. **Heat Pump 1 (HP1) is on nearly 90% of the time during peak heating months whereas Heat Pump 2 (HP2) is on only 10% of the time, while during peak cooling months they are both on less than 40% of the time.** The PTIU of each unit is shown in Figure 4.36. At first glance, having only one of the units accomplish the majority of the heating may not be an ideal way to operate the system as one of the heat pumps may wear out before the other due to increased usage. On a day that approached design heating conditions (Feb 7th, 2013, see Section 3.2.7) HP1 was on for 99% of the time but HP2 was only on 2% of the time. Collectively, it would seem that only 50% of the available capacity is being used on an approximate design day suggesting that the the heat pumps are oversized for the load. On a day that approached design cooling conditions (July 17th, 2013, see Section 3.2.7), HP1 was operating 53% of the time and HP2 was operating 56% of the time. Again, only about half of the available capacity was required on one of the warmest days of the year and this indicates the system is likely oversized.
2. **The cycle time of HP1 is typically twice to three times that of HP2 during peak heating or cooling.** Cycle times are shown in Figure 4.37. HP1's peak heating and cooling cycle times are 160 and 60 minutes, respectively, while that for HP2 is 90 minutes and 20 minutes. HP1's cycle time is the longest seen in this study. Cycle time must be examined in the context of the other performance metrics but typically short cycle times are associated with poorer COPs and increased component wear. HP1 at least does not appear to have any issues with short cycling.
3. **The circulator pumps are not interlocked to the heat pumps but rather are controlled by the BAS, and they are often operating when the heat pumps are off with potentially minimal performance benefit to the system.** There is some benefit to not perfectly interlocking the pumps to the heat pump. For example, the heat exchangers take time to heat up when the unit first turns on and therefore, for optimal performance it may be best to turn the circulator pumps on after the heat pumps rather than at the same time. Similarly, the heat exchangers do not cool down instantly so there is some benefit to running the circulator pumps for a short time after the unit has turned off. Furthermore, depending on the pump, it may require time to reach full flow. Figure 4.38 separates the monthly energy consumption into that consumed when the heat pump is on and that consumed when it is off (due to circulator pumps that haven't been interlocked). The red shaded areas represent energy that could have been saved if the pumps had been interlocked although, as previously noted, interlocking the pumps perfectly is not always ideal for performance. If this is considered to be wasted energy then the resultant effect on COP is shown in Figure 4.39. **The COP is degraded by as much as 40% in the shoulder months but less than 5% during the peak heating and cooling seasons.** Overall, the effect could result in a COP degradation of 10%.
4. **Energy savings of 25% could be achieved if all loads were shifted to an off-peak time-of-use bracket.** The time-of-use energy consumption and cost are shown in Figures 4.40 and 4.41, respectively. This may not be feasible for as a retrofit on this particular site but next generation geoexchange systems might incorporate predictive control, increased ground loop sizing and increased thermal storage to notably reduce operating costs.

5. **The average entering source temperature fluctuates between 9°C and 20°C.** The variation in entering source temperature throughout the year is shown in Figure 4.42. For reasons discussed in Section 3.2.3, the ground loop sizing seems sufficient for the heating and cooling loads and would tend more towards better performance than optimized cost on the cost/efficiency spectrum.

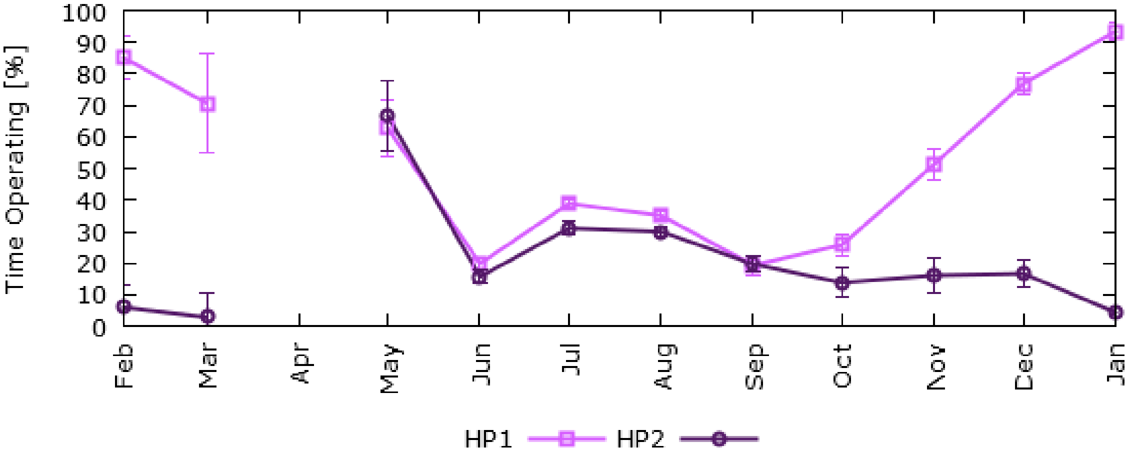

Figure 4.36: The percentage of time each heat pump spend in-use is notably different. It seems that heating is accomplished almost by HP1 alone but cooling is shared evenly amongst both units.

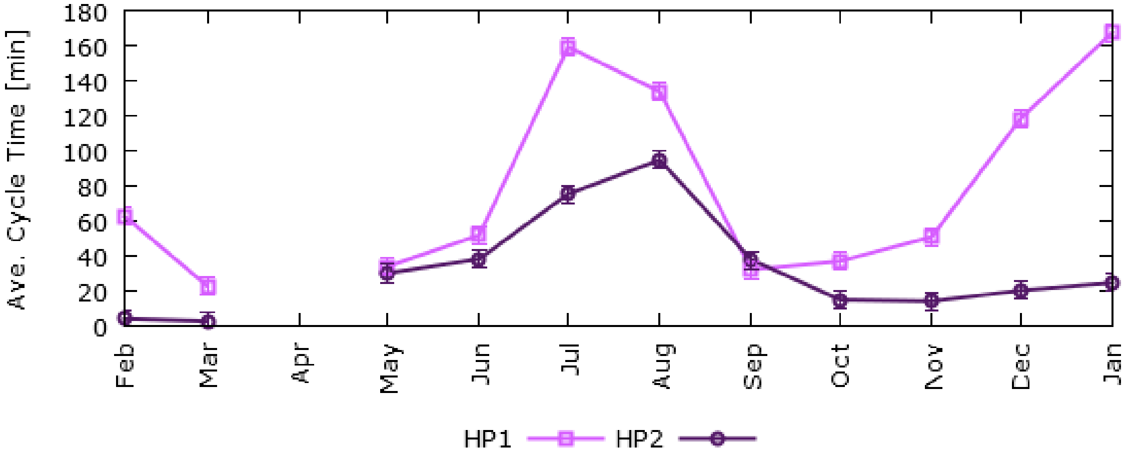

Figure 4.37: The average cycle time is typically 2 to 3 times greater for HP1 than HP2.

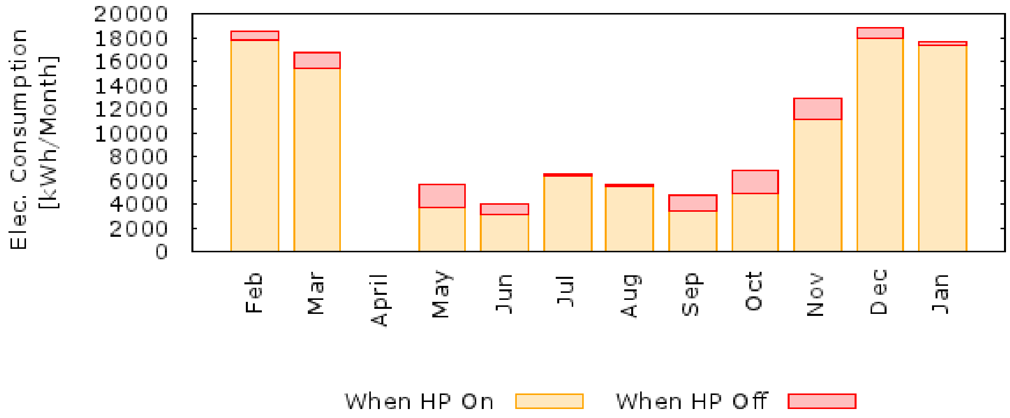

Figure 4.38: The total geoexchange system power consumption is shown broken down into that consumed when the heat pump is on and when it is off. The red sections are due to ground loop circulator pumps operating when the heat pump is off and may not actually be contributing to heat performance.

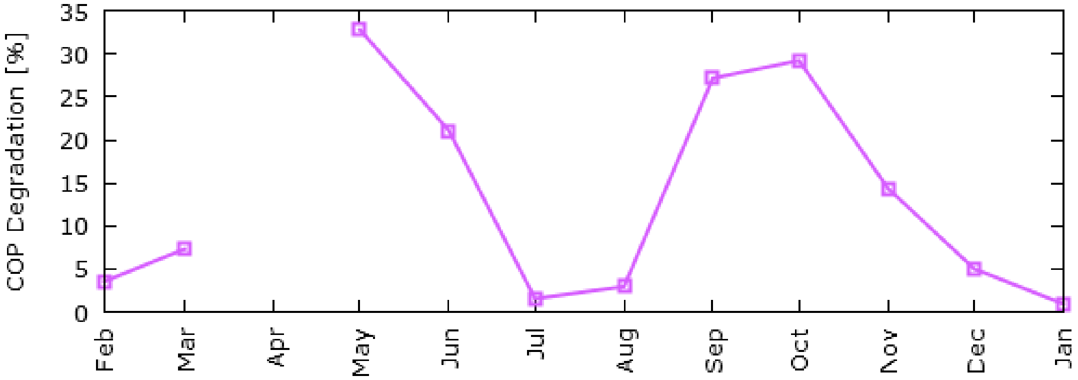

Figure 4.39: The COP degradation due to circulator pumps not being interlocked to the heat pump. It is highest for those months when the heat pumps operate more infrequently.

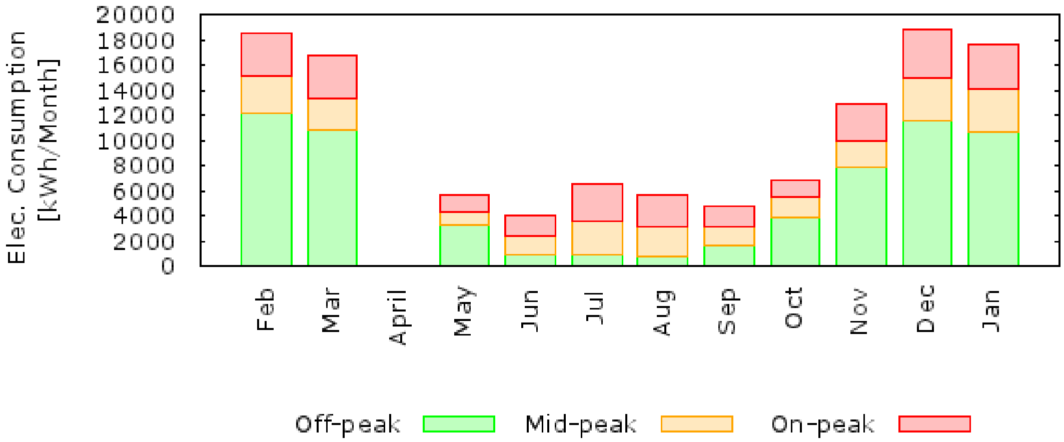

Figure 4.40: The time-of-use electrical consumption for the geoexchange system. The usage is primarily during mid and on-peak TOU brackets.

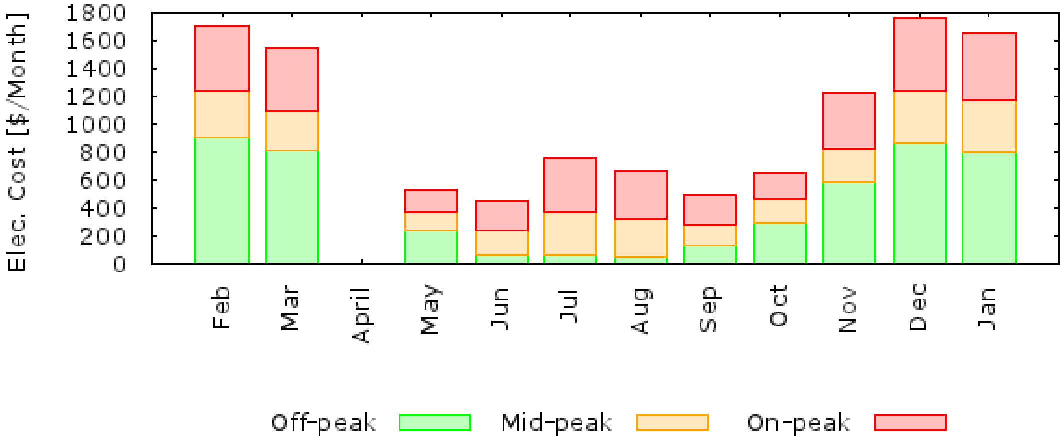

Figure 4.41: The time-of-use cost of electricity for the system is primarily due to peak and mid-peak operation.

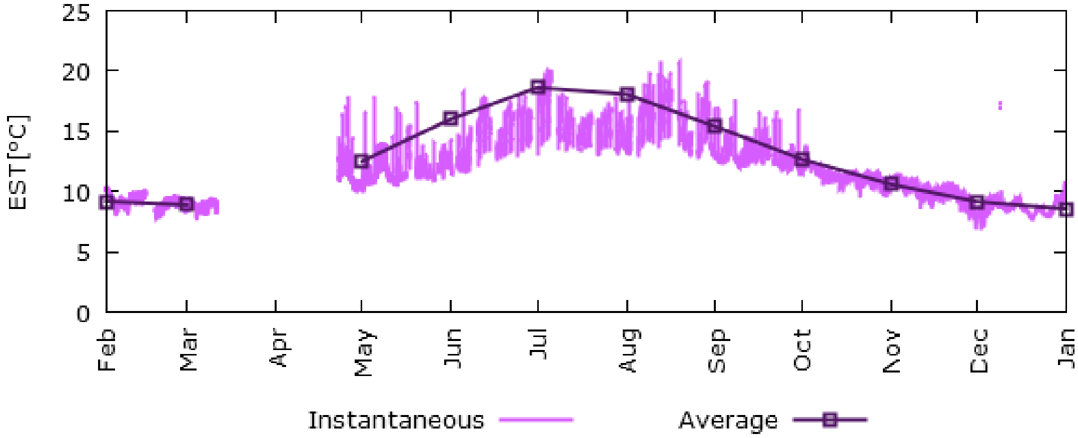

Figure 4.42: The average entering source temperature varies between 9 °C and 20 °C.

