



Performance Assessment of Heat Pump Systems

TECHNICAL BRIEF



A ground source heat pump extracts heat from the ground surface through an open loop (pumping well water) or closed loop system (heat transfer fluid within underground pipes). An air source heat pump extracts heat from the indoors or outdoors, depending on the season. An air-to-water source heat pump extracts outdoor heat and transfers it to the water distribution system during the cooling season; the process is reversed during the heating season.

This study evaluates the performance of air source heat pump (ASHP) and ground source heat pump (GSHP) systems individually and as part of their associated heating and cooling distribution systems in two semi-attached houses. Over the monitoring period, the performance of both heat pumps exceeded manufacturer and EnerGuide ratings, with Coefficients of Performance (COPs) above 5 in the cooling season and above 3 in the heating season. These COPs decreased by between 9 and 53% when energy inputs associated with the heating and cooling distribution systems were considered. Modelled optimization scenarios showed that considerable increases in system efficiencies could be achieved by configuring fans and pumps to operate only when the heat pump compressor is on, and by upgrading the GSHP from a single stage to a two stage system to reduce compressor cycling. Performance of the ASHP was more adversely affected by declining winter temperatures than the GSHP. However, the ASHP continued to maintain indoor thermal comfort at temperatures as low as minus 24°C without supplementary heat. Model simulations for five major Canadian cities showed that both technologies can perform well in the Canadian climate, but that residential GSHP systems are better suited to climates where winter temperatures fall below minus 24°C.

Heat pump technology is not new. A bicycle pump is a variation by taking ambient air and compressing it into a tire where the excited molecules produce heat. Similarly, a refrigerator pump removes the heat from ambient air through compression and radiates it from the back side of the fridge.



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A simple cost analysis relative to conventional electric heating and cooling revealed that although up-front equipment and installation costs are high for both systems, the ASHP is more affordable with a simple payback of approximately 10 years. Even though the GSHP is slightly more efficient, simple payback is over two times longer due to higher initial capital costs. However, since the GSHP has a longer expected service life than the ASHP, the financial case for these systems would be more accurately assessed through a full life-cycle cost analysis. This simple cost analysis also omits the substantial benefits these systems offer in reducing greenhouse gas emissions.

INTRODUCTION

Between 1998 and 2004, the housing sector accounted for 17% of secondary energy use in Canada and 16% of the country's greenhouse gas emissions (Natural Resources Canada, 2006). Space and water heating are the dominant residential end uses of energy, typically representing 58% and 22% of total household consumption, respectively (Cuddihy *et al.*, 2005). Roughly 26% of the household contribution to total emissions is from residential fuel use and the production of electricity for use in the home (Statistics Canada, 2008).

Heat pumps are among the most energy efficient technologies for heating and cooling buildings and providing hot water. Heat pumps function by moving heat from one place to another. A ground source heat pump uses the ground as the source and sink for heat, while air source heat pumps take heat from the outdoor air and transfer it indoors. Both can be used with a conventional forced air or hydronics system. Since air temperatures fluctuate much more

than ground temperatures, air source heat pumps often require a back-up source of heat during very cold weather to maintain indoor temperatures at desired levels.

This study assesses and compares the performance of a horizontal loop coupled 13.3 kW high efficiency ground source heat pump and a high efficiency variable capacity 10.5 kW air source heat pump. The heat pumps are installed in each of two attached LEED™ platinum houses at the Living City Campus at Kortright in Vaughan, Ontario.

STUDY SITE

The two semi-attached houses, hereafter referred to as House A and House B, are 3-storey south facing houses with similar floor areas, internal volumes, and levels of insulation (R-30 above grade, R-20 below). Structurally insulated panels were used for the roof of both houses. House B has roughly 20% more window coverage than House A, and has triple glazed windows with higher thermal resistance than the double glazed windows in House A. The design heating loads of House A and House B are 7.91 kW and 7.94 kW when outdoor and indoor temperatures are -22 °C and 22 °C, respectively. Differences in the mechanical systems are discussed below. The Archetype Sustainable House has been awarded LEED™ Platinum, EnergyStar and GreenHouse certifications.

