Gas Absorption Heat Pump Performance Mapping and Projections of Energy, Cost, and Carbon Savings, for Different Heating Applications in a Cold-Climate

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ABSTRACT

This article summarizes a study evaluating a gas-driven air-source heat pump (GHP) for building heating applications in a cold-climate. The first component of the study mapped the efficiency and capacity of the GHP in a lab environment. The second component used the measured performance data to develop savings projections for different locations and applications. The analysis projected annual gas heating efficiencies up to 128%. The best application for the GHP is domestic hot water (DHW) preheating for a larger DHW boiler. In ideal conditions, DHW preheating applications in Vancouver were projected to save up to 20 tons CO_2e and $2,400 in natural gas per year when compared to a high-efficiency boiler, feasibly bringing the simple payback for the technology in this application below 10 years. Savings for other applications and locations were lower and, in some cases, cost increases were projected. It follows that, while GHPs are a very promising technology for carbon reductions, the performance varies greatly with location and application and this must be taken into account when considering the technology.

INTRODUCTION

Modern electrically-driven variable capacity heat pumps are capable of efficiencies several times greater than conventional building heating technologies. This can result in significant energy and carbon reductions. However, electrically-driven heat pumps are not yet widely deployed for cold-climate heating applications in North America, and the largest barrier in many jurisdictions is the cost disparity between natural gas and electricity. Gas-driven heat pumps (GHPs) may hold promise for a better business case in the near-term because they are able to generate energy and carbon savings without having to switch to a higher-cost fuel like electricity.

GHP standardized performance ratings are very promising. Performance ratings from the Robur Corporation [1] show a heating mode efficiency of 126%, but it is worth noting this value applies to specific operational conditions. It is not clear how this would translate into an average annual efficiency for different climates and applications because the performance fluctuates greatly with the operational conditions. In a real-world installation located in Toronto, Ontario, Canada, a GHP used for DHW in combination with boilers was measured to achieve an average efficiency of 116% during the winter of 2017-2018 [2]. However, in general, GHPs have not been widely deployed for cold-climate heating applications in North America, and there is limited data or experience with the technology in this jurisdiction.

The study evaluated the performance of a commercially-available gas absorption heat pump for cold-climate applications. The study consisted of two components. In the first component, detailed laboratory measurements were taken for the system capacity and efficiency, creating a performance map of the GHP. In the second component, the performance map was used alongside weather data and representative building loads to project the energy, cost, and carbon savings associated with the GHP when used in different applications and at different locations.

TECHNOLOGY AND STUDY SITE

The study GHP was an air-source heat pump in that it absorbed heat energy from the ambient outdoor air. It had 10 tons of nominal heating capacity and could be used in large homes, multi-unit residential buildings (MURBs) and buildings in the industrial-commercial-institutional (ICI) sectors. It was installed outdoors on a concrete pad (Figure 1) at the Archetype Sustainable House (ASH) Lab located in Vaughan, Ontario, Canada (Figure 2). The GHP received warm or cool fluid from the building and then supplied heated fluid back to the building. The GHP is single-packaged with a self-contained refrigerant circuit using ammonia as a refrigerant. It was installed and commissioned in the summer of 2017 by a standard gas fitter with no further specialized training or expertise. A 50% propylene glycol solution was used to provide freeze protection for extreme cold temperatures. A high-level schematic of the ASH Lab hydronic system, with key monitoring points, is shown in Figure 3. During the performance mapping, an auxiliary fan coil load was used to manually trim the return temperature to precise values, allowing the research team to operate the system in a steady-state.

Figure 1. The gas absorption heat pump installed outdoors on a concrete pad at the ASH Lab

METHOD: PERFORMANCE MAPPING

The overall aim of the performance mapping was to define the capacity and efficiency of the GHP as a function of the outdoor ambient temperature, return glycol temperature and cycle time. The performance map is a property of the GHP itself rather than this specific installation and, as such, it could be used to help estimate the performance in other buildings. The performance mapping incorporated two different types of testing: steady-state and cycling.