4.5.4 Findings: Summary

Table 4.18 summarizes relevant metrics for this geoexchange system. On the hottest summer days and the coldest winter days this system is only operating at 50% of the time. This suggests that it actually has twice as much capacity as is ever actually needed and it is therefore oversized.

Table 4.18: Downsview Park Office Building geoexchange performance metrics

System Sizing	
PTIU – design heating day	0.99/0.02
Maximum PTIU – heating month	0.93/0.16
PTIU – design cooling day	0.53/0.56
Maximum PTIU – cooling month	0.39/0.31
Total annual heat delivered [kWh per ft^2]	N/A
Total annual heat removed [kWh per ft^2]	N/A
Maximum average monthly heating mode cycle time [min]	160/25
Maximum average monthly cooling mode cycle time [min]	168/95
System Efficiency	
Annual Heating mode COP	N/A
Annual Cooling mode EER	N/A
Ground Loop Sizing	
Lowest heating mode EST [^{o}C]	9
Highest cooling mode EST [^{o}C]	20
Imbalance [kWh per ft borehole length]	N/A
System Electrical Energy Consumption	
Total annual heating [kWh per ft^2]	N/A
Total annual cooling [kWh per ft^2]	N/A
Total annual [kWh per ft2]	5.2
Emissions Savings	
Annual GHG savings [kg eCO$_2$ per rated heating ton]	N/A

4.5.5 Operational Lessons Learned and Recommendations

1. The heating load was primarily met by one heat pump operating as much as 90% of the time with the other heat pump hardly operating at all. This resulted in long cycles for the operating heating pump and this is likely to benefit performance. **However, if only one heat pump is to be used in heating mode, it may be advisable to switch it on an annual basis.** That way both heat pumps will receive a more even amount of wear and tear and would then need to be replaced at approximately the same time.
2. The BAS controls the circulator pumps and they are not interlocked perfectly to the heat pump units. This caused COP degradation. **It would be advisable for the operator to give further consideration as to why the circulation pumps frequently operate when the heat pumps are off and perhaps adjust the control algorithm to more closely interlock the components.**
3. There were temperature sensors at this site that were not installed correctly. Additionally, the monitoring plan should have identified that constant flow monitoring was necessary if the COP was to be determined. **These issues could have been caught early on if a more thorough commissioning of the monitoring system was completed. Appendix A offers a sample monitoring workflow that includes monitoring system commissioning that is recommended for future projects.**

4. HP2 short cycles during the heating season. This is likely because the system is oversized for the load. **It may be beneficial to just operate one heat pump at any given time, but rotate which heat pump it is, so as to encourage longer cycles times and have more even component wear.**
5. Future geoexchange systems might employ methods to shift peak and mid-peak loads to off-peak. **For this system, approximately25% of the electricity fuel cost (not including regulatory and distribution charges) could have been saved if the system operated primarily in an off-peak time-of-use bracket.** This would benefit utilities via peak shaving but would require added system complexity and cost.
6. **A timescale shorter than 5 minutes would be beneficial to more accurately characterize the system performance.**

4.6 Durham College

4.6.1 Geoexchange System Overview

The geoexchange system at Durham College is a retrofit commissioned in 2010. It uses a 70 ton Multistack variable flow water-cooled chiller and a forced air distribution system. The difference between a chiller and a heat pump would be that a heat pump has a reversing valve that allows it to transfer heat between the heat exchanger coils in either direction while the chiller can only operate in one direction. External valves must be used with a chiller to obtain the same functionality. The fact that the chiller is water-cooled allows it to be connected to a ground-loop to form a geoexchange system. In heating mode, the chiller's evaporator is connected to the ground loop and the condenser provides heat to the building while in cooling mode, the condenser connects to the ground loop and the evaporator cools the building. The fact that it is variable flow means that it can operate at different capacities and not just in an on/off configuration. System back-up is accomplished by existing boilers on the main campus. The ground loop is composed of 32 boreholes going down to a depth of 600 ft.

Figure 4.43: Durham College[57]

Table 4.19: Building and geoexchange system overview for Durham College

Building	
Square footage58	13,500 ft^2
Usage	8 – 10pm Mon – Fri, Occasional weekend usage. Typically used between Sept – May, with some usage through summer months
Geoexchange System	
GSHP Unit(s)59	Multistack Chiller MS70X6C1H0-R410A 30 ton (360 MBtu/hr) nominal capacity 26.7 Btu/hr per ft^2 Variable capacity Commissioned 2010
Ground-loop	Vertical loop 32 boreholes 600 ft deep 53.3 ft borehole length per MBtu/hr nominal capacity
Distribution	Forced-air

4.6.2 Monitoring Overview

The monitoring system and building is described in Table 4.20.

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[57] Durham College, 2014. Online document : http://www.durhamcollege.ca/bargaining (Accessed Nov. 1st/2014)

[58] This is the net conditioned floor area reported by the building operator.

[59] Multistack, 2014. Water Cooled Modular Chiller Product Catalog. Online document: http://www.multistack.com/Portals/0/Literature/Catalogs/Water%20Cooled%20Catalog_Web.pdf (Accessed Dec. 21st/2014)

Table 4.20: Monitoring overview for Durham College

Flow	
Onicon models F-1210 single turbine & F-1310 dual turbine insertion flow meters. Flow measured on condenser and evaporator side of chiller as well as geo-loop.	Accuracy: ±2% of reading
Temperature	
Siemens immersion well temperature sensors on entering and leaving temperatures of chiller evaporator, condenser and ground loop.	Accuracy: ±0.5°C
Power	
Power was not measured	
Acquisition	
Existing BAS	
Monitoring Period	
January 2013 – December 2013	
Data Logging Interval	
Data logged based on change-of-value rather than a timescale, i.e. a data point will not be logged unless has changed from a previous value by some predefined amount. For temperatures, that predetermined amount appeared to be 1°C. This style of logging is typically used to limit the amount of data collected and can be useful for troubleshooting. However, it is not sufficient for performance monitoring. It was likely chosen in this case because the BAS was not intentionally configured to log performance data.	

4.6.3 Findings: Performance Plots

1. **Data logging based on change-of-value (COV) was not ideal for performance evaluation.** In COV data logging, a data point will only be logged if has changed from a previous value by a given amount, referred to in this report as a COV value. To perform energy calculations, the data would need to be interpolated (see Fig. 4.44) to fill in the missing data between successive COV logging events and this is a cumbersome addition to the analysis that could be avoided if time-based logging was used. It appears that the COV value is approximately 1 °C. This is too large considering that energy calculations rely on measuring the small differences between entering and leaving temperatures that are typically on the scale of only a couple degrees.
2. **Several of the temperature sensors are not reading sufficiently accurately.** Figure 4.45 shows the temperature difference between the entering and leaving temperatures (subsequently referred to as the “dT”) for the both the evaporator and condenser sides of the heat pump as well as the ground loop. If an evaporator is always cooling then the entering temperature should always be warmer than the leaving temperature. If follows that the EST – LST should always be positive (or LST – EST should always be negative) and it should certainly not the case that dT is positive at times and negative at other times. However, this was observed in Figure 4.45 with the interpolated dataset. This indicates that the sensors on the evaporator and condenser are

either: (i) not sufficiently matched, (ii) giving erroneous readings or (iii) that interpolating the data set is causing errors. The issue is not related strictly to the measurement error of the sensors which is only 0.5°C. In the current state, these two sets of sensors are not useful for performance evaluation. In contrast, the ground loop dT does look reasonable. In heating mode it is always above zero and in cooling season it is always below. Any calculations would have to be based on the ground loop temperature sensors. It should be possible to calculate the heat removed from or rejected to the ground but not for the building because the compressor power draw is not known.

3. **Greater than 6 times as much heat may be being rejected to the ground then is being removed from the ground.** Figure 4.46 shows the monthly heat rejected to or removed from the ground. In the cooling months, much more heat is rejected to the ground than is removed from the ground in the heating months. This could cause a net ground temperature increase which could degrade cooling mode performance. The total annual net heat gain of the ground is 190,000±80,000kWh. This 9.9 kWh per ft borehole length.
4. **The circulator pumps are not interlocked.** Figure 4.47 shows that the circulator pumps are operating in a nearly constant flow mode with only small variations. In this case, constant flow may be an intentional part of the geoexchange system design, however, unless the geoexchange system is operating a large percentage of the time, constant flow is normally associated with degradations in performance. It is also worth noting that the chiller may be varying in capacity but the flow rate is not changing. It follows that at times there will more flow than is actually required and this would waste pump energy and degrade performance.
5. **The entering source temperature stays relatively warm in the winter and cool in the summer.** Figure 4.48 shows entering source temperature as a function of time over the heating and cooling seasons. In the heating season it is typically above 12 °C and in the cooling season it averages between 16 and 17 °C. Best practice guidelines[60] suggest that optimal ground loop sizing, taking into account both cost and performance, would yield variations in entering source temperature on the scale of 16 to 25°C between the coldest EST in winter and the warmest in summer. The variation here is on the scale of 4 to 5°C. It would seem that, according to the given criteria, there is more ground loop that would be optimal from a cost-performance perspective. This makes sense given that there is 53.3 ft borehole length per MBtu/hr nominal capacity, which is much more than other installations. However, the additional ground loop sizing will help to buffer the system imbalances and may be an intentional part of the design.

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[60] Kavanaugh, S. and Rafferty, K., 2014.

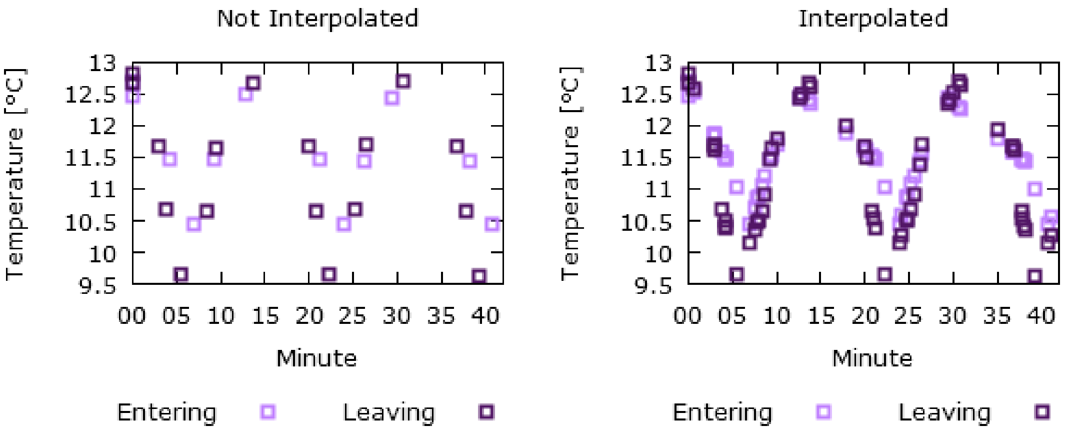

Figure 4.44: The COV value appears to be 1 ^{o}C. This is too large to perform accurate energy calculations. The data needs to be interpolated prior to analysis. A time-based logging strategy should be used for performance evaluation.

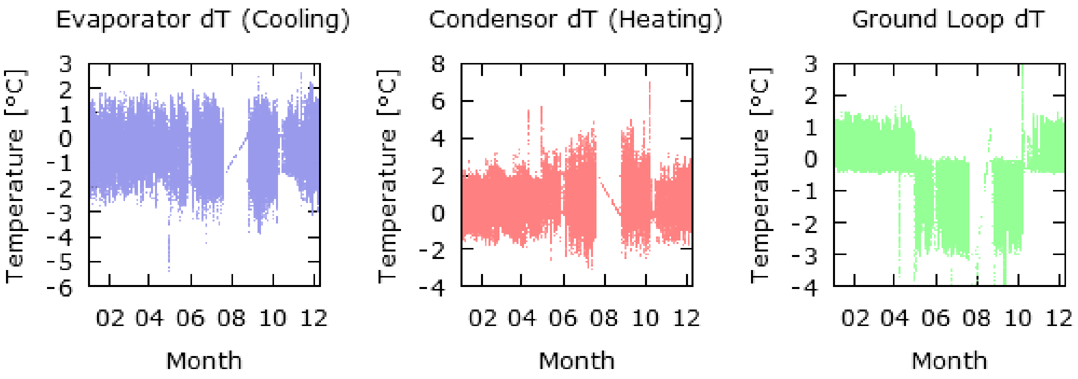

Figure 4.45: The temperature difference (dT) between entering and leaving temperatures is shown for the heat pump evaporator, condenser and ground loop. The evaporator and condenser dT values should not be both positive and negative because a condenser always heats and an evaporator always cools. This shows that the evaporator and condenser sensors are not sufficiently configured for performance calculations.

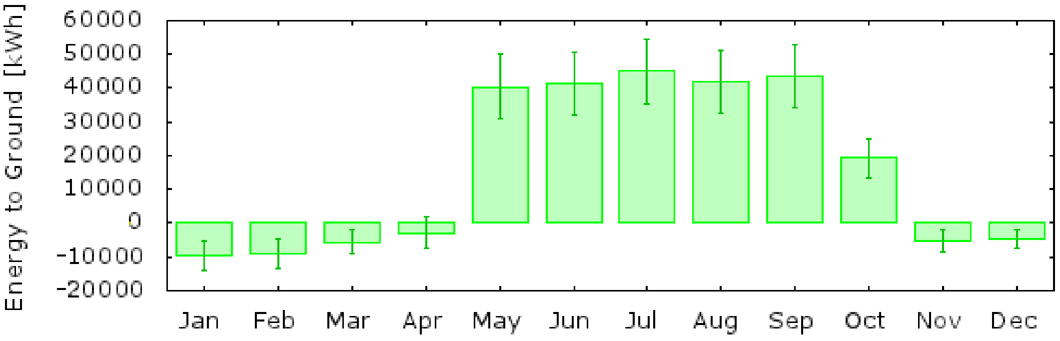

Figure 4.46: The heat rejected to the ground is approximately 6 times larger than the heat absorbed from the ground. This system is highly imbalanced. Error bars does not include error due to interpolation. Error is high because dT is low, at approximately 1.5 ^{o}C in cooling months but only 0.6^{o}C in heating months.