Energy Audit

Air leaks through the exterior envelope increase energy use. A blower door test was conducted to determine how much air was leaking into the houses. This entailed mounting a large fan to the

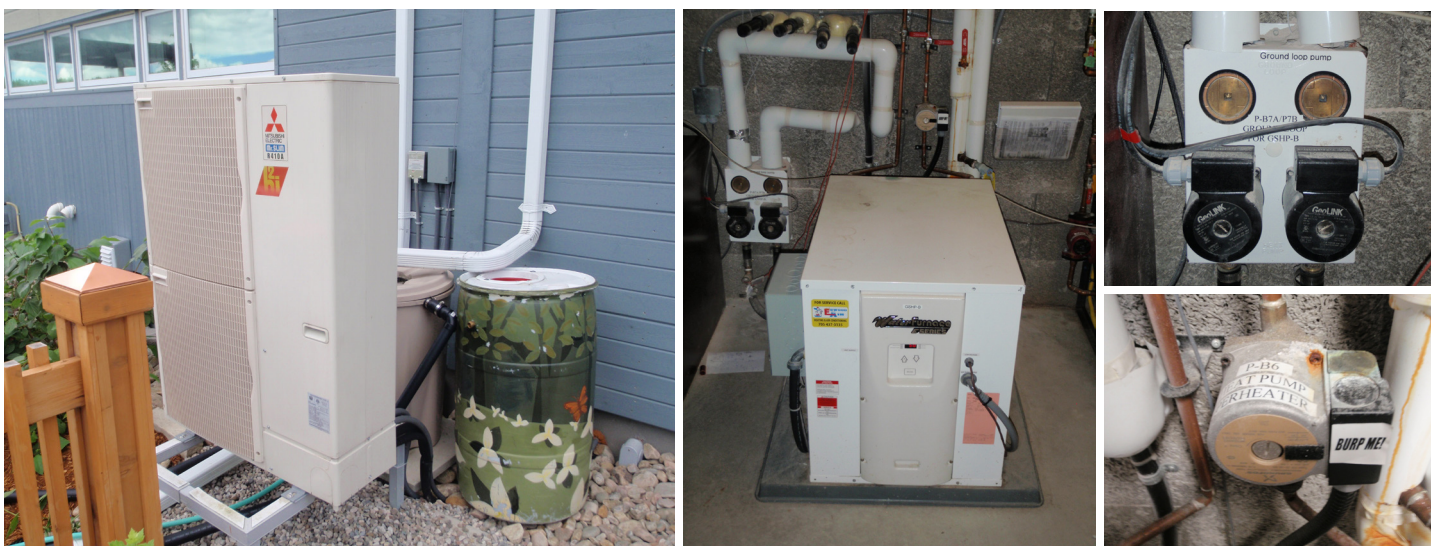


Figure 1. The ground source heat pump installation is shown on the left. The different components of the ground source heat pump are shown on the right.

Table 1. Summary of airtightness results for House A and House B. CFM - cubic feet per minute. ACH - air changes per hour. Source: Fung *et al.*, 2009.

	Units	House A	House B
Net Floor Area	m ²	345	350*
Internal Volume	m ³	986	1036*
Volumetric Flow Rate	CFM	699	665
ACH @ 50 Pa	ACH	1.204	1.091

* Excluding Guest Suite

door frame and drawing air out of the house to calculate the rate of air leakage and assess where the leaks were most prominent. The tests were conducted with outside temperature of -7.7°C and inside temperature of 20.0°C .

Results of the blower test, presented in Table 1, showed that the exterior building envelopes were better sealed than most homes, particularly House B, which registered only 1.1 air changes per hour (ACH) during the blower test (more air changes mean leakier houses). By comparison, the Energy Star label requires a maximum of 2.5 ACH, and the new 2012 Ontario building code allows 3.1 ACH. Model simulation results using HOT2000 indicate that the energy efficiency of both houses exceeds the R-2000 energy efficiency standard,

Table 2. Mechanical Features of the Archetype Sustainable Houses.