The steady-state testing evaluated the performance of the GHP in the limit of very long cycle times and unvarying conditions. It did not incorporate losses from start-up. These losses were included in the cycling testing. It may be helpful

Figure 2. Archetype Sustainable House (ASH) Lab located in Vaughan, ON, Canada

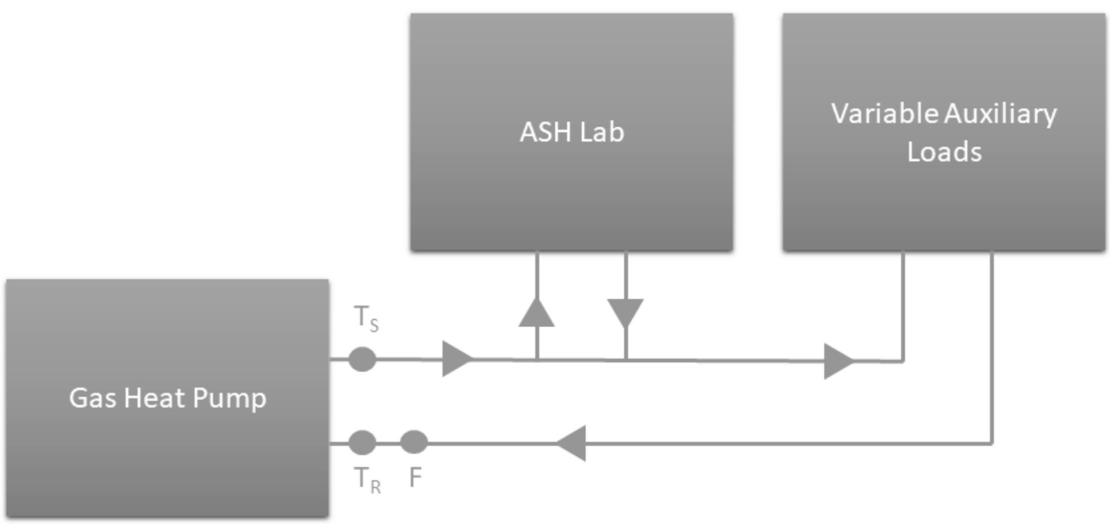

Figure 3. The ASH Lab was connected to the GHP primary loop. The glycol passes through the variable auxiliary load before returning to the GHP. Glycol supply (TS), return (TR), and flow rate (F) monitoring points are also shown.

to preview the results shown in Figures 7 and 8 for a clear understanding of the desired performance map.

Performance data were desired across a continuous range of outdoor temperatures and three different glycol return temperatures were selected for testing: 32, 40 and 48°C. For design flow conditions, the supply temperature is approximately 10°C higher than the return. These temperatures were selected based on what was achievable with the experimental set-up and they were intended to represent different applications towards which the GHP could be applied.

During a steady-state test, the GHP was manually forced on. Set-points and other parameters were adjusted in the ASH Lab to load the system to a point where the actual glycol return temperature was near the desired value for the test. The operator would keep the system in a steady-state by manually adjusting the auxiliary loads for a duration of approximately 45 minutes.

Average heating capacity and efficiency was then calculated for the test data. For each return temperature, a polynomial fit of the experimental data defined a performance curve. For clarity, it is again helpful to preview the results in Figures 7 and 8, where each data point is the result of an individual steady-state test and the lines show a polynomial fit of the results across all tests for each return temperature considered.

During cycling testing, the GHP was used to meet the load of the ASH as required by thermostat calls. Individual cycles were extracted from the trends and the total cycle efficiency was compared against the efficiency once it reached a steady-state. This was used to calculate a cycling derate. Figure 4 shows capacity and efficiency over a representative cycle. It is clear that there is a ramp-up period and a steady-state period. The ramp-up period occurs from $t = 0$ to $t = t_R$ and the steady-state period occurs for $t > t_R$ until the GHP turns off. Efficiency is lower during the ramp-up period and the overall cycle efficiency is lower when the ramp-up time comprises a notable portion of the cycle. This means that shorter cycles have a lower overall efficiency.