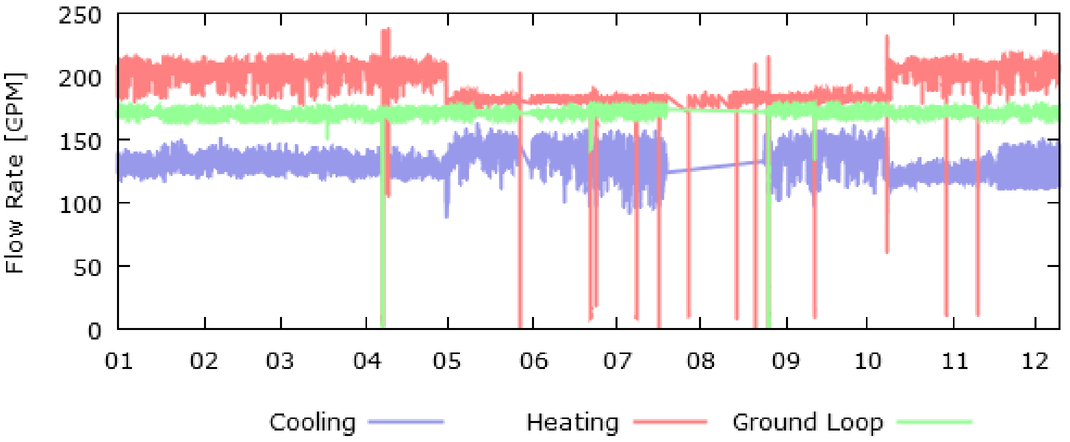

Figure 4.47: The circulator pumps are operating nearly in a constant flow mode. This may be a part of the geoexchange system design but if the heat pump is not on all the time it is often associated with performance degradation.

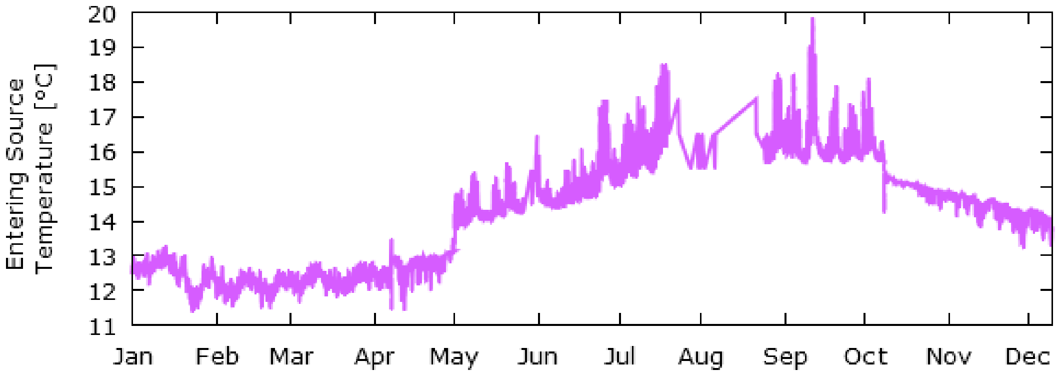

Figure 4.48: The variation in entering source temperature is very small. There is likely more ground loop then is required by the load but the additional ground loop sizing will help the system cope with imbalances.

4.6.4 Findings: Summary

It was not possible to determine if the geoexchange system is sized appropriately for the load because there was insufficient data. It was also not possible to determine the system COP or EER. However, it was apparent that the system is highly imbalanced and is likely to have an oversized ground loop. Table 4.21 summarizes the findings and Section 4.6.4 further outlines lessons learned and recommendations.

Table 4.21: Durham College geoexchange performance metrics

System Sizing	
PTIU – design heating day	N/A
Maximum PTIU – heating month	N/A
PTIU – design cooling day	N/A
Maximum PTIU – cooling month	N/A
Total annual heat delivered [kWh per ft^2]	N/A
Total annual heat removed [kWh per ft^2]	N/A
Maximum average monthly heating mode cycle time [min]	N/A
Maximum average monthly cooling mode cycle time [min]	N/A
System Efficiency	
Annual Heating mode COP	N/A
Annual Cooling mode EER	N/A
Ground Loop Sizing	
Lowest heating mode EST [^{o}C]	12
Highest cooling mode EST [^{o}C]	17
Imbalance [kWh per ft borehole length]	9.9
System Electrical Energy Consumption	
Total annual heating [kWh per ft^2]	N/A
Total annual cooling [kWh per ft^2]	N/A
Total annual [kWh per ft2]	N/A
Emissions Savings	
Annual GHG savings [kg eCO$_2$ per rated heating ton]	N/A

4.6.5 Operational Lessons Learned and Recommendations

1. A full performance analysis was not possible due to insufficient data and apparently erroneous temperature readings. **The following needs to be implemented before a full analysis is possible:**
    a. data logging should be time-based rather than COV-based with a logging interval that is reasonable for the system and the storage constraints;
    b. compressor and circulator pump power consumption also needs to be added, and
    c. the temperature sensors on the condenser/evaporator supply and return should be checked. Ideally these sensors are matched pair, calibrated and using the same mounting style.
2. The constant flow operation of the circulator pumps might be hindering the system efficiency. If the chiller is operating with variable capacity then it would be ideal if the circulator pumps were able to operate at variable capacity as well. **If the existing pumps are variable speed then an alternative control strategies might be worth pursuing. On future installations, installing and operating variable speed pumps with variable capacity chillers or heat pumps would certainly help to boost the system efficiency.**

3. It appears that there is a large imbalance in the system with roughly 6 times the amount of heat being rejected to the ground during the cooling season than is absorbed from the ground in heating mode. However, the ground loop appears to be oversized and may help to buffer against any net heat gain in the ground. **It might be worthwhile to revisit the system design documents and complete further modeling on the ground loop performance to see if the temperature gain of the ground is expected to remain within recommend limits given the new experimental data.** To create a more balanced system when a building is cooling dominant buildings it may be beneficial to use the geoexchange system for snow melting or similar applications during the heating season.
4. **To get the best performance out of the geoexchange system, it is would be worth examining why the system is so imbalanced.** For example, it may be that the supplementary heating is handling a larger portion of the load than intended.

4.7 Earth Rangers Centre

4.7.1 Geoexchange System Overview

The Earth Rangers Centre, located on the Toronto and Region Conservation Authority's Living City Campus in Vaughan, ON, was constructed in 2004 as the base of operations for Earth Rangers, a children-oriented conservation organization. At 60,000 ft^2,[61] the building is LEED-Platinum certified and it was built with the mandate to showcase a wide-range of sustainable building technologies and practices.

The geoexchange system at the Earth Rangers Centre was a retrofit installed in 2010 when the parking lot was expanded. It is powered by a Carrier 30HXC chiller with approximately 80 tons nominal heating capacity. The ground loop below the parking lot consists of 44 vertical boreholes going down to a depth of 120 m. The building uses a radiant in-floor/slab distribution system for both heating and cooling. In total there is 22 km of tubing used in the radiant heating and cooling system. Typically radiant slab cooling is avoided due to condensation issues, however, the building automation system (BAS) at Earth Rangers regulates flow through the slabs to control the cooling slab temperature to be above the dew point, thereby preventing any condensation. The back-up heating system is a boiler, which was the system used prior to the geoexchange retrofit.

To reduce the latent cooling load the humidity levels in the building are kept higher than normal but the temperatures are kept lower, thereby decreasing energy consumption with minimal impact on occupant thermal comfort. High thermal mass reduces peak heating and cooling demand. Drastic improvements in geoexchange cooling mode performance were observed by operating the geoexchange system in a free-exchange mode where the heat pump was bypassed entirely and the cool water entering the building from the ground loop was directly circulated through the cooling slabs without the use of the heat pump. In this mode the only electrical consumption is that consumed by the circulator pumps,

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[61] This is the square footage reported by the building operator and it does not include the basement.

which is much less than that consumed by the heat pump, and the somewhat higher temperatures available when not using a heat pump are fine given that the cooling slabs are regulated at higher temperatures anyway so as to be above the dew point.

Figure 4.49: (Left) Aerial view of Earth Rangers Centre showcasing reflective white roof, green roof and solar thermal panels. (Top right) Ground source heat pump in mechanical room. (Bottom right) Energy monitoring boxes.

Table 4.22: Building and geoexchange system overview for Earth Rangers Centre

Building	
Square footage	60,0000 ft^2
Usage	Office Building
Geoexchange System	
GSHP Unit(s)62	Carrier 30HXC 086 83 tons (996 MBtu/hr) nominal capacity 16.6 Btu/hr per ft^2 Variable capacity Commissioned 2004
Ground-loop	44 vertical boreholes 400 ft deep 17.7 ft borehole length per MBtu/hr nominal capacity
Distribution	Radiant slab heating and cooling. Distribution system can be directly interfaced with ground loop via a heat exchanger, bypassing the heat pump. This mode of operation is termed “free-exchange” and it allows for highly efficient cooling mode operation.

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[62] Carrier, 2014. AquaForce Product Data. Online document: http://dms.hvacpartners.com/docs/1005/Public/0F/30HX-12PD.pdf (Accessed Dec. 21st/ 2014)

4.7.2 Monitoring Description

The monitoring system and building is described in Table 4.23 and Figure 4.50 shows the monitoring points of the system. This is a simplified schematic that does not show the system's ability to operate in free-exchange mode.

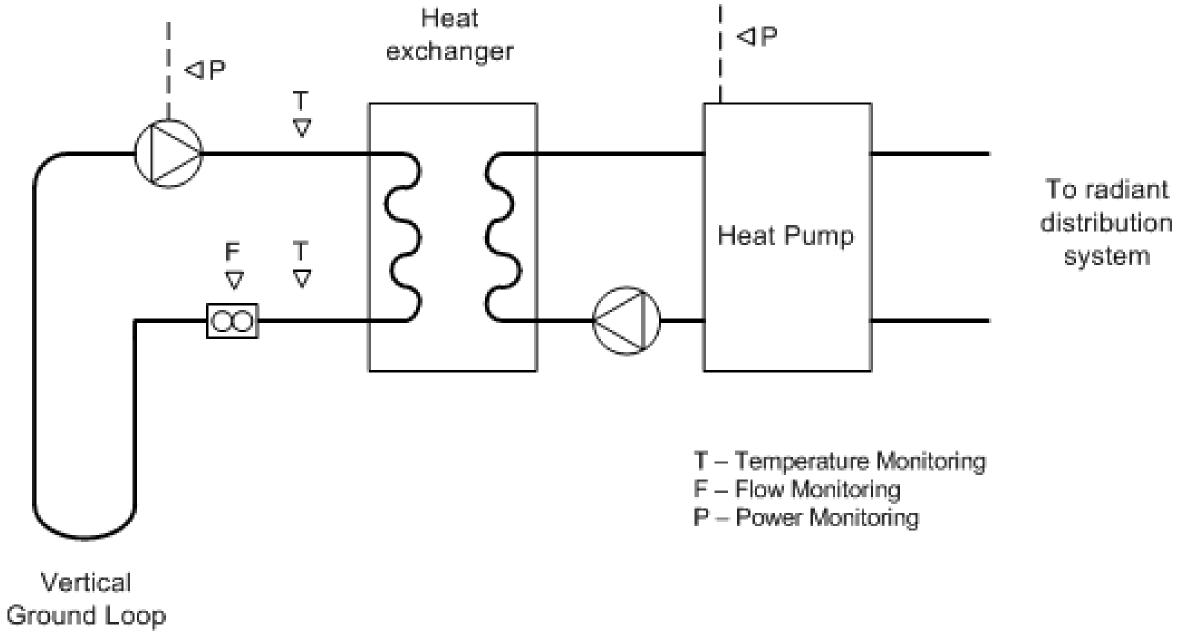

Figure 4.50: Schematic diagram of Earth Rangers geoexchange system showing monitoring points

Table 4.23: Monitoring overview for Earth Rangers Centre

Flow	
Heat energy is measured with Onicon System 10 Btu Meter but the specific flow meter used was not determined. Onicon manufactures a number of different types of flow sensors to use with their Btu meter. The worst accuracy of their flow sensors is ±2% and this is what was assumed in the analysis.	Accuracy: ±2% of reading
Temperature	
N.I.S.T. traceable solid state temperature sensors mounted in thermal wells supplied with Onicon System 10 Btu Meter	Accuracy: The error in the difference between two matched-sensor pair is ±0.1^{o}C
Power	
Power measurement device was not determined	The assumed accuracy of the power measurement is 0.5%.
Acquisition	
Existing BAS	
Monitoring Period	
January 2013 – November 2013	
Data Logging Interval	
The Btu meter outputs heating energy data (which is instantaneous heating or cooling capacity integrated over time) as well as instantaneous readings. The energy values were used in the analysis and were recorded on an hourly basis. Electrical energy consumption was also logged hourly.	

4.7.3 Findings

1. **The building's cooling load was met primarily using a free-exchange mode of operation with the heat pump only turning on for 12 total days during June, July and August, resulting in daily COPs that frequently exceeded 10.** Figure 4.51, 4.52 and 4.53 show: (i) the daily heat removed by the geoexchange system, (ii) the electricity consumed by the heat pump and ground loop circulator pump as well as (iii) the COP. Note that the COP is shown on a log scale because it varies widely based on the cooling load and whether or not the heat pump is on. On the days when the heat pump was operating, the performance was good, with COPs mostly between 4 and 5. In contrast, on days when the heat pump was not operating, and the cooling load was met by free-exchange, the only electrical load considered in the COP calculation was the ground-loop circulator which is typically less than a tenth of the heat pump load. The resultant COPs for these days are typically between 10 and 100 and are highly dependent on the daily cooling load.
2. **Free-exchange was a successful cooling-mode strategy because: (i) the distribution system is radiant-slab, (ii) the building has a high thermal mass and (iii) the system operates with very cool entering source temperatures possibly due to oversized ground loop.** The latter is evident from the fact that there is minimal seasonal fluctuation in the entering source temperature,

shown in Figure 4.54 In cooling mode the entering source temperature hardly surpasses 13 ^{o}C. This temperature is sufficiently cold to use for the building's radiant slab distribution system. If the ground loop was sized smaller, the entering source temperature may be too large to be suitable for free-exchange. It should also be noted that free-exchange is well-suited to radiant-slab cooling because the distribution-side heat exchange area is very large, and therefore it is permissible to have higher fluid temperatures. The suitability for free-exchange with a forced-air cooling system needs to be further examined.