Features	House A	House B	Guest Suite
Solar collector	Flat plate collectors	Evacuated tube collectors	From House B
PV system	No	4.08 kWp	No
Wind turbine	No	1.8 kWp	No
Heating and cooling	Variable capacity air source heat pump packaged with AHU	Ground source heat pump (GSHP) with horizontal loops, desuperheater and buffer tank	From House B
	Wall mounted mini gas boiler*	Stirling engine micro-cogeneration unit with buffer tank (heating alternative to the GSHP)*	From House B
DHW system	Flat plate collector with one tank system	Evacuated tube collector with preheat tank and TOU based electric backup, GSHP desuperheater on the auxiliary tank, and auxiliary heat from the cogen.	None
Ventilation system	Heat recovery ventilator (HRV)	Energy recovery ventilator (ERV)	HRV with an air heater
Auxiliary water heating	Mini gas boiler	Time-of-Use (TOU) electric	From House B
Infloor heating	Basement only*	All three floors & basement	No
Drain water heat recovery	Yes	Yes	No
Air heater	No	No	Yes

* The infloor basement heating and wall mount mini boiler in House A, and the Stirling engine micro-cogeneration unit in House B were not operating over the duration of this study.

which is much higher than the energy efficiency ratings required under Canadian building codes.

Mechanical Systems

Table 2 shows the mechanical systems in the two Houses. These mechanical systems were selected from 19 mechanical system alternatives based on a decision support matrix that used pre-defined criteria such as energy consumption, life cycle costs and greenhouse gas emissions to evaluate alternatives (Rad *et al.*, 2007).

Based on this analysis, the system selected for House A is a 10.5 kW (3 ton) high efficiency variable capacity air-to-air source heat pump manufactured by Mitsubishi™ with a direct expansion coil air handling unit (AHU) and a multi-speed fan to supply warm and cold air for space heating and cooling (Figure 1). The system is coupled with a mini-boiler which supplies hot water to the heating coil of the AHU when the ASHP alone is not able to supply sufficient heat due to low outdoor air temperatures. The mini-boiler was not operating during the study period.

The mechanical systems in House B consist of a 13.3 kW high efficiency ground source heat pump manufactured by WaterFurnace™ connected to two 152.3 m (500 ft) horizontal loops in the yard

(Figure 1). A propylene glycol mixture is used as the heat transfer fluid. In the cooling season, the GSHP supplies chilled water to the multi-zone AHU. A radiant in-floor heating system is used for space heating on each floor during the winter. A buffer tank is used between the GSHP and the infloor system/AHU to minimize equipment cycling. A Stirling Engine micro-cogeneration unit was installed in House B as a heating alternative to the GSHP but was not functioning over the duration of the testing period.

In houses with tight envelopes, ventilation systems are needed to maintain adequate indoor air quality. To avoid wasting energy, a heat recovery ventilator (HRV) is used in House A to pre-heat or pre-cool incoming fresh air by extracting the heat or coolness from indoor air being exhausted from the house. An energy recovery ventilator (ERV) installed in House B operates in a similar fashion but also provides moisture control. House A and B also include a 0.91 m long grey water heat exchanger for grey water heat recovery.

APPROACH

The Archetype Sustainable House was designed and constructed as a laboratory for green building technology testing and research with over 300 calibrated sensors installed to monitor the performance of the electrical/mechanical systems and energy fluxes into and out of the house. A National Instruments data acquisition system is used to process data received from the various sensors. LabVIEW software has been programmed to provide real-time monitoring and data processing. Measurements are collected at 5 second intervals and recorded in an MS SQL database (TRCA and Ryerson, 2011).