The impact of cycle time (t_{cyc}) on efficiency was evaluated for a number of cycles during the testing. A cycling derate was calculated for each cycle. It is shown in Equation 1 and is essentially a ratio of the overall efficiency of the entire cycle divided by the steady-state efficiency determined from $t > t_R$.

$$F_{cyc} = \frac{\eta_{overall}}{\eta_{SS}} \qquad \text{Eq (1)}$$

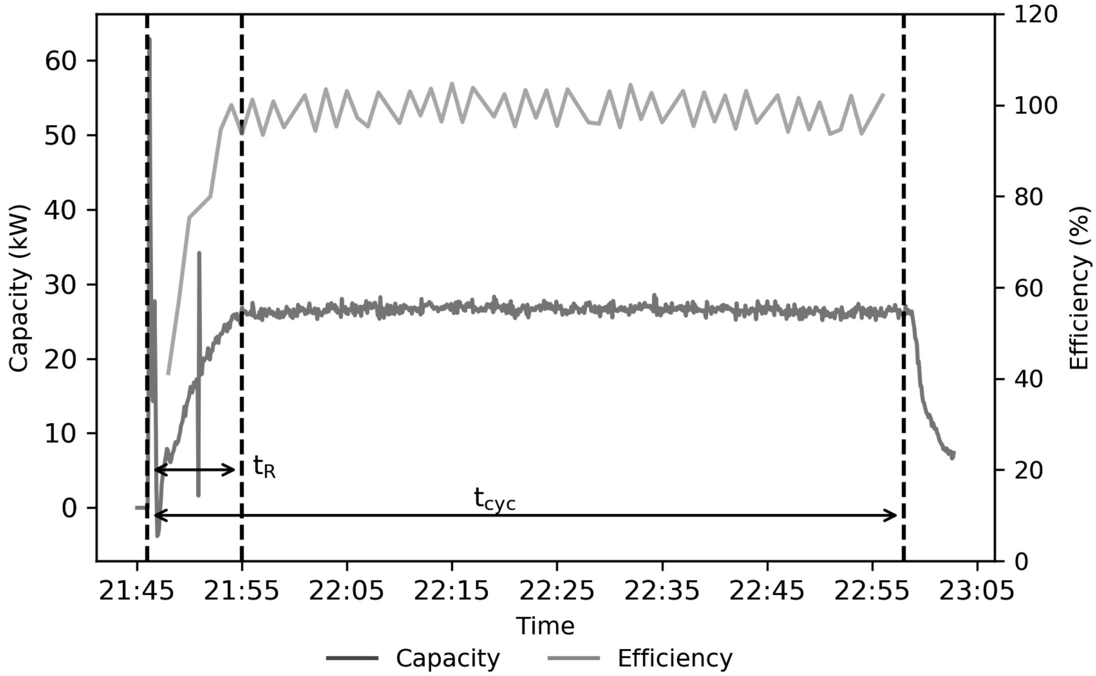

Figure 4. The GHP cycle goes through two stages: a ramp-up period and a steady-state period

METHOD: ENERGY, COST AND CARBON REDUCTION PROJECTIONS

The second component of the study estimated the annual efficiency as well as the gas, cost and carbon reductions for a variety of different scenarios considering different locations and applications. Three Canadian locations were considered: Toronto, Edmonton and Vancouver. Figure 5 shows binned outdoor temperature data for each location.

Five applications were considered, including low-temperature space heating, medium-temperature space heating, high-temperature space heating, replacement of a DHW boiler and preheating for a much larger DHW boiler. As an example, Figure 6 shows the load and capacity curve for a low-temperature space heating (i.e., utilizing a 32°C return temperature) application in Toronto. The space heating load curve was defined such that there was zero load at an assumed building balance point of 18°C and the load curve intersects the corresponding GHP capacity at the design temperature for that climate. Medium- and high-temperature space heating used the capacity curves corresponding to a 40°C and 48°C return, respectively.