3. **The geoexchange system is heating dominant.** Figure 4.55 shows, on a monthly basis, the heat delivered to, or removed from the building by the geoexchange system. When appropriately taking into account the compressor heat, the total heat removed from the ground in heating mode over the year is 25% greater than the heat rejected to the ground in cooling mode.
4. **There is potentially deleterious cooling mode operation during the heating months.** In Figure 4.55, the winter months show cooling mode operation. This occurs whenever the heat pump is not operating but the ground loop circulator pump is running (it runs all the time). All measurements indicate that heat is being removed from the building. This is likely not intentional but is a consequence of the fact that the circulator pumps do not turn off when the heat pumps turn off, and a small amount of heat exchange continues to happen between the building and the ground.
5. **The total heating season COP was 2.4±0.2 and the cooling season COP 8.2±2.** Figure 4.56 shows the monthly heating and cooling mode COPs. The error in the cooling mode COP is so much larger because, in free-exchange mode, there is a smaller temperature difference across the heat exchanger and when this is the case, there is a greater relative uncertainty. The heating mode COP is low and the reason for this is not clear.
6. **During the heating season the heat pump is on nearly all the time because it is variable capacity and during the cooling season it is rarely on because of free-exchange mode operation.** Figure 4.57 shows that heat pump is on at least 80% of the time during heating months. With the exception of May, the heat pump only rarely turns on in cooling mode because it primarily operates in free-exchange mode. Figure 4.58 shows that cycle times are on the scale of hours, tens or even hundreds of hours.
7. **The electricity cost is split in half between off-peak and mid or on-peak usage.** Figures 4.59 and 4.60. If the entire mid and on-peak load was shifted to off-peak there would be a cost savings of 25%. Since this building has so much thermal mass it may be feasible to develop a control strategy that shifted some of the mid and on-peak load to off-peak to obtain a lower operating cost.

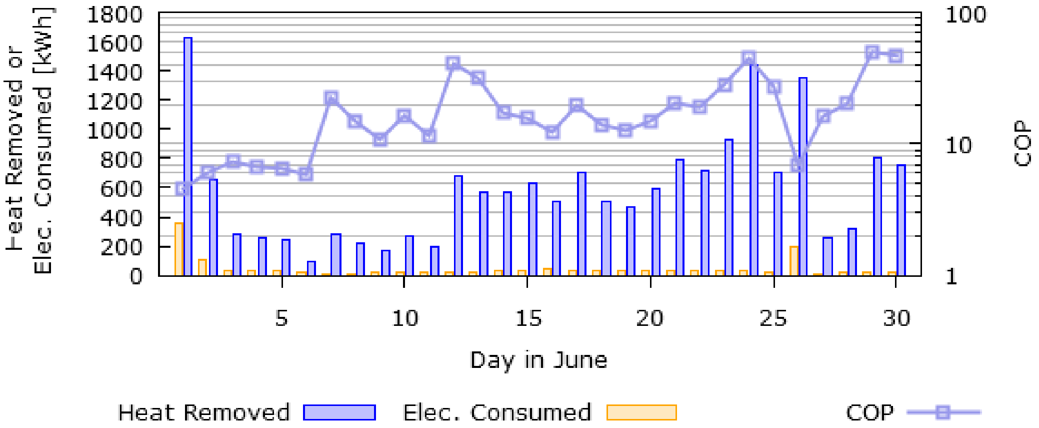

Figure 4.51: The daily totals for the heat removed, electricity consumed by the geoexchange system and the COP are shown for June. The heat pump appears to have only turned on for 3 days total and substantial heat was removed via free-exchange. The COP reached as high as 40.

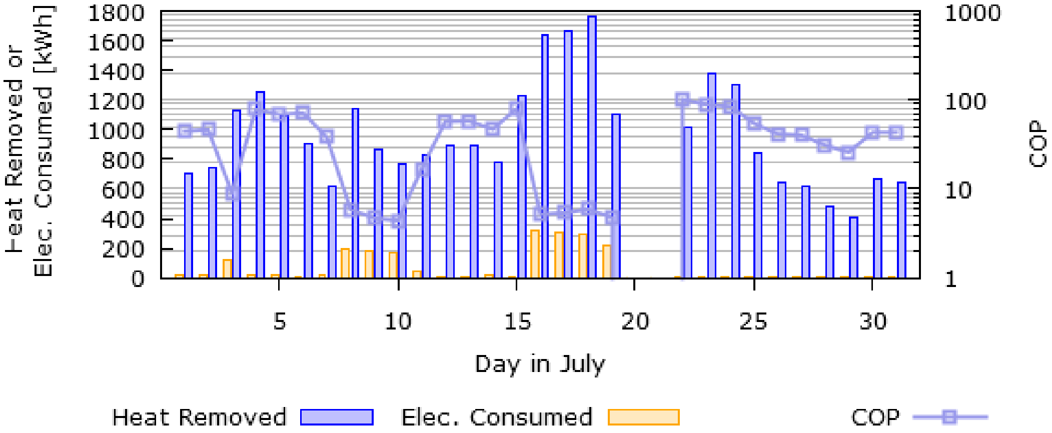

Figure 4.52: The daily totals for the heat removed, electricity consumed by the geoexchange system and the COP are shown for July. The heat pump appears to have turned on for 8 days.

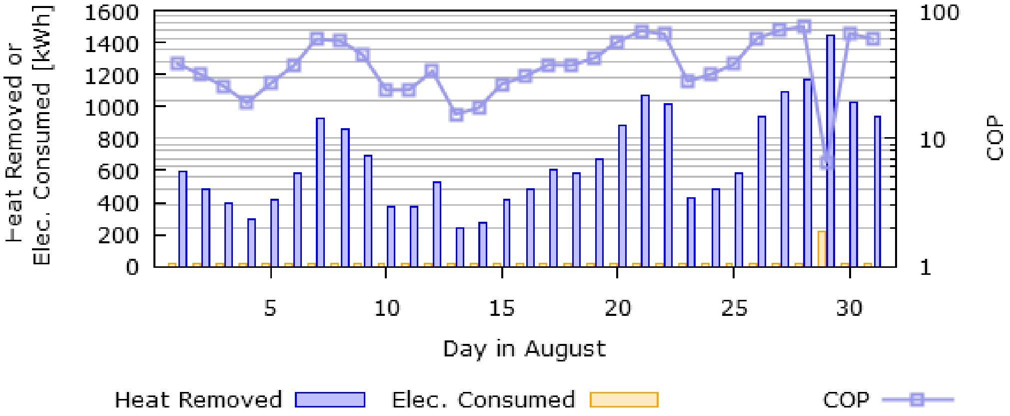

Figure 4.53: The daily totals for the heat removed, electricity consumed by the geoexchange system and the COP are shown for August. The heat pump appears to have turned on only once.

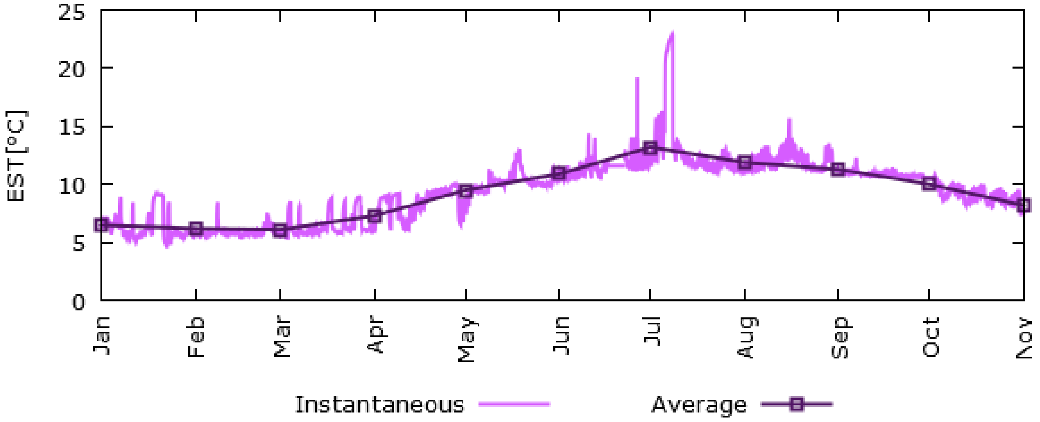

Figure 4.54: The average entering source temperature reaches a low of 6 °C in the heating season and a high of 12 °C in the cooling season. The relatively even temperatures suggest that the loop sizing is large relative to the load. The spike in July is likely a result of the pump being off (or the sensor being briefly removed) and the temperature equilibrating to ambient.

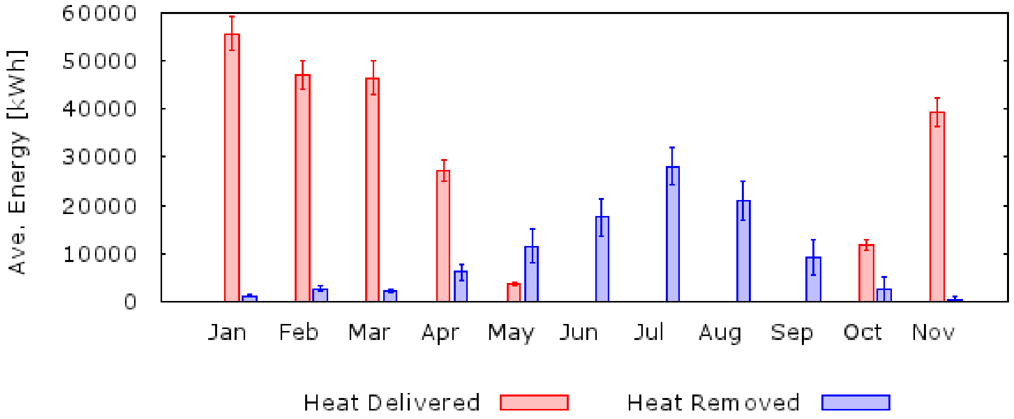

Figure 4.55: The heat delivered and removed from the building on a monthly basis is plotted. The cooling mode operation in winter appears to be due to a small of heat being transferred to the ground by circulator pumps that continue to operate when the chiller turns off.

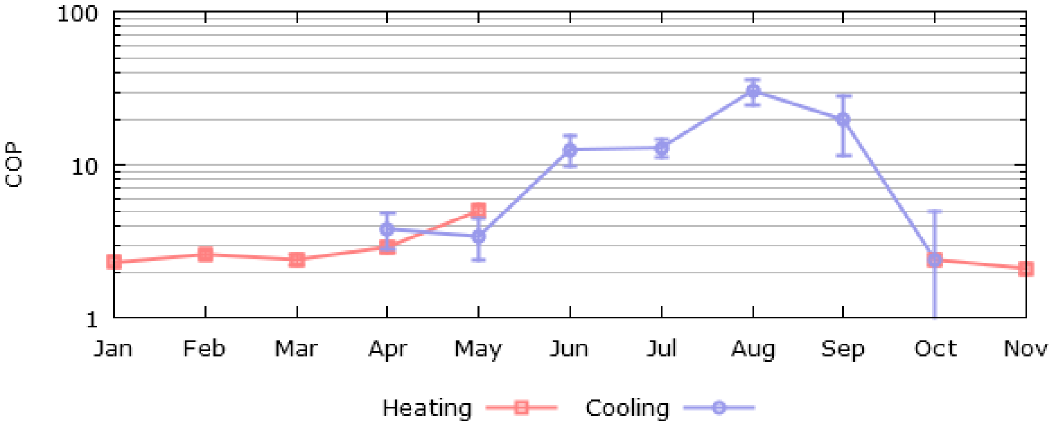

Figure 4.56: The monthly COP is shown on a log scale due to the wide range of COPs observed. The high cooling mode COPs are due to free-exchange operation. The reason behind the low heating mode COPs is not immediately clear.

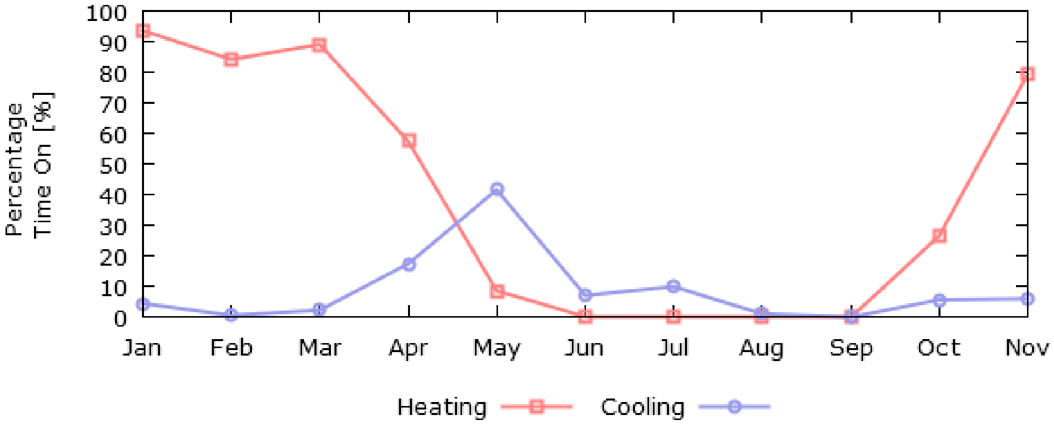

Figure 4.57: The heat pump is on nearly all the time during heating months because it is variable capacity but in the cooling season it is rarely on due to free-exchange opeation. It is likely that prior to June contol for free-exchange just had not been implemented yet because free-exchange ought to be even more effective in April and May due to cooler ground temperatures.

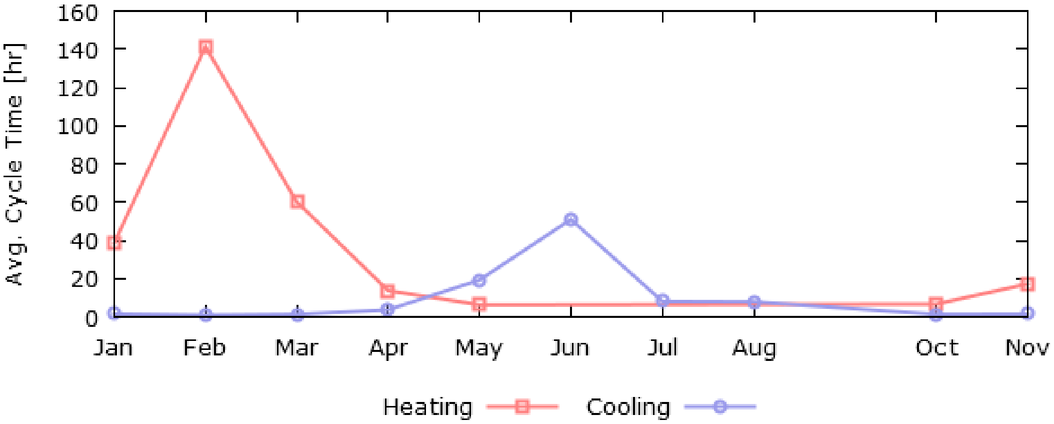

Figure 4.58: Cycle times are on the scale of hours, tens and even hundreds of hours, again heavily influenced by variable capacity heating and free-exchange cooling.