Data for this study were collected under controlled and non-controlled conditions year round except during system maintenance. The summer and winter controlled test periods extended from August 23 through September 15, 2010 and from December 24, 2010 to January 12, 2011, respectively. During this period, all uses of the house were controlled and recorded. Hot water was dumped

daily in accordance with the IEA Schedule Task 26 model for a typical Canadian family of four people (Safa, 2012). Data collected during controlled conditions were used to provide 'clean data' for benchmarking and model calibration. The calibrated model (TRNSYS) was subsequently used to simulate energy performance over the entire heating (October 1 to May 21) and cooling seasons (May 22 to September 30) based on climate normals derived from a 30-year historical record of solar irradiance and temperature.

Under non-controlled conditions, occupant activities were not restricted, resulting in energy gains and losses due to meetings, tours and other events in the houses. Since these activities were not recorded, and the effects on energy use were not quantified, the data collected during this period could not be used to benchmark energy use in the house. Nevertheless, data collected during this period provided general performance information that could be used to evaluate overall performance of the equipment, and verification of the model used for results extrapolation.

FINDINGS

Both systems performed well over the one year study period, exceeding rated performance across all measured indicators. Table 3 compares actual performance during the heating and cooling seasons to the corresponding EnerGuide and equipment manufacturer ratings. Coefficients of performance for both heat pump systems exceeded 3 during the heating season and 5 during the cooling season, indicating that the systems provided over 3 kWh of output heat and 5 kWh of output cooling for each kWh of energy consumed. The GSHP performed particularly well during the cooling season when performance well exceeded both the manufacturer and EnerGuide ratings for the technology. During the heating season, the COP for the GSHP was only slightly higher than the manufacturer and EnerGuide ratings. Although the ASHP had marginally lower COP and energy efficiency ratios compared to the

Table 3. ASHP and GSHP performance relative to ratings.

		Manufacturer	EnerGuide	Test	Season
ASHP	Seasonal Energy Efficiency Ratio	16	≥14	18	Cooling
	Coefficient of Performance	2.75	2.05	3.23	Heating
GSHP	Seasonal Energy Efficiency Ratio	12.9	≥14.1	19.7	Cooling
	Coefficient of Performance	3	≥3.3	3.44	Heating

Table 4. ASHP and GSHP system performance during the cooling season.

Performance Metric	ASHP		GSHP	
	Standalone	System as installed	Standalone	System as installed
Seasonal Cooling Output (kWh)		2289		2459
Seasonal Power Consumption (kWh)	434	653	425	907
Seasonal Energy Efficiency Ratio	18	12	20	9
Seasonal Coefficient of Performance	5.37	3.5	5.78	2.71

Table 5. ASHP and GSHP system performance during the heating season.

Performance Metric	ASHP		GSHP	
	Standalone	System as installed	Standalone	System as installed
Seasonal Heating Output (kWh)		17579		18764
Seasonal Power Consumption (kWh)	5442	8195	5460	5979
Seasonal Coefficient of Performance	3.23	2.14	3.44	3.14

GSHP, it exceeded the EnerGuide rating during the heating season by a much greater margin. Performance of the two technologies relative to manufacturer ratings was also significantly higher during both seasons (Table 3).

Electricity consumption by the heating and cooling distribution systems in the houses strongly influenced overall power consumption and performance of the HVAC systems.

When analyzed as a standalone technology, without considering power consumption by the hydronics and forced air distribution systems specific to each house, the heat pumps consumed roughly the same amount of electricity, while delivering similar heating and cooling outputs (Tables 4 and 5). However, when the entire system as installed is considered, the GSHP underperforms the ASHP by 29% during the cooling season, and outperforms it by 32% during the heating season. These differences are largely due to the power consumed by the heat pump distribution systems and how they were set up to operate. The air handling unit (AHU) in House A has a

variable speed fan that ran continuously during the heating season, but was set up to operate only when the ASHP compressor was on during the cooling season. By contrast, the GSHP circulates water through the radiant floor during the heating season with a pump that consumes only 10% of the energy of the AHU fan in House A. During the cooling season, cool air is provided through an AHU system and a pump that circulates water from the buffer tank to the AHU. The House B distribution system (system as installed minus standalone usage) consumed a similar amount of electricity during the heating and cooling season (519 and 482 kWh, respectively). By comparison, the AHU fan integrated with the ASHP in House A consumed roughly 13 times more electricity during the heating season (2,753 kWh), when it was operating continuously, than in the cooling season (219 kWh), when it operated only when required.