DHW loads were assumed to be a constant value with respect to temperature and the magnitude of the load was selected such that, under the design outdoor temperature, the GHP was sufficient to meet the load. The capacity and efficiency curves corresponding to a return glycol temperature of 48°C were used. The DHW preheating scenario assumed that the overall load was large enough that the GHP could be operated at full capacity at all times while utilizing a low return temperature (i.e., 32°C).

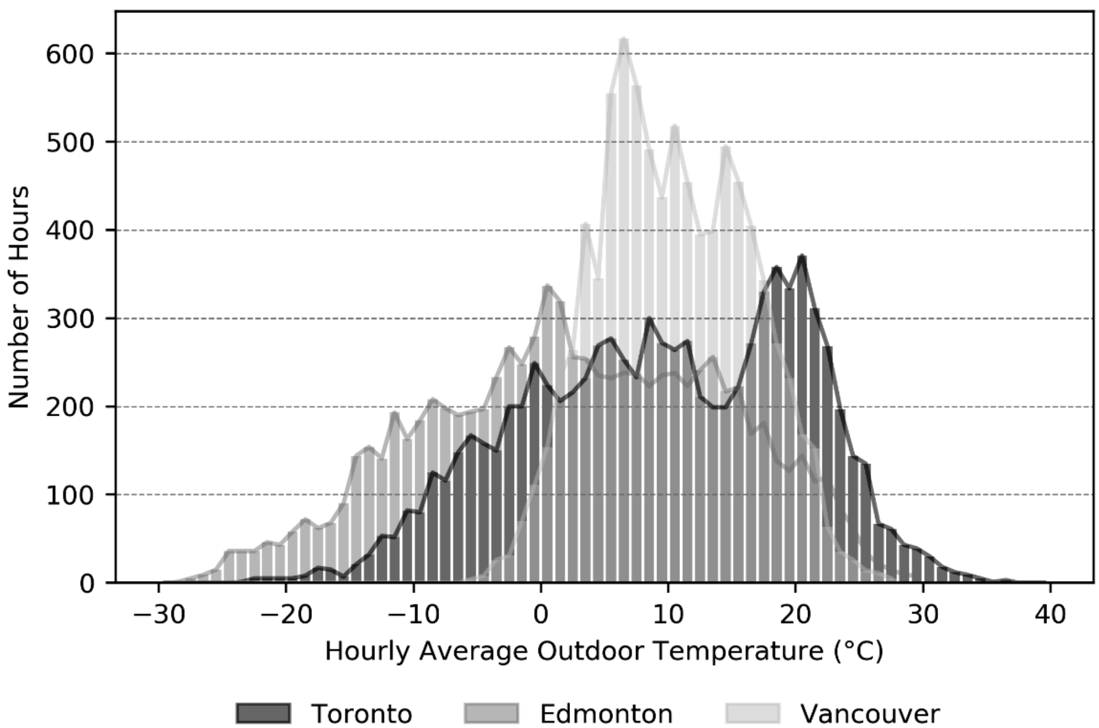

Figure 5. The hourly frequency distribution of outdoor temperatures for each location considered.

An overview of the steps used in the annual performance calculations is provided below. The calculation procedure is provided for a complete explanation of the method and to provide a reference for those wanting to replicate the calculation for their location. For those interested primarily in the results, it is possible to simply continue on to the next section. For the sake of simplicity, the cycling derate was not incorporated into the calculation. The cycling derate curve, presented further on in this article, can be referenced to evaluate the impact of short cycling on annual performance.