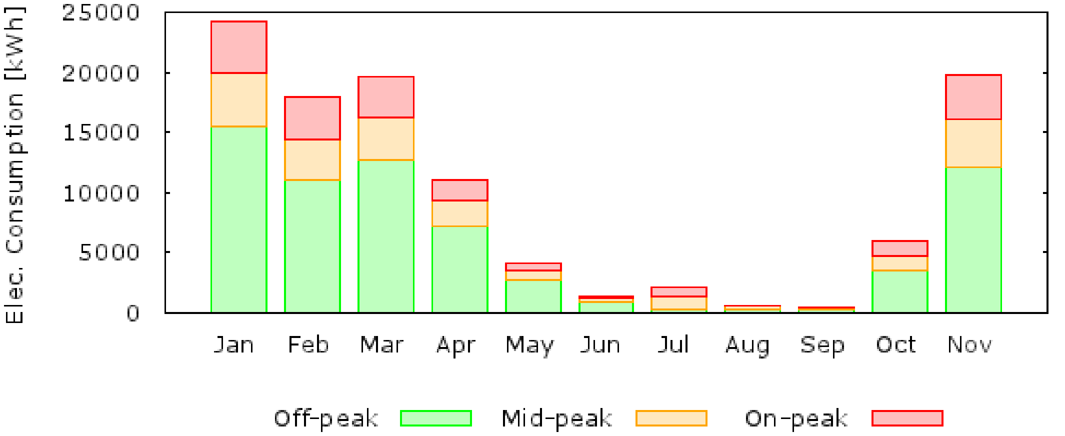

Figure 4.59: The time-of-use energy usage is shown monthly. Cooling season energy consumption is low due to free-exchange.

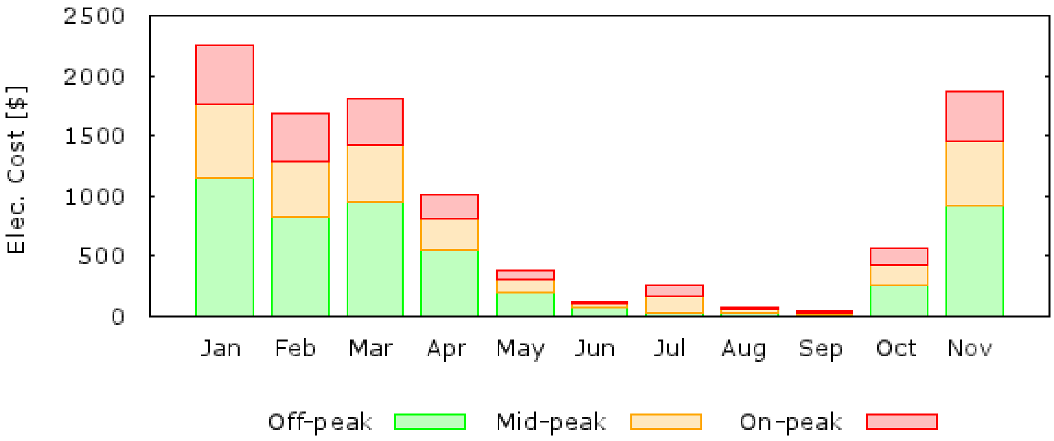

Figure 4.60: The cost of operating the heat pump is split evenly between off-peak and mid or on-peak. By shifting the entire load to off-peak it could result in a 25% reduction in electricity costs.

4.7.4 Findings: GHG Emissions Analysis

GHG emissions reduction is according to the procedure outline in Section 3.2.9. Emissions analysis results are shown in Table 4.24. For reasons explained in Section 3.2.9, these are likely very conservative estimates.

Table 4.24: GHG reduction analysis for Earth Rangers Centre

Heating Scenario	Efficiency	Heat Delivered [MWh]	Electricity Consumed [MWh]	Eq. CO2 Emissions from Electricity [103 kg eq. CO2]	Natural Gas Used [m3]	Eq. CO2 Emissions Natural Gas [103 kg eq. CO2]	GHG Emission Reduction Achieved by Using Heat Pump [103 kg eq. CO2]	Equivalent number of cars off the road [cars/year]
Heat Pump	2.4	232.0	96.7	10.6	0	0	N/A	N/A
Natural Gas	0.75	232.0	0.0	0.0	29305	55.4	44.8	13.3
Natural Gas	0.84	232.0	0.0	0.0	26165	49.5	38.8	11.6
Natural Gas	0.95	232.0	0.0	0.0	23136	43.7	33.1	9.8
Electric Resistance	1	232.0	232.0	25.5	0	0.0	14.9	4.4

4.7.5 Findings: Summary

Geoexchange system sizing was not analyzed because the system is variable capacity and the procedure outline in Section 3.2.7 is really only useful for units that are not variable capacity. The small seasonal temperature variation in EST would likely mean that the ground loop was oversized to some degree if this were a typical installation. However, in this case, to make use of free-exchange operation the ground loop likely needs to be oversized so as to maintain fluid temperatures that are cool enough to cool the building directly. The heating COP is low and it isn't clear why that ought to be the case. The cooling COP is very impressive due to the free-exchange mode of operation.

Table 4.25: Earth Rangers Centre geoexchange performance metrics

System Sizing	
PTIU – design heating day	N/A
Maximum PTIU – heating month	94
PTIU – design cooling day	N/A
Maximum PTIU – cooling month	42
Total annual heat delivered [kWh per ft^2]	3.9
Total annual heat removed [kWh per ft^2]	1.7
Maximum average monthly heating mode cycle time [min]	8460
Maximum average monthly cooling mode cycle time [min]	3060
System Efficiency	
Annual Heating mode COP	2.4
Annual Cooling mode EER	28.0
Ground Loop Sizing	
Lowest heating mode EST [^{o}C]	6
Highest cooling mode EST [^{o}C]	13
Imbalance [kWh per ft borehole length]	-1.6
System Electrical Energy Consumption	
Total annual heating [kWh per ft^2]	1.6
Total annual cooling [kWh per ft^2]	0.2
Total annual [kWh per ft2]	1.8
Emissions Savings	
Annual GHG savings [kg eCO$_2$ per rated heating ton]	470

4.7.6 Operation Lessons Learned and Recommendations

1. The seasonal cooling mode COP resulting from free-exchange operation is 8.2. This is remarkably good. At least three building characteristics made this possible: (i) radiant slab distribution, (ii) a very large thermal mass and (iii) very low entering source temperatures. It may be the case that any given geoexchange installation would not be capable of free-exchange because of these specific building requirements. **It would be useful if architects were made aware of this technology such that energy efficient buildings could be designed with these attributes and make use of this ultra-efficient method of cooling.**
2. Air-source heat pumps may well be one of the largest competitors to geoexchange but it is worth noting that **the ultra-efficient cooling mode operation offered by free-exchange is not possible with air-source heat pump technology.**
3. **The wintertime cooling mode operation should be further examined by the building operator because ultimately it is serving to increase the heating load.**

4. The system is slightly imbalanced with approximately 25% more heat being removed from the ground than is rejected. **Ground loop modeling would need to be employed to determine if this will cause a prohibitively large long-term increase in ground temperature.**
5. Approximately 25% of electricity fuel cost could be saved by shifting the entire load to off-peak. **Since this building has such a large thermal mass it may be feasible to pre-heat the building during the heating season for a notable cost savings.**
6. The heating COP is low. The reason for this is not clear. More comprehensive monitoring and analysis of the system would be required to diagnose this issue.

4.8 Ebenezer Community Hall

4.8.1 Geoexchange System Overview

The Ebenezer Community Hall, shown in Figure 4.61, was built as a one-room schoolhouse in 1892 and was formerly known as “The Ebenezer School.” It was continually used for that purpose until 1973 when it became the Toronto Gore Township Chambers. It’s most recent usage is as a community hall for social gatherings and meetings, as well being a local heritage site. The geoexchange system is powered by two Compax CMM060 reversing two-stage chillers operating in parallel. The distribution system is forced air. There are 6 boreholes going to a depth of 200 ft.

Figure 4.61: Ebenezer Community Hall in the process of getting moved back from the road.[63]

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[63] Brampton Guardian, 2010. "Ebenezer schoolhouse moved,” Dec. 11, 2010.

Table 4.26: Building and geoexchange system overview for Ebenezer Community Hall

Building	
Square footage	2,000 ft^2 (estimated)
Usage	Community hall
Geoexchange System	
GSHP Unit(s)64	Compax CMM060 reversing two-stage chiller There are 2 units COP/EER not specified Capacity for chiller is not standardized in same way as with heat pumps. Specification suggests a heating capacity of 44.3 MBtu/hr for an LLT of 38^{o}C and an LST of 2^{o}C. The unit has a cooling mode capacity of 50.8 MBtu/hr for an LLT of 10^{o}C and LST of 27^{o}C. These conditions are similar to the capacity rating conditions for heat pumps. Commissioned 2011
Ground-loop	6 boreholes 200 ft deep 13.5 ft borehole length per MBtu/hr nominal heating capacity
Distribution	Forced air

4.8.2 Monitoring Description

The monitoring system is described in Table 4.27. The monitoring for this system appears to be intended for control purposes. However, it is insufficient for a performance analysis. This is because: (i) temperature values are logged over timescales which are too long to be useful for performance analysis, (ii) historical data was often not being stored for periods longer than a few months, (iii) heat pump power consumption is not monitored and (iv) flow was not monitored. A very limited analysis was conducted with the data that were available.

Table 4.27: Monitoring overview for Ebenezer Community Hall

Flow
Not present
Temperature
Not determined
Power
Not present
Acquisition
Johnson Controls BAS
Monitoring Period
Data for different parameters was available for different period of time. The longest available interval was for the EST which was available from January to July 2014.
Data Logging Interval
Temperature values are stored every 30 minutes. The state of the heat pumps (on/off) was stored every 10 minutes.

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[64] Compax, 2014. CMM 060 Product Information. Online document: http://www.compaxchiller.com/prod_perf.php#selection (Accessed Dec. 21st/2014)

4.8.3 Findings: Performance Plots

1. **The ground is likely appropriately sized for the load**. Figure 4.62 shows that the instantaneous EST ranges from as low as 6°C to as high as 22°C, resulting in a seasonal variation in EST of 16°C. Best practice documents (see Section 3.2.3) suggest that a ground loop optimized for both cost and performance would see a variation in EST of between 16 and 25°C.

2. **The cycle times are between 20 and 120 minutes for both heat pumps.** Figure 4.63 shows the cycle time over the period of four months for which data was available. The error in the cycle time is equal to the logging period (±10 minutes). It is possible that HP2 might be considered to be short cycling in cooling mode.

3. **The geoexchange system sizing was not evaluated**. PTIU (shown in Figure 4.64) is only available for the first half of the 2014 cooling season. The temperatures during this season were very mild. The hottest day for the available monitoring period was July 1st, 2014, with a high of 30.3°C but the cooling system did not even turn on. In any of the monitored months, the system never had to use more than half of its capacity but the average heating and cooling loads were low**.**

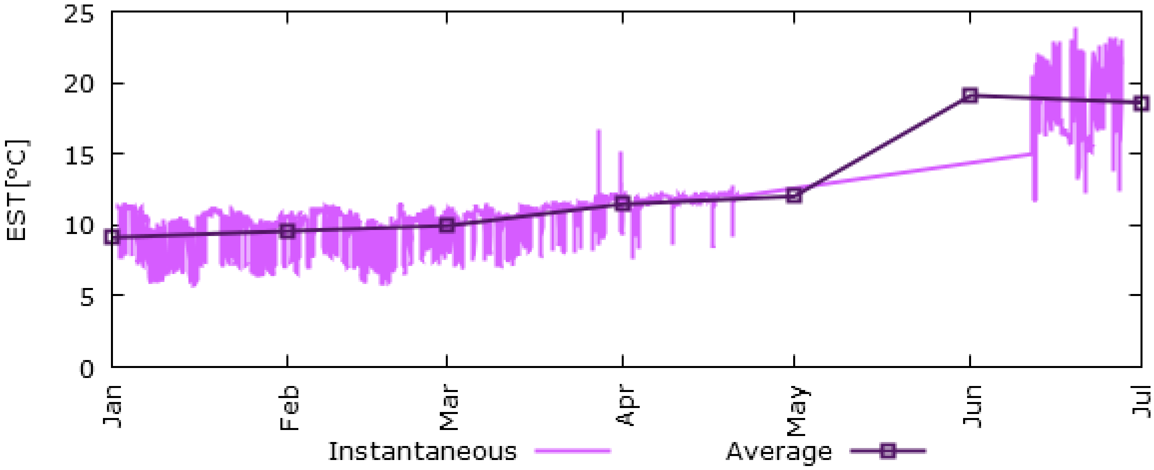

Figure 4.62: The average monthly entering source temperature is approximately 9 °C at the coldest and approaching 20°C at the warmest

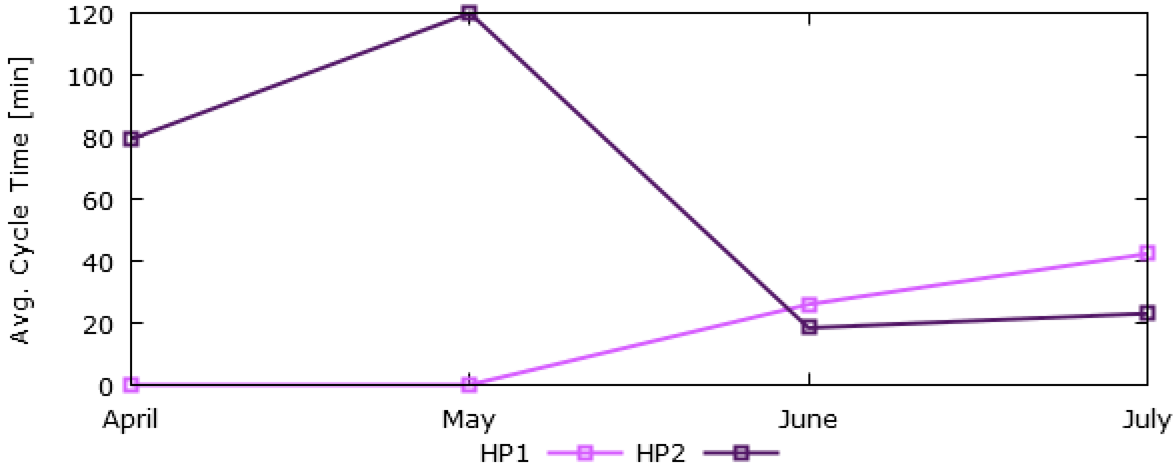

Figure 4.63: The cycle time during peak cooling is 40 minutes and 20 minutes for HP1 and HP2 respectively