Modelled optimization scenarios showed substantial energy savings can be achieved by configuring the systems to operate more efficiently.

When the AHU for the ASHP was modelled to operate during the heating season only when the compressor was on, rather than running continuously, electricity consumption fell by almost 37% and the COP increased from 2.25 to 3.54. Similarly, the pumps from the GSHP to the buffer tank and from the buffer tank to the AHU were optimized by operating them only when the compressor was on, resulting in a 28% reduction in electricity use and a dramatic increase in the as-installed COP from 2.64 to 3.68. This highlights the importance of understanding the various components that make up the system, including HEPA filters and heat recovery ventilators, and ensuring these are optimally configured to maintain high levels of efficiency and energy performance. Deviation typical for thermally driven winds, while higher K values are typical for the high and steady wind regimes of trade winds. This finding points to the lack of strong winds required for wind power generation at the study site.

The variable capacity ASHP cycled on and off much less frequently than the single stage GSHP resulting in improved overall efficiency.

Lower on-off cycling of heat pumps improves performance by making the operation of heat pumps more efficient. The ASHP system achieved lower cycling through the variable capacity feature which allowed the compressor to operate primarily on part load drawing less than half the electricity than would otherwise have occurred. During the cooling season test period the compressor operated between 3 and 11 hours per day and turned on and off only once. The single stage GSHP system operated during the cooling season test period between 1 and 6.5 hours and cycled on and off up to 25 times a day (Figure 2). This is an indication of an oversized

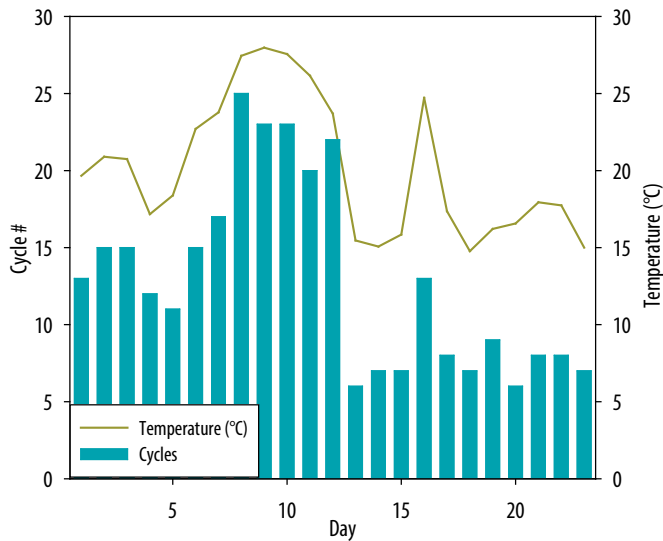


Figure 2. The number of daily on-off cycles for the GSHP in relation to outdoor temperature.

