

Performance Assessment of Urban Geoexchange Projects in the Greater Toronto Area

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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.

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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;

[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.

[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	3.1[10]
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[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

[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 [^oC]	6	9	1	5	12	N/A
Highest average cooling mode EST [^oC]	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

[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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