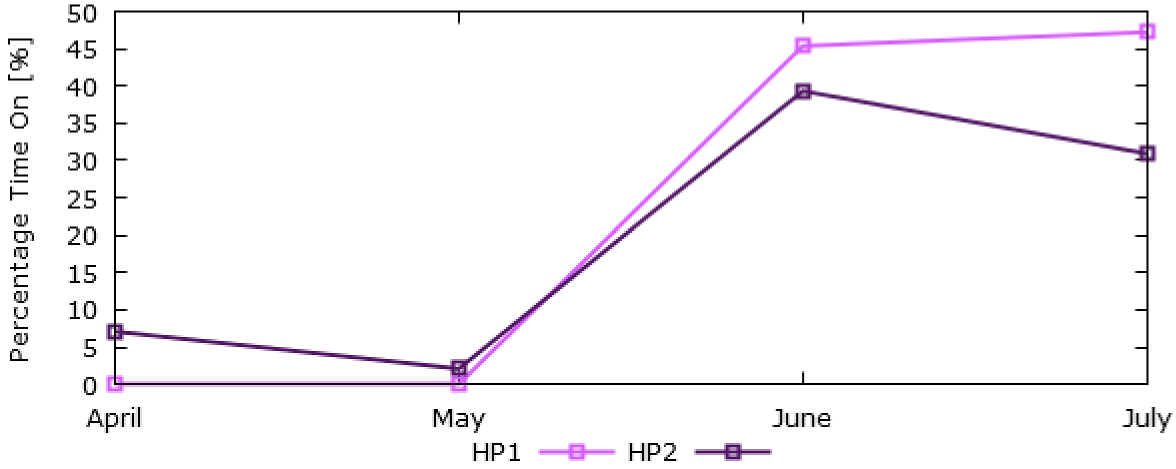

Figure 4.54: The heat pumps are on between 20% and 50% of the time during peak cooling months

4.8.4 Findings: Summary

Geoexchange system sizing and performance was not determined due to insufficient data. The seasonal variation in EST suggests that the ground loop is likely to be appropriately sized.

Table 4.28: Ebenezer Community Hall geoexchange performance metrics

System Sizing	
PTIU – design heating day	N/A
Maximum PTIU – heating month	N/A
PTIU – design cooling day	N/A
Maximum PTIU – cooling month	47/31
Total annual heat delivered [kWh per ft^2]	N/A
Total annual heat removed [kWh per ft^2]	N/A
Maximum average monthly heating mode cycle time [min]	N/A
Maximum average monthly cooling mode cycle time [min]	41/21
System Efficiency	
Annual Heating mode COP	N/A
Annual Cooling mode EER	N/A
Ground Loop Sizing	
Lowest heating mode EST [^{o}C]	5
Highest cooling mode EST [^{o}C]	20
Imbalance [kWh per ft borehole length]	N/A
System Electrical Energy Consumption	
Total annual heating [kWh per ft^2]	N/A
Total annual cooling [kWh per ft^2]	N/A
Total annual [kWh per ft^2]	N/A
Emissions Savings	
Annual GHG savings [kg eCO$_2$ per rated heating ton]	N/A

4.8.5 Operational Lessons Learned and Recommendations

1. **It should be clear that a BAS configured to control the geoexchange system and possibly aid in troubleshooting is not necessarily sufficient to determine the performance.** However, in many cases it ought to be possible to use the BAS for this purpose with some adjustments. To monitor performance the following would be necessary:
    a. additional monitoring for source side flow rate;
    b. additional monitoring point for compressor and circulator pump power draw;
    c. historical data logging with a one minute instantaneous logging interval (or 5 minute averaged logging interval) for ideally a full year, and
    d. matched-pair temperature sensors (if not already present).

2. Due to the insufficient data it is not possible to conclude if this installation is performing well or if the system is appropriately sized for the load. However, the EST data suggests that at least **the ground loop is likely to be well sized for the load.** Further instrumentation and analysis is required for a more detailed assessment.

3. **The average cycle time of HP2 may be short.** This should be analyzed in greater depth if this system is to be studied further. No specific recommendation can be made in this regard without further data.

5.0 SUMMARY OF FINDINGS AND RECOMMENDATIONS

5.1 Summary of Findings: Residential

A summary of the findings for residential buildings studied in this report is presented in Table 5.1. Several observations can be made:

1. The design heating day PTIUs suggest that all geoexchange systems have been appropriately sized for their loads. All systems are on the majority of the time on an approximate design day. Systems sizing for the condominium apartments was notably less than Peel House A but comparable to Peel House B when normalizing for square footage. Both of the Peel houses are group homes with multiple occupants so they are likely to have higher internal heat gains than a conventional detached home. Differences in occupancy and usage profile partly account for the differences in sizing.
2. The annual energy required by the geoexchange systems to heat and cool the condominium apartments was notably less than that for Peel House A and Peel House B when normalizing for square footage.[65] The energy-efficient Archetype House B geoexchange system consumed a comparable amount of electricity per unit conditioned floor area when compared with the condominiums.
3. The performance of Peel House A is notably worse than Peel House B. The primary observed difference between the two sites is that Peel House A has shorter cycle times. The two buildings may also have different occupancy profiles.
4. All buildings are heating dominant but where imbalances exist, it is due to more heat being rejected to the ground than is removed.
5. Buildings had an annual GHG savings of approximately 1000 kg eCO_2 per nominal ton heating capacity of the system. In other words, one ton of installed geoexchange system saves one ton of GHG emissions annually. This is comparable to findings from elsewhere,[66] but it is a conservative estimate with the actual savings likely being much better.

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[65] Note that Peel House A and B both had back-up systems and this was not considered in the study. It should also be noted that the Greenlife Condominium numbers include the compressor box and distribution-side blower (the unit is water-to-air) but not the ground loop circulator.

[66] Canadian Geoexchange Coalition, 2010.

Table 5.1: Summary of findings for residential buildings in this study

	Peel House A	**Peel House B**	**GLC Unit 1**	**GLC Unit 2**	**GLC Unit 3**	**Archetype House B**[67]
System Sizing						
Building Type	Detached house	Detached house	Condo apt.	Condo apt.	Condo apt.	Semi-detached house
GSHP heating capacity [Btu/hr per ft2]	28.6	9.3	10.6	7.1	7.1	12.1[68]
GSHP cooling capacity [Btu/hr per ft2]	27.4	9.0	14.8	10.0	10.0	11.5
PTIU – design heating day	0.70	0.82	0.75	0.87	0.70	N/A
Maximum PTIU – heating month	0.55	0.68	0.55	0.45	0.73	N/A
PTIU – design cooling day	0.90	0.88	0.26	0.40	0.06	N/A
Maximum PTIU – cooling month	0.57	0.68	0.15	0.20	0.06	N/A
Total annual heat delivered [kWh per ft^2]	13.1	4.6	N/A	N/A	N/A	5.0
Total annual heat removed [kWh per ft^2]	9.1	4.0	N/A	N/A	N/A	0.66
Maximum average monthly heating mode cycle time [min]	11	27	13	18	81	N/A
Maximum average monthly cooling mode cycle time [min]	20	41	16	13	43	N/A
System Efficiency[69]						
Annual heating mode COP	2.8	3.5	N/A	N/A	N/A	3.1[70]
Annual cooling mode EER	10.9	13	N/A	N/A	N/A	19.7
Ground Loop Sizing						
Loop orientation	Vertical	Vertical	Vertical	Vertical	Vertical	Horizontal & Vertical
Borehole length or horizontal loop length [ft per MBtu/hr rated heating capacity]	8	8	N/A	N/A	N/A	11.0 (Vertical)
Lowest average heating mode EST [°C]	N/A	N/A	9	9	9	N/A
Highest average cooling mode EST [°C]	N/A	N/A	18	18	18	N/A
Imbalance [kWh per ft borehole length]	15	12.5	N/A	N/A	N/A	N/A
System Electrical Energy Consumption[71]						
Total annual heating [kWh per ft^2]	4.8	1.3	N/A	N/A	N/A	1.6
Total annual cooling [kWh per ft^2]	2.9	1.1	N/A	N/A	N/A	0.1
Total annual [kWh per ft^2]	7.7	2.4	1.5	0.7	1.6	1.7
Emissions Savings						
Annual GHG savings [kg eCO$_2$ per rated heating ton]	990	1100	N/A	N/A	N/A	920

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[67] Safa, A., 2012.

[68] Net floor area in (Safa, A., 2012) is listed as 350 m^2 (3770 ft^2). This includes the basement.

[69] Includes the compressor box and ground loop circulator power consumption.

[70] See Table 22, pg. 100, in (Safa, A., 2012). Includes ground loop circulator and compressor unit.

[71] Includes the compressor box and ground loop circulator power consumption.

5.2 Summary of Findings: Non-Residential

A summary of the findings for non-residential buildings is given in Table 5.2. Several observations can be made:

1. The Downsview Park Office Building geoexchange system seems to be oversized. It has twice the capacity per square footage than the other two office buildings (however, both of these are LEED certified). It is only operating approximately 50% of the time during approximate design heating days and cooling days. The reason for its oversizing is at least partly evident from the fact that it likely has a much larger load per square footage because the geoexchange system is consuming roughly two times more electricity to operate the geoexchange system than the other office buildings.
2. The Earth Rangers Centre site studied in this report demonstrated that free-exchange operation can **increase monthly cooling mode COPs by between 2 to 3 times compared with conventional heat pump operation.** Free exchange involves using the ground loop to directly cool a building without the use of a heat pump. This is especially relevant as air-source heat pumps gain in popularity because air-source heat pumps are not able to operate in free-exchange mode and therefore they are not capable of these exceptionally high cooling COPs. Free-exchange worked well in this application because the ground loop temperatures were exceptionally cool and the radiant-slab distribution system had very large heat exchange surface area, allowing warmer fluid temperatures to be used for cooling. Further studies would be required to determine the effectiveness of free-exchange for other applications.
3. The constant flow operation of the circulator pumps at the Restoration Service Building **decreased the monthly COP by as much as 80% and increased annual operating costs by 50%**. Earth Rangers Centre, Downsview Park Office Building and Durham College also showed evidence of suboptimal circulator pump operation.
4. The time-of-use energy consumption profiles of these sites suggest that there is the potential to shift the peak and mid-peak loads to an off-peak time-of-use bracket for an **electricity cost savings of between 20 and 25%.** This might involve the use of larger ground loops, greater thermal storage, predictive heat pump control and potentially other advanced design attributes.
5. Durham College appeared highly imbalanced with 6 times more heat rejected to the ground than removed. However, when the imbalance is normalized, the kWh per ft borehole length is does not seem large compared with the imbalances seen in residential system. This is because it has about 3 times more borehole length per MBtu/hr rated heating capacity building area when compared with other systems. The reason for this sizing is not clear.
6. Based on the criteria presented in Section 3.2.3, **there was no evidence to suggest any of the ground loops were undersized. If anything, they tended towards optimized performance as opposed to optimized cost.**
7. **Short cycling was only observed in cooling mode at the Restoration Services Building.** This is because the system is sized to meet the heating load and is oversized for the cooling load. It is worth noting that other buildings had variable capacity or two-stage heat pumps.

Table 5.2: Summary of findings for non-residential buildings in this study

	Earth Rangers Centre	**Downsview Park Office Building**	**Restoration Services Building**	**Ebenezer Community Hall**	**Durham College**	**GTAA North Fire hall[72]**
System Sizing						
Building Type	Office	Office	Office	Community Hall	College	Firehall
GSHP heating capacity [Btu/hr per ft^2]	16.6	27.7	15.2	44.3	26.7	202[73] MBtu/hr
GSHP cooling capacity [Btu/hr per ft^2]	N/A	35.1	15.3	50.8	N/A	202 MBtu/hr
PTIU – design heating day	N/A	0.99/0.02	88	N/A	N/A	N/A
Maximum PTIU – heating month	94	0.93/0.16	68	N/A	N/A	N/A
PTIU – design cooling day	N/A	0.53/0.56	36	N/A	N/A	N/A
Maximum PTIU – cooling month	42	0.39/0.31	16	47/31	N/A	N/A
Total annual heat delivered [kWh per ft^2]	3.9	N/A	N/A	N/A	N/A	N/A
Total annual heat removed [kWh per ft^2]	1.7	N/A	N/A	N/A	N/A	N/A
Maximum average monthly heating mode cycle time [min]	8460	160/25	55	N/A	N/A	N/A
Maximum average monthly cooling mode cycle time [min]	3060	168/95	14	41/21	N/A	N/A
System Efficiency						
Annual Heating mode COP	2.4	N/A	3.5	N/A	N/A	2.6
Annual Cooling mode EER	28	N/A	14.1	N/A	N/A	15.0
Ground Loop Sizing						
Loop orientation	Vertical	Vertical	Horizontal	Vertical	Vertical	Vertical
Borehole length [ft per MBtu/hr rated heating capacity]	17.7	12	N/A	13.5	53.3	N/A
Lowest average heating mode EST [^{o}C]	6	9	1	5	12	N/A
Highest average cooling mode EST [^{o}C]	13	20	20	22	17	N/A
Imbalance [kWh per ft borehole length]	-1.6	N/A	N/A	N/A	9.9	N/A
System Electrical Energy Consumption						
Total annual heating [kWh per ft^2]	1.6	N/A	2.8	N/A	N/A	N/A
Total annual cooling [kWh per ft^2]	0.2	N/A	0.3	N/A	N/A	N/A
Total annual [kWh per ft^2]	1.8	5.2	3.1	N/A	N/A	N/A
Emissions Savings						
Annual GHG savings [kg eCO$_2$ per rated heating ton]	0.5	N/A	N/A	N/A	N/A	N/A

5.3 Recommendations: Performance

1. **Circulator pumps should be interlocked to the heat pumps unless there is a compelling reason otherwise.** The performance degradation associated with non-interlocked circulator pumps has been quantified in two cases. Interlocking needs to be considered by geoexchange system

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[72] AMEC, 2013.