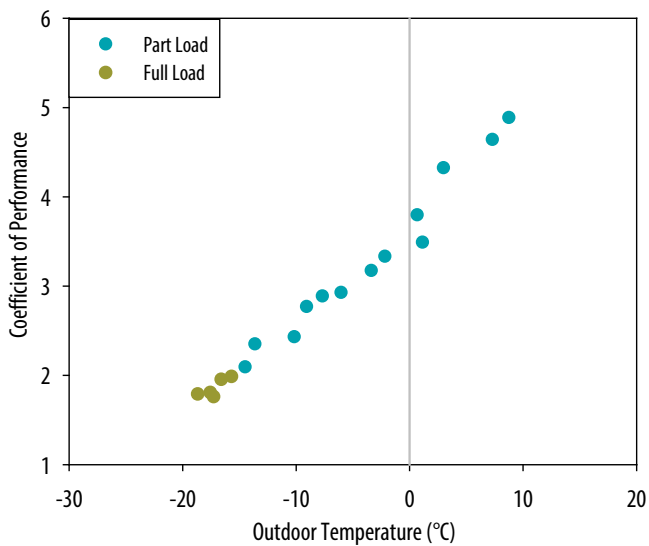


Figure 3. Coefficient of performance (COP) for the variable capacity air source heat pump at varying outdoor temperatures during the winter test period (December 1, 2010 to February 9, 2011)

system capable of operating only at a constant output. Equipment reliability and thermal comfort are adversely affected by frequent compressor cycling.

Performance of the ASHP fluctuated more than the GSHP as temperatures declined in the winter, but even at temperatures as low as minus 24°C, the ASHP continued to maintain indoor thermal comfort at desired levels without supplementary heat. The performance of GSHP systems is more constant

than ASHP systems during the heating season because the temperature of the ground from which heat is drawn is more constant than air. Figure 3 shows a decline in the COP of the ASHP from 4.9 to 1.6 as outdoor temperatures fell from 9 to -19°C during the winter. Below -24°C, the heat pump is less efficient than a conventional electric heating system, and a supplementary heat source would be required. At temperatures above roughly minus 15°C, the variable capacity ASHP compressor operates on part load, drawing less than half the electricity (2 – 3 kW) required under full load conditions (6 kW). Only when outdoor temperatures dropped below minus 15°C did the ASHP compressor switch to full load (Figure 3). By comparison, the GSHP system maintained a more constant COP of about 3.0 regardless of outside temperature conditions.

Model simulations for five Canadian cities revealed the two technologies to function well under varying climates with comparable levels of performance. The simulations were based on historical weather and ground temperature data from the selected cities. Figure 4 shows temperatures, degree days and coefficients of performance for each of the cities during the heating and cooling seasons. The ASHP displayed a wider range of COPs across the various cities during the winter because ASHP performance is more strongly influenced by differences in air temperature. This is evident from the lower COPs in Montreal and Edmonton, where a supplementary heat source would be required at temperatures below -24°C (Table 6). In Vancouver, the warmer and more even year round temperatures resulted in higher ASHP performance. During the cooling season, the GSHP system slightly outperformed the ASHP in all cities, with COPs ranging narrowly from 5.8 to 6.1.

A simple cost analysis showed the ASHP to be more affordable than the GSHP based on performance and initial capital costs. In this analysis, the costs of both heat pump systems were compared to a conventional electric heater during the heating season, and an air conditioning system during the cooling season (Table 6). The electricity consumed by the air and hydronic distribution systems was ignored because this was assumed to be similar on both the conventional and more sustainable systems. At a Toronto electricity rate of 11.3 cents (including transmission, distribution, debt retirement, and regulation), the annual cost of energy for the ASHP was \$664 while the conventional system energy cost was \$2,074. At an initial equipment cost of \$14,500 the simple payback would be 10.3 years. This does not include the cost of a supplementary heating system, which would be required when temperatures fall below -24°C.