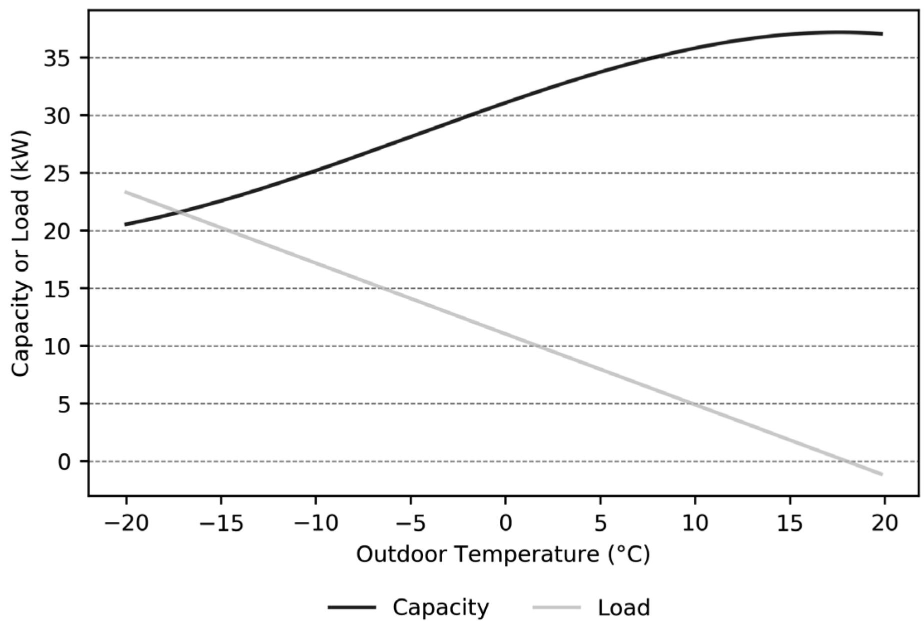

Figure 6. Example space heating load curve for Toronto.

CALCULATION PROCEDURE

Step 1: Select the application (DHW boiler replacement; DHW preheating for a larger boiler; low-, medium-, or high-temperature space heating).

Step 2: Select the required return temperature (32, 40 or 48°C) and corresponding efficiency and capacity curves determined from a polynomial fit of the experimental performance map (curves are shown later in Figures 7 and 8).

$$\eta_{GHP}(T), \dot{q}_h(T)$$

Step 3: Define the load curve based on the application and the return temperature (an example of a space heating load curve was shown in Figure 6).

$$L(T)$$

Step 4: Select the weather data and then determine the frequency of hourly outdoor temperatures for 1°C bins (Figure 5).

$$n(T_i)$$

Step 5: Calculate the total energy delivered to the load on an annual basis by multiplying the load for each temperature bin (in units kW) by the number of hours for that bin using Equation 2.

$$Q_{load} = \sum_{i=1}^{N_{bins}} L(T_i) \cdot n(T_i) \quad \text{Eq (2)}$$

Step 6: Based on the load curve, climate, and efficiency curve, calculate the gas energy required to meet the load with the GHP using Equation 3.

$$Q_{GHP} = \sum_{i=1}^{N_{bins}} \frac{L(T_i) \cdot n(T_i)}{\eta_{GHP}(T_i)} \quad \text{Eq (3)}$$

Step 7: Calculate the annual efficiency as a ratio of the delivered energy over the gas energy required by the GHP using Equation 4.

$$\eta_{tot} = \frac{Q_{load}}{Q_{GHP}} \quad \text{Eq (4)}$$

Step 8: Calculate the total annual operating hours of the heat pump using Equation 5.

$$t_{annual} = \sum_{i=1}^{N_{bins}} \frac{L(T_i)}{\dot{q}_h(T_i)} \cdot n(T_i) \quad \text{Eq (5)}$$

Step 9: When the GHP turns on, it has a constant electrical power draw to operate fans, controls and an internal pump. Using the average electrical draw and the total annual operating hours, calculate the total annual electrical energy consumption using Equation 6.

$$Q_{elec} = \dot{q}_{elec} \cdot t_{annual} \quad \text{Eq (6)}$$

Step 10: Calculate the annual energy consumption of a base case boiler using Equation 7.

$$Q_{boiler} = \sum_{i=1}^{N_{bins}} \frac{L(T_i) \cdot n(T_i)}{\eta_{boiler}} \quad \text{Eq (7)}$$