[73] Square footage not determined.

designers, building automation controls technicians and system installers. Ideally, checking that pumps are appropriately interlocked would be a part of a standardized commissioning template but this does appear to be currently available.

2. Short cycling times, on the scale of 10 minutes, were associated with poor performance in at least one installation. **Effort should be taken by system designers and installers to avoid short cycle times were possible.** This could include making adjustments to aquastat or thermostat settings, incorporating an appropriately-sized buffer tank or in installations with multiple heat pumps, temporarily taking units offline during periods of low-load.
3. In systems with multiple heat pumps, it might be advisable to **develop controls that allow each heat pump do an even amount of work**. This would help to ensure a longer life for the system as a whole by not wearing any given heat pump much earlier than others in the installation.
4. **Architects and geoexchange system designers should be aware of the ultra-efficient cooling mode operation that free-exchange provides**. Further research into free-exchange is warranted to determine at which applications/sites it is most suitable. A financial evaluation is also recommended as the payback may be notably affected if the system is capable of annual cooling mode EERs that surpass 28.0.
5. **TOU control of geoexchange systems should be further researched and developed. This has the potential to reduce electricity fuel costs (not including regulatory and distribution charges) by between 20 and 25%.** It also would provide benefits to utilities in the form of peak-shaving. Future incentive schemes might consider the incorporation of TOU control to some degree because of these multiple benefits.
6. Table 5.1 and 5.2 offer experimental operational data that may be useful for modeling sizing guidelines and benchmarking exercises.
7. The development of standardized commissioning procedures may be useful to prevent the occurrences of short cycle times, un-interlocked circulator pumps and other issues that might potentially degrade performance.

5.4 Recommendations: Performance Monitoring

1. **A BAS configured to log certain monitoring points for control of the geoexchange system will not necessarily provide sufficient data for a performance analysis.** The monitoring system used to run the BAS could also be used for performance monitoring; however, the requirements for performance monitoring are more stringent. Several geoexchange systems studied in this project were controlled and monitored by a BAS but the data obtained from this level of monitoring was often either incomplete for a performance analysis or not sufficiently accurate. In many cases the BAS provided at least some of the points required for a performance analysis. A more comprehensive performance monitoring program could likely be achieved with minimal additional effort. **Appendix A contains a suggested workflow for implementing geoexchange performance monitoring**. It could be used as a general guide for utilizing the BAS system for performance monitoring.
2. **Matched pair temperature sensors are necessary for accurate performance results but they are not necessarily standard on all energy meters**. Appendix B shows that the greatest source

of error when calculating the COP is the measurement which determines the difference between the entering and leaving source (or load) temperatures of the heat pump. The difference is often small, sometimes on the scale of 1 to 2 °C, and it is difficult to determine with any level of accuracy unless matched pair temperature sensors are used. Failure to consider this potential source of error could result in a COP calculation with prohibitively high error.

3. **Flow measurements may be difficult to obtain after the fact. It is easier and more cost effective to install a monitoring apparatus while the geoexchange system is being installed**. The flow measurement is a necessary component of any COP or capacity calculation. The flow ought to be determined during the design sizing process but for accurate results it needs to be measured as well. If there is no flow measurement device installed in the plumbing circuit than it needs to be measured using a surface mounted measurement device like an ultrasonic meter. This becomes more difficult as the system ages because corrosion may cause the pipe surface to dimple and an ultrasonic flow measurement requires a smooth surface. Ultrasonic meters are also expensive. It is easier and more accurate to install a flow measurement device within the plumbing circuit during geoexchange system construction and installation. Sufficiently accurate flow measurement devices are available at a reasonable expense. Depending on the complexity of the system, a single flow rate measurement at one point in time may not be sufficient.
4. **Surface mounting temperature sensors is permissible but the sensors must be firmly attached to the pipe.** If thermal wells were not installed in the geoexchange system during the initial construction phase, then the easiest method of obtaining fluid temperature measurements is by firmly securing a temperature probe on the surface of the pipe with thermal tape and cable ties, then covering the sensor with insulation. In one of the sites studied, a technician did not attach the sensor to the pipe but rather placed it loosely under the insulation. Since it did not contact the pipe, the sensor was measuring the air temperature in the vicinity of the pipe which was somewhere between the pipe temperature and the ambient air temperature. The error introduced was not easy to correct and ultimately the COP and capacity calculations were abandoned due to the uncertainty of the temperature measurement.
5. **Develop a monitoring plan with objectives clearly defined.** This is further discussed in Appendix A. There are several different reasons why a system owner or operator may choose to monitor their geoexchange system and the type and extent of the monitoring involved will vary with the monitoring goals and the scale of the system. To ensure the monitoring system will achieve the desired goals it is useful to clearly document those goals and develop/document a monitoring plan capable of achieving it.
6. **Assign a staff person to periodically inspect the data to ensure the monitoring system is functioning as intended.** The monitoring plan ought to have some provision for an individual to check the data at routine intervals. This could involve thoroughly checking that the data are reasonable or it could be just a cursory check to at least see if the data are being recorded and stored appropriately. The option chosen would depend on the resources available for the monitoring program. If the system has been properly commissioned it would likely be sufficient to simply check that the data are being recorded and stored. In one of the sites studied here there was no individual assigned to look at the geoexchange monitoring data due to a staffing

change. It turned out that several months of data were lost because the plan expired on the SIM card for the GSM modem.

7. **Commission your monitoring system and document the commissioning for future use and knowledge transfer.** Errors are more likely to be caught early on if the monitoring system installation is followed by a commissioning procedure. Otherwise, they may only be found at the end of the monitoring period when it may be too late to rectify them. A commissioning report was not available for any of the systems studied in this report. In most cases, knowledge of the monitoring systems had been partially lost due to staffing changes.
8. **It is important to check that the data are consistent and reasonable.** Methods of ensuring data integrity are listed below.
    a. Run circulator pump with the heat pump off while monitoring EST and ELT. The difference should be negligible if sensors are a matched pair.
    b. Monitoring and all the relevant temperature points, that is ELT, LLT, EST and LST, as well as the both the source and load flow rates will allow you to verify your capacity measurements. For example, in heating mode, the heat removed from the ground should equal the heat delivered to the building plus the compressor power draw.
    c. Calculate instantaneous capacity as well as overall heat delivered. This value should agree with the manufacturers rating provided entering source, load and flow rates are comparable. If it is significantly off their may be an error.
    d. Compare power draw to manufacturer spec sheet at a comparable rating point.
    e. If temperature sensors are not calibrated matched pair for the factory, perform an in-house calibration and include it in a commissioning report.
    f. Compare flow rates to recommended manufacturer flow rates.
    g. Compare data to a benchmark of expected performance based on modeling

6.0 CONCLUSIONS

This study examined performance monitoring data from 10 geoexchange sites, ranging in size from small-scale residential to large-scale institutional/commercial, with the aim to:

- evaluate geoexchange system performance to determine whether the systems were performing according to expectations;
- identify areas of improvement for systems that did not meet expectations;
- identify system design attributes or control strategies that lead to exceptionally good performance in systems that exceeded expectations, and
- identify areas where performance monitoring may be improved.

All systems surveyed were sized sufficiently to meet their heating and cooling loads. In at least one case, this also meant that the system may have been prohibitively oversized but this didn't appear common. A range of system performances were observed, with cases that fell short, met and even exceeded manufacturer rated values. Where performance fell short, attempts were made to identify contributing factors but in most cases there was limited data to consult which made it difficult to more specifically identify the cause. It was suggested that the performance of current systems might be improved by taking measures to improve cycle times and interlock circulator pumps. Future system's performance might be improved (or costs reduced) with TOU control algorithms or with advanced operational strategies such as free-exchange.

In some cases, performance monitoring fell short of fully realizing all monitoring goals. This was because (i) where monitoring was based on a BAS, the BAS was never configured to be used for performance monitoring purposes and (ii) mistakes were made in the mounting of sensors or acquisition of data. The latter was potentially avoidable had a more thorough planning and commissioning of the monitoring system been completed. A suggested workflow is present in Appendix A. Following this workflow will help to avoid future monitoring errors.

APPENDIX A – SUGGESTED MONITORING WORKFLOW

1. **Identify and document monitoring goals**. This ideally occurs while the geoexchange system is in the planning stages. Example monitoring goals are listed below. This list is not exhaustive.
    a. Energy or GHG emissions savings calculations against baseline consumption
    b. Monthly COP and heat delivered
    c. System optimization
    d. Ground loop performance/system balance
2. **Develop and document the monitoring plan**
    a. Obtain a line drawing of the geoexchange system showing the plumbing connections. System types can vary and a line drawing will be crucial to the development of a monitoring plan.
    b. Identify how data are to be analyzed. Existing monitoring protocols such as the International Performance Measurement and Verification Protocol (IPMVP) may be useful in creating study design.
        i. What are the performance metrics upon which the system performance will be analyze?
        ii. What equations are to be used? This will inform which monitoring points are required. Some products may have built-in analytics that could save considerable time.
        iii. Will data be manipulated in a spreadsheet program, a database or something else?
        iv. Identify error tolerances and perform an error analysis on the equations to be used such that sensors can be chosen to meet error tolerances.
    c. Identify the points in the systems that need to be monitored to perform the analysis.
        i. Note that additional points may help with data integrity checks.
        ii. The performance metrics and equations to be used should help identify what monitoring points are necessary.
    d. Identify the logging interval.
        i. If logging is via cellular networks than data cost may be an important consideration and lower resolution may be desirable.

    ii. If data is to be analyzed in Excel or a similar spreadsheet program then lower resolution data may be easier to handle. A year's worth of one-minute resolution data will result in 500,000+ rows of data. Excel can't handle much more than 1,000,000 and will not do that efficiently.
    iii. If heat pump cycling is a part of the analysis then the data logging interval must be less than the cycling time, ideally much less.
    iv. Average logging over the given interval or instantaneous logging. Instantaneous logging will assume that the data taken at one point in time is the same for the whole interval. If the system is rapidly changing then this may result in large errors.
    v. Logging based on change-of-value will not likely be sufficient for an accurate performance analysis.
    vi. If the logging interval is changed part of the way through the monitoring period then it will add to the time it takes analyze the data. It is better to think it through first and not change it.

e. Procure the monitoring hardware
    i. The monitoring hardware will be different depending on who is doing the monitoring. In many of the examples shown in this report the monitoring system has been done by an external party with established methods of monitoring for external sites. These monitoring systems may not be the ideal choice if the monitoring is to be done internally by the building manager or system operator. If there is an existing BAS or SCADA system then the new monitoring system should be capable of integrating with the existing system.
    ii. The monitoring plan will likely require one or a combination or temperature measurements, flow measurements and power measurements. A single meter may combine some or all of these measurements in one unit. Furthermore, some dataloggers or meters are equipped with software that can perform analytics on the data, saving considerable time but potentially more prone to error.
    iii. Temperature sensors should be matched pair. The error associated with the temperature difference is the most important source of error. Ideally, temperature sensors are mounted in thermal wells submersed in the fluid flow. Surface mounted temperature sensors are possible as well but they ought to be firmly attached to the pipe with thermal tape, cable ties and covered with pipe insulation. Sensors should be mounted in the same way such that they experience any thermal lag in the same way.

        iv. Flow measurement is easier if there is a flow measurement device installed in the circuit. It may be more difficult and more expensive to rely on non-intrusive ultrasonic flow measurements after the system has been built, ie. pipe corrosion may make surface-based measurement, like ultrasonic, impossible or inaccurate. If the circulator pump is constant speed than a flow measurement at one point in time may be all that is required and even an inexpensive flow meter or other flow measurement device, installed in-line, may yield results with an acceptable level of error. This could add minimal additional cost provided it is installed with the geoexchange system.

        v. Once the schedule of parts is established. All documents related to the equipment (i.e. model no.'s, reference numbers, specs, etc.) should be stored with the monitoring plan.

3. **Install and commission the monitoring system (<u>and document</u> the commissioning)**

    a. A commissioning document should document, to a reasonable degree, the installation of the monitoring points in the system and note any relevant points on how each was installed.

        i. If temperature sensors are installed on the surface of a pipe it would be useful to document, with pictures, that the sensors are in fact in secure and firm contact with the pipe such that subsequent employees working on the system can be sure that they have been installed in accordance with best practices. An inexperienced technician might improperly install a temperature sensor and, despite the money and time invested in the project, the plan could fall short of meeting the monitoring goals.

        ii. The locations of current CTs should be documented as well. For example, the CT may monitor only the heat pump compressor box but often, the ground loop or distribution circulator pump is interlocked to the unit as well and a CT installed at a service panel would actually monitor the power of the compressor box and the circulator pumps. The documentation should be clear enough to distinguish what the power measurement includes to ensure the accuracy of the results.

    b. If possible, notes on how the heat pump is controlled should be gathered as well. A simple system might have a single heat pump charging a buffer tank in which case it would be useful to record the buffer tank aquastat settings. More complicated systems would require more complicated notes.

    c. Time should be taken to configure the datalogger and any other measurement device and important parameters should be documented. For example, an ultrasonic flow meter may have several pages of parameters that need to be set up properly for an accurate result. If a data analyst sees strange measurement results than one of the first things to consider is whether meter has been set-up properly. If it has been properly documented it may only be a quick check, if has not been documented then a site-visit may be required and this adds time and cost. Similarly, the datalogger (or BAS or SCADA system) should be configured with descriptive names of monitoring point and units such that the data files can be easily interpreted afterwards.

   d. Once installed the system is installed, the monitoring technician should verify that all monitoring points are properly logging and reading reasonable values. The system can then be left for a short period of time (in the range of a day to a week). The data should then be gathered and analyzed in full according to the monitoring plan. At this point in time, data integrity checks (mentioned previously) can be performed as well. This will verify that the data is reasonable and that the data is sufficient to perform the analysis outlined in the monitoring plan. If any changes need to be made to the monitoring system, this is the time to do it as changes made later on will complicate the data analysis. Relevant plots resulting from the data analysis should be stored in the commissioning report for future reference. This would conclude the commissioning of the system.