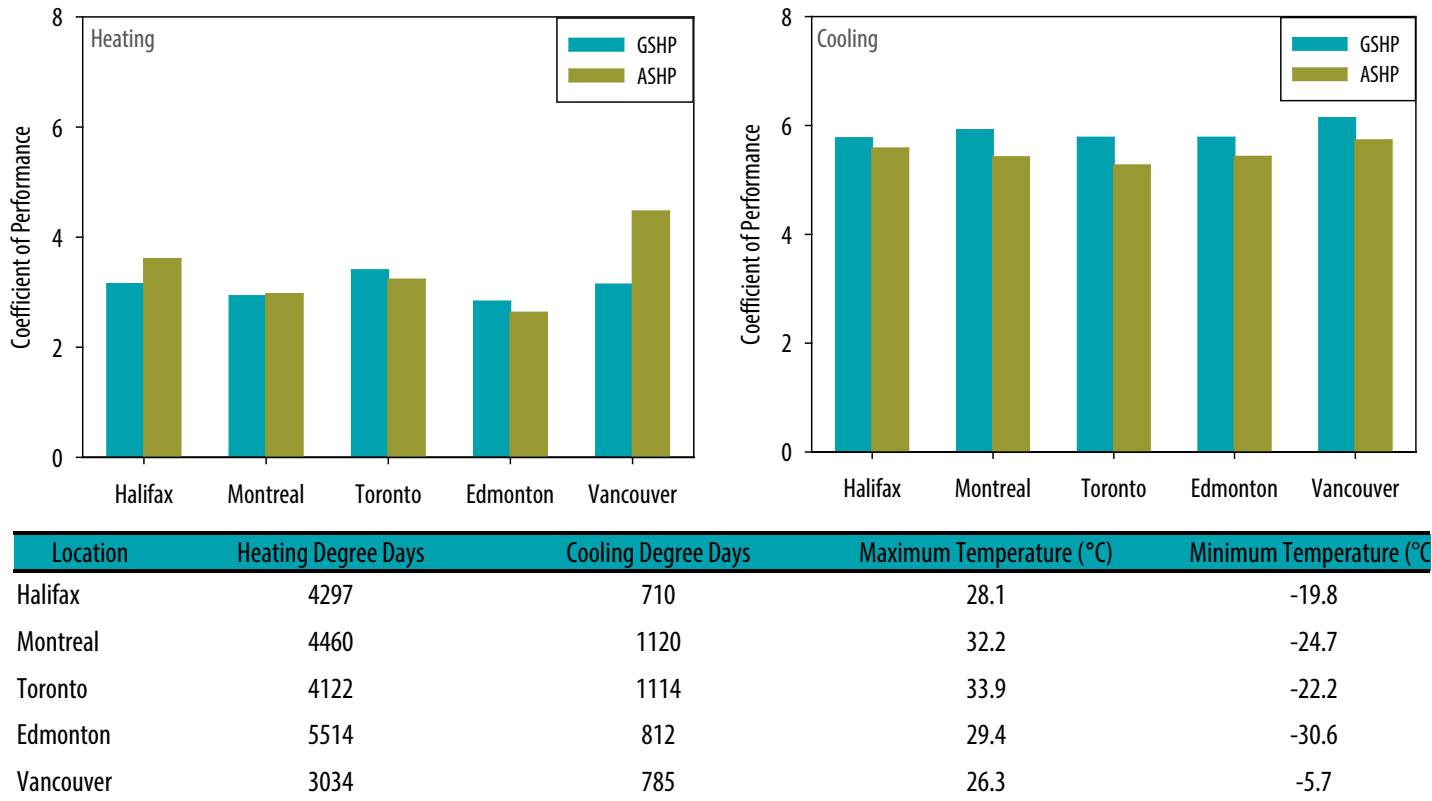


Figure 5. Heating and cooling degree days, temperatures and modeled coefficients of performance for ASHP and GSHP systems in selected Canadian cities.

The annual cost of energy for the GSHP was \$725 while the conventional system energy cost was \$2205. Accounting for an equipment and installation cost of \$34,500 the simple payback was 23.3 years. Thus, although the GSHP is slightly more efficient, the higher GSHP equipment and installation costs make the ASHP a less expensive option. If life cycle costs and benefits were considered, this price gap would narrow because the ground loop is a one time cost and the GSHP compressor is subject to fewer mechanical and thermal stresses with a longer expected service life (20 to 25 years). If the two systems were compared to a natural gas furnace and air conditioner, the paybacks would have been considerably longer because current natural gas costs are less than one fifth the cost of electricity per unit of thermal energy provided.