Step 11: Calculate the gas energy savings using Equation 8.

$$Q_{savings} = Q_{GHP} - Q_{boiler} \quad \text{Eq (8)}$$

Step 12: Calculate the m^3 gas savings using Equation 9, where ε is the energy density of gas in kWh/m^3.

$$S_{gas} = \epsilon \cdot Q_{savings} \quad \text{Eq (9)}$$

Step 13: Calculate the cost savings using Equation 10, taking account both the decreased usage of gas and the increased usage of electricity. The gas and electricity rates in units \$/m^3 and \$/kWh are β_{gas} and β_{elec}, respectively.

$$S_{cost} = \beta_{gas} \cdot S_{gas} - \beta_{elec} \cdot Q_{elec} \quad \text{Eq (10)}$$

Step 14: Calculate the carbon savings resulting from the reduction in gas consumption, also taking into account the increase in electricity consumption using Equation 11. The electricity and gas emission factors are EF_{gas} and EF_{elec}, respectively.

$$S_{carbon} = EF_{gas} \cdot S_{gas} - EF_{elec} \cdot Q_{elec} \quad \text{Eq (11)}$$

To keep the analysis simple, calculations were conducted using estimates of current utility rates and no fuel cost escalation was considered. Electricity rates have been taken from a recent analysis, conducted by Hydro-Québec, of average rates for major North American cities [3]. No comparative analysis was available for natural gas rates. Estimates for these rates were generated using sample bills and rate schedules provided from Fortis, a major utility in British Columbia and the Ontario Energy Board. Note that the results of the analysis are sensitive to the utility rates estimates. Prospective system owners are encouraged to consider the impact of their own rates. Parameter values used in annual performance calculations are given in Table 1.

In summary, the capacity and efficiency data collected during steady-state testing was used to determine the GHP annual efficiency and savings within an hourly bin analysis for different scenarios. Assumptions were made to be as simple as possible while still sufficiently capturing the impacts of the factors considered. In general, the aim of the analysis was to appropriately weight or derate the GHP performance curves according to location and application to

Table 1. Parameter values used for the annual performance calculations

	Toronto	Edmonton	Vancouver
Base Case Boiler Efficiency	0.88		
Emission Factor of Gas (kg CO_2e/m^3) [4]	1.89		
Electricity Cost ($/kWh) [3]	0.14	0.15	0.12
Gas Cost ($/m^3)	0.30	0.33	0.32
Emission Factor Electricity (kg CO_2e/kWh)	0.159 [5]	0.900 [6]	0.012 [7]

identify a range of expected efficiencies and savings potentials. The authors acknowledge that more rigorous building energy modelling would be required to estimate the GHP performance for specific buildings. Because the procedure did not incorporate losses from cycling, the projections are an upper limit of possible performance.

RESULTS AND DISCUSSION

Figure 7 and Figure 8 show the steady-state capacity and efficiency data, respectively. Note that Figure 8 is gas efficiency only and does not include electrical power draw, which was measured at approximately 1 kW whenever the system was operating. Electrical power draw was taken into account during the annual performance calculations. In general, efficiency improves with warmer outdoor temperatures and cooler return temperatures.

The cycling derate data from 36 different cycles are shown in Figure 9. The start-up time was determined at approximately 8 minutes. It is clear that the cycle time has a notable impact on the overall efficiency. For example, at 15 minutes, the cycling derate factor is 0.78. This means the actual efficiency for a 15-minute cycle is 22% lower than the steady-state efficiency. Beyond 35 minutes the cycle factor is greater than 0.90. To achieve optimal efficiency in practice, longer cycle times should be encouraged within the system design and control.

Projected annual efficiencies, based on higher-heating value (HHV), for each location and application are shown in Figure 10. The best efficiency is achieved for preheating applications in Vancouver. This is because Vancouver has a warmer climate than the other cities. DHW is also a year-round load and this weights the overall performance for higher-efficiency operating points occurring in the summer and shoulder seasons. The low return temperature assumed in the preheating scenario further bolstered efficiency.

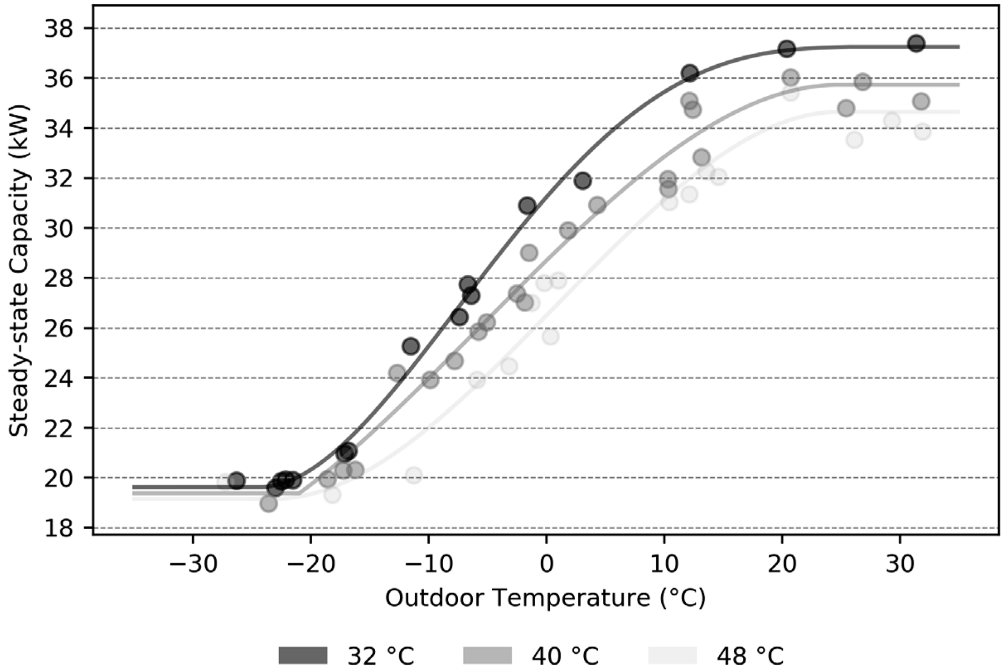

Figure 7. Steady-state capacity of the GHP for different return temperatures.

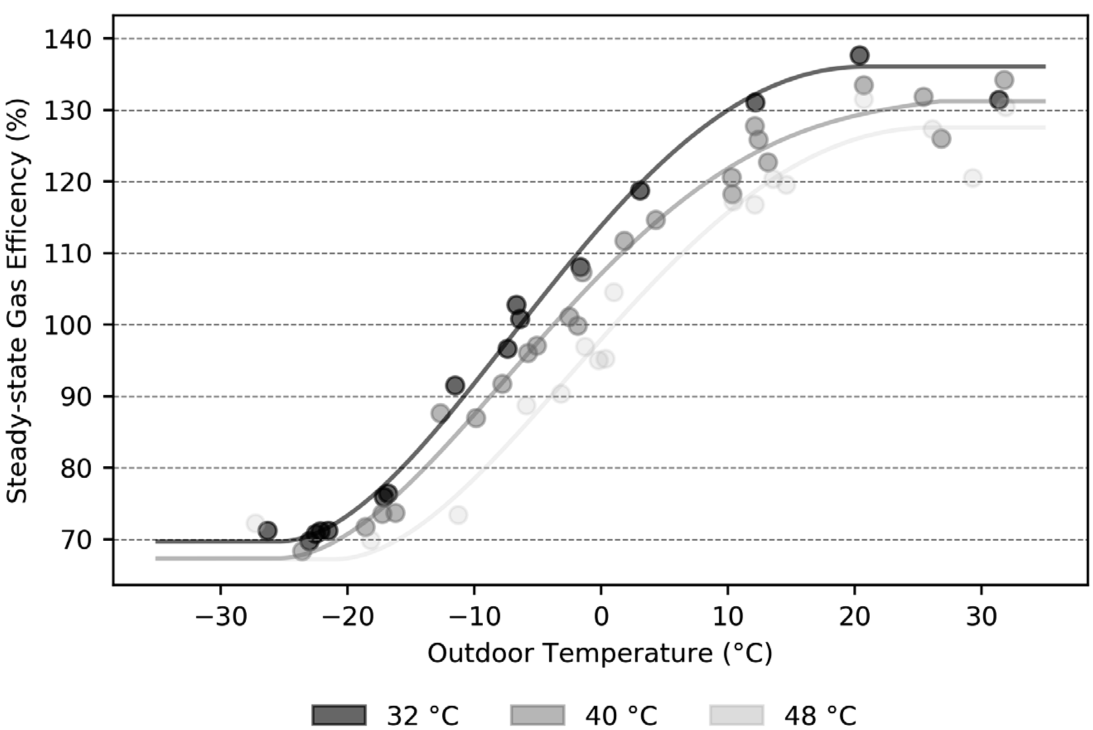

Figure 8. Steady-state efficiency curves of the GHP (according to gas HHV).

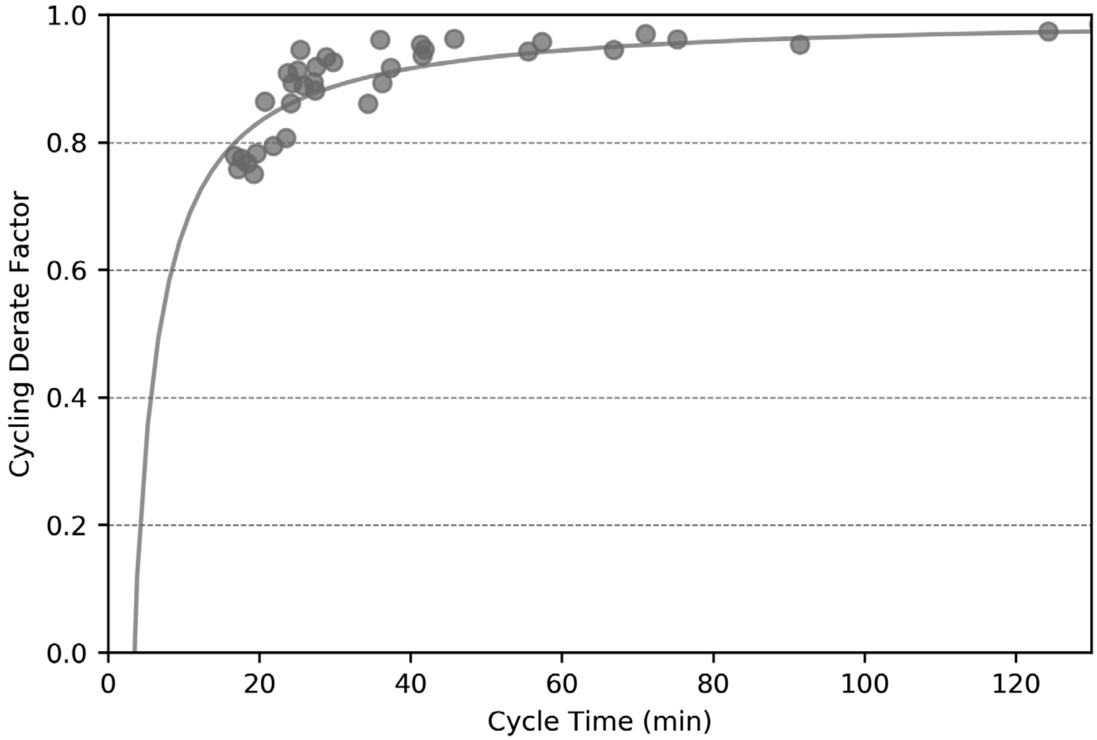

Figure 9. Overall efficiency is lower for shorter cycles caused by start-up losses.