4. **Periodically check the data.**

   a. At minimum, a technician should be assigned to periodically check that the data is being logged properly. If the system was commissioned properly and the integrity of the data was verified during the commissioning process then a periodic check may only consist of checking if the data is actually there and is generally reasonable looking, without any additional analysis required. This would only take a few minutes and, as such, it would be reasonable to do on a monthly or bi-monthly basis. Some logging, BAS or SCADA programs also have e-mail warnings if parameters are out of a predefined range and this could be a useful way to automate data checks. Furthermore, these programs may also be capable of logging “meta-points”, ie. a data point calculated from other data points, such that heating capacity, COP and other parameters could be logged as a data point directly rather than calculated during post-processing.

   b. A data checking schedule and checklist could be created to help ensure that the data checks are performed.

   c. Document any servicing that gets done on the monitoring system. Including changes to any system paremeters. This will help interpret any abrupt changes to the data during the analysis phase.

5. **Perform the analysis**

   a. If attention was paid to the previous steps then analysis should be straightforward. It is simply a matter of following the procedure outlined in the monitoring plan and since a full analysis had already been performed during the commissioning phase the complete analysis ought to proceed smoothly.

APPENDIX B – ERROR

Error from non-matched pair sensors

Eq. 8.1 shows the propagation of uncertainty in a multivariable function Q(X,Y,…) where the function variables have uncertainties denoted by δX, δY and so on. Eq. 8.2 is the distribution-side heating capacity equation. Applying Eq. 8.1 to Eq. 8.2 yields Eq. B.3.

$$\delta Q(X,Y,\dots) = \left(\left(\left(\frac{\partial Q}{\partial X}\right)\cdot\delta X\right)^2 + \left(\left(\frac{\partial Q}{\partial Y}\right)\cdot\delta Y\right)^2 + \cdots\right)^{\frac{1}{2}} \tag{8.1}$$

$$Cap_H = GPM \cdot 0.264 \cdot (LLT - ELT) \tag{8.2}$$

$$\delta Cap_H = ((0.264\cdot(LLT-ELT)\cdot\delta GPM)^2 + (0.264\cdot GPM\cdot\delta LLT)^2 + (-0.264\cdot GPM\cdot\delta ELT)^2)^{\frac{1}{2}} \tag{8.3}$$

At 9:54 am on Feb. 10th 2013, the ELT, LLT and GPM of Peel House B were 40.3±0.5°C, 43.5±0.5°C and 18.3±0.4 respectively. Using Eq. B.2 the instantaneous capacity was 15.5±3.4kW. The uncertainty is 22%. If ELT was 41.3 °C or 42.3°C, then the uncertainty would be even larger at 32 or 59% respectively. This shows that δCap_H is highly sensitive to the small differences in (LLT-ELT) when matched-pair sensors are not used.

If matched-pair sensors are used, it is possible to get δ(LLT-ELT) to lower than ±0.1°C. Since the error is associated with the difference rather than the absolute value, Eq. B.3 needs to be rewritten as in Eq. B.4.

$$\delta Cap_H = ((0.264\cdot(ELT-LLT)\cdot\delta GPM)^2 + (0.264\cdot GPM\cdot\delta(LLT-ELT))^2)^{\frac{1}{2}} \tag{B.4}$$

Repeating the calculation shows a notable reduction in the uncertainty, yielding values of 4, 5 and 9% when ELT is 40.3, 41.3 or 42.3°C respectively. It follows that matched-pair temperature sensors need to be used to mitigate the otherwise high uncertainty in geoexchange performance calculations due to the small difference between ELT and LLT (or EST and LST).

Error from instantaneous logging

A data logging device will have a given logging interval. This is the quantity of time between successive data points. Depending on the device settings, a given logged data point is likely to be either: (i) an instantaneous value, (ii) an average value for the logging interval or (iii) a running total.

Instantaneous values will not give any information about the given data point's value over the course of the logging interval. For example, if the logging interval is one minute, then one data value would be logged at minute 0 and another data value would be logged an minute 1 and whatever happened in between would be completely ignored. During analysis, the instantaneous value might be assumed to representative of the entire logging interval but, as already explained, this may not strictly be true.

The Badger Meter Series 380 Btu Meter at Peel House A and B was capable of both instantaneous measurement and determining a running energy total, but instantaneous values were used in the analysis. There were two issues with using the running energy total in the analysis: (i) a temperature sensor calibration was conducted, requiring a recalculation of energy that could only be applied to the instantaneous data and (ii) as shown in Eq. B.4, the error for the energy calculation cannot be simply determined based on the energy reading from the Btu meter but rather must be calculated for each logging interval and then summed accordingly. It follows that to apply a calibration and to determine the measurement error, the instantaneous values must be used in the analysis. The error introduced by using instantaneous values is negligible. This is explained below.

The total energy delivered by the geoexchange system over the course of a cycle is given by 8.5. Where t_i is the start of the cycle and t_f is the end. In this equation, GPM, LLT and ELT, are all functions of time. However, because an instantaneous value is logged every one minute, equation 8.5 must be approximated by Eq. 8.6, where Δt is equal to 1 min (or 1/60 hours to achieve unit kWh). The error associated with instantaneous logging is then given in Eq. 8.7.

$$Heat\ Energy = \int_{ti}^{tf} GPM\ \cdot 0.264\ \cdot (LLT - ELT) \cdot dt \tag{8.5}$$

$$Heat\ Energy = \sum_{j=t1}^{t2} GPM_j\ \cdot 0.264\ \cdot \left(LLT_j - ELT_j\right) \cdot \Delta t \tag{8.6}$$

$$\begin{aligned} \delta Heat\ Energy_{Inst} &= \int_{ti}^{tf} GPM\ \cdot 0.264\ \cdot (LLT - ELT) \cdot dt \\ &- \sum_{j=ti}^{tf} GPM_j\ \cdot 0.264\ \cdot \left(LLT_j - ELT_j\right) \cdot \Delta t \end{aligned} \tag{8.7}$$

It is more straightforward to evaluate 8.7 graphically. Figure 8.1 shows the capacity (in red) over a heating cycle at Peel House A from 8:31 pm to 8:48 pm on March 16th 2013.[74] The area under the red curve is equal to Eq. 8.5. The area of the blue rectangles is equal to Eq. 8.6. The difference between the two areas is negligible, especially when compared with the sensor error. This source of error is therefore not considered further and instantaneous logging at a one minute is deemed sufficiently accurate for

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[74] Note that the red capacity curve is actually from instantaneous logging with a one minute logging interval and has been interpolated to create a smooth curve that is assumed to very closely approximate the actual capacity curve. It could be argued that it is possible to just numerically integrate the red curve to obtain a more accurate result since it, as well, was obtained from instantaneous logging. However, that would be computationally more challenging and, as shown, Riemann-sum integration is sufficient.

performance evaluation. Note that this is the case because the change in capacity over time is very small when compared with the logging interval. If the logging interval was much longer, or the capacity curve more variable, then the error would be larger.

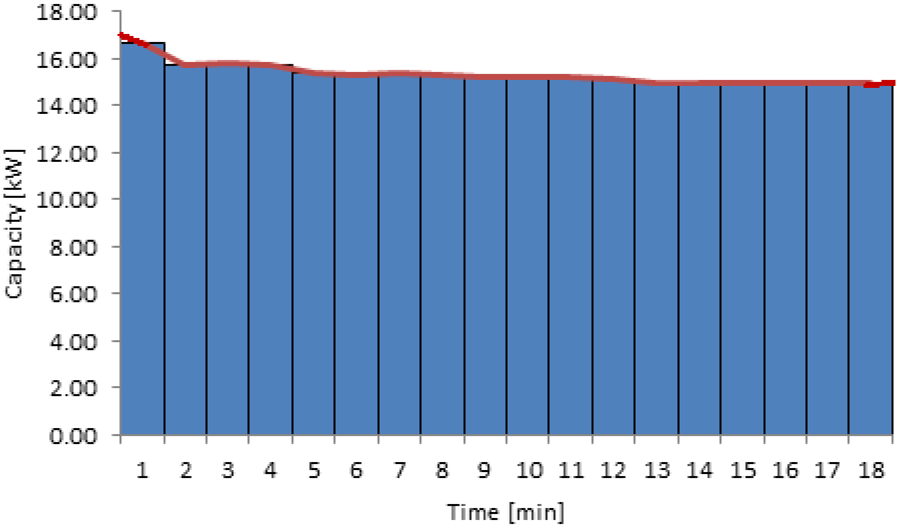

Figure B1: The capacity is shown for a given heating cycle from Peel House A. The area under the red curve is equal to the total energy delivered during the cycle and the area of the blue rectangles is the energy that is calculated based on instantaneous logging. The areas are sufficiently similar and instantaneous logging with a 1 minute logging interval is permissible for geoexchange capacity calculations.

A secondary source of error with instantaneous logging comes from the first and last logging intervals. The problem is that it isn't known precisely when the cycle starts and ends. It could have started at any time less than 1 minute (assuming the logging interval is one minute) before the first data point was logged and similarly, it could have ended at any time less than 1 minute after the last data point was logged. The consequence of this is that the error in the length of a cycle is ±1 min, and in the context of Figure B.1, the calculated energy, which is equivalent to the total area of the blue rectangles, has an uncertainty that is roughly equal to the area of a single rectangle (which represents 1 minute of operation). In other words, the uncertainty of the energy calculation determined over a given cycle is approximately equal to the total calculated energy divided by the number of logging intervals. However, in the analysis, the energy is reported in terms of totals on a monthly basis and the truly random nature of this source of error is assumed to approximately cancel itself out when the energy from a sufficiently large number of cycles is added together.

All the previous arguments also apply to the electrical energy consumption calculation. The corresponding plot is shown in Fig. B.2. Again, the area under the red curve represents actual electrical consumption and the area of the blue rectangles is the calculated energy consumption from instantaneous logging. The difference is negligible.

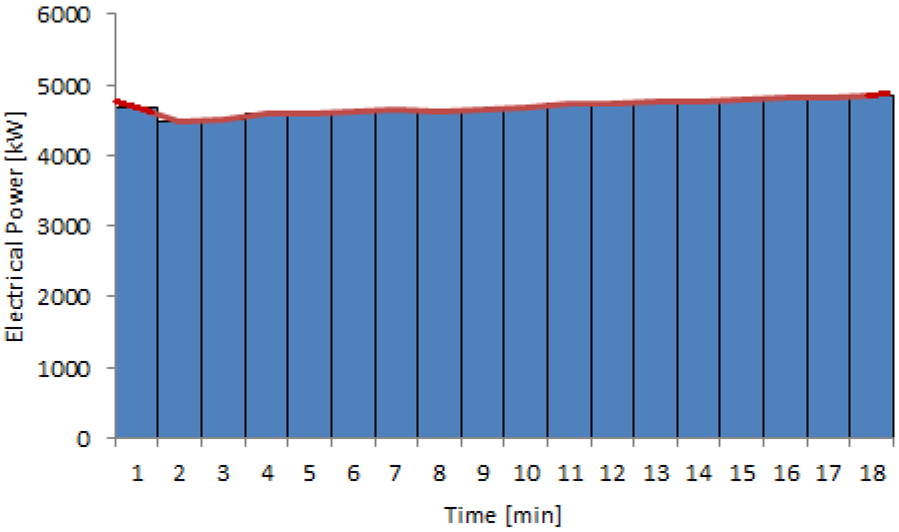

Figure B2: The electrical power consumption is shown for a given heating cycle from Peel House A. The area under the red curve is equal to the actual total energy consumed during the cycle and the area of the blue rectangles is the energy that is calculated based on instantaneous logging. The area sufficiently similar and instantaneous logging with a 1 minute logging interval is permissible for geoexchange power consumption calculations.

A similar analysis would should that averaged logging with a longer logging interval (eg. 5 minutes) would also yield negligible error provided that the sampling interval was chosen appropriately. This is because averaged logging approximates Eq. 8.5 in the same way as Eq. 8.6 but with a Δt that is equal to the sampling interval rather than the logging interval and it is normally possible to choose a sampling interval that is much less than a minute.

Performance metrics error calculations

Table 8.1 displays the uncertainty calculations used to generate error bars for the various performance metrics used in the analysis. Equations are all based on Eq. 8.1. Error bars are not presented for GHG calculations because there are several important limitations to this analysis that are discussed qualitatively in Section 3.2.9. The symbols used in these equations have largely been discussed in Section 8.2. In addition, $E_{Elec,H/C}$, N_{cycle}, t_{cycle} and t_{total}, are the electrical energy consumed in heat/cooling, the total number of cycles, the length of time of a given cycle and the length of time over which the performance metric is calculated.

Table B1: Uncertainty calculations for performance metrics

Metric	Equation	Error Equation
Heating/Cooling capacity from distribution-side measurements	$Cap_{H/C} = \pm GPM \cdot 0.264 \cdot (LLT - ELT)$	$\delta Cap_{H/C} = ((0.264 \cdot (ELT - LLT) \cdot \delta GPM)^2 + (0.264 \cdot GPM \cdot \delta(LLT - ELT))^2)^{\frac{1}{2}}$
Heating/Cooling capacity from source-side measurements	$Cap_{H/C} = \pm GPM \cdot 0.258 \cdot (EST - LST) \pm P_{Comp}$	$\delta Cap_{H/C} = \left((0.258 \cdot (EST - LST) \cdot \delta GPM)^2 + (0.258 \cdot GPM \cdot \delta(EST - LST))^2 + \left(\delta P_{Comp}\right)^2\right)^{\frac{1}{2}}$
Heat delivered or removed	$E_{H/C} = \sum^{Total\ Time} Cap_{H/C} \cdot \Delta t$	$\delta E_{H/C} = \sum^{Total\ Time} \delta Cap_{H/C} \cdot \Delta t$
COP	$COP_{H/C} = \frac{Cap_{H/C}}{E_{Elec,H/C}}$	$\delta COP_{H/C} = \left(\left(\frac{\delta Cap_{H/C}}{E_{Elec,H/C}}\right)^2 + \left(\frac{Cap_{H/C} \cdot \delta E_{Elec,H/C}}{{E_{Elec,H/C}}^2}\right)^2\right)^{\frac{1}{2}}$
Percentage time in-use	$PTIU = \frac{\sum^{N_{cycles}} t_{cycle}}{t_{total}}$	$\delta PTIU = \frac{\sum^{N_{cycles}} \delta t_{cycle}}{t_{total}} = \frac{N_{cycles} \cdot \Delta t}{t_{total}}$
Average cycle time	$\overline{t_{cycle}} = \frac{\sum^{N_{cycles}} t_{cycle}}{N_{cycles}}$	$\delta \overline{t_{cycle}} = \Delta t$