Energy savings from the use of these more efficient heat pump systems translated into significant reductions in greenhouse gas

emissions relative to conventional alternatives. Annual electricity savings relative to a conventional electric furnace and air conditioner were converted to the equivalent carbon dioxide based on electricity generation sources in Ontario to arrive at emission reductions of 2,330 and 2,449 kg eCO₂ for the ASHP and GSHP, respectively. If instead, the heat pump displaced natural gas during the heating season, the annual emissions reductions would rise to 3329 and 3549 kg eCO₂. By comparison, average per capita emissions from private vehicles in Canada was 2149 kg eCO₂ in 2007 (Statistics Canada, 2010). Thus, the emissions savings from heat pumps are greater than the savings achieved by a family that chooses to replace all annual car travel with zero emission alternatives such as walking or biking. As the electrical grid in Ontario continues to decarbonize, future emissions reductions associated with heat pump systems will also continue to rise.

Table 6. Cost analysis of ASHP and GSHP systems relative to conventional electrical energy systems.

	Annual cost of ASHP/GSHP energy	Annual cost of conventional energy	Initial equipment cost	Simple payback
ASHP	\$664	\$2,074	\$14,500	10.3
GSHP	\$725	\$2,205	\$34,500	23.3

CONCLUSIONS

In this study, two heat pumps were evaluated both as stand-alone technologies and as part of the overall systems installed in the houses. As stand-alone technologies, the systems performed exceptionally well, showing heating and cooling efficiencies above both EnerGuide and manufacturer rated performance. Both heat pump systems had COPs above 3 during the heating season and above 5 during the cooling season. Adding the energy inputs associated with the heating and cooling distribution systems installed in each house lowered overall performance by between 9 and 53%. Optimization scenarios showed that these systems could be set-up to function between 28 and 37% more efficiently by operating the fans and pumps only when the heat pump compressor is on. Upgrad-

ing the GSHP to a variable capacity system would further enhance performance by reducing cycling and increasing operating times on the more efficient part load setting.

The cost of sustainable heat pump systems relative to conventional heating and cooling systems continues to be a barrier to wider adoption of these technologies. The ASHP system was shown to be a cost effective alternative to conventional electric furnace and air conditioner but the more expensive GSHP was less affordable with a simple pay back of over 20 years. A full life cycle cost assessment of the optimized technologies would be required to provide a more accurate assessment of the affordability of the two systems relative to one another and to conventional alternatives.

REFERENCES

- Cuddihy J, Kennedy C., Byer P (2005) Energy use in Canada: environmental impacts and opportunities in relationship to infrastructure systems. *Canadian Journal of Civil Engineering*, **32**, 1-15.
- Fung A, Dembo A, Zhou J (2009) Summary of Detailed Audit and Building Simulation on Archetype Sustainable House, Woodbridge, ON. In Proceedings of CANCAM 2009 Conference, Halifax, NS, May 31-June 4, 2009.
- Natural Resources Canada (2006) The State of Energy Efficiency in Canada, Office of Energy Efficiency Report 2006. Online document: <http://oe.nrcan.gc.ca/publications/statistics/see06/housing.cfm?attr=0>.
- Rad F, Tse H, Fung A (2007). Analysis of Different Mechanical Systems for Ontario's Housing Market using HOT 2000 and RETScreen, Ryerson University, Toronto
- Safa Amir (2012) Performance Analysis of a two stage variable capacity air source heat pump and a horizontal ground loop coupled ground source heat pump system. Master of Applied Science Thesis, Department of Mechanical Engineering, Ryerson University. Toronto, Ontario.
- Statistics Canada (2008) EnviroStats Winter 2008, Vol. 2, No. 4. Minister of Industry. Ottawa, Ontario.
- Statistics Canada (2010) Greenhouse gases from private vehicles in Canada, 1990 to 2007. Accessed on-line August 1, 2012 at <http://www.statcan.gc.ca/pub/16-001-m/2010012/part-partie1-eng.htm>
- TRCA and Ryerson University (2011) The Archetype Sustainable House: Overview of Design and Monitoring Systems – Living City Campus, Kortright Centre, Vaughan, Ontario.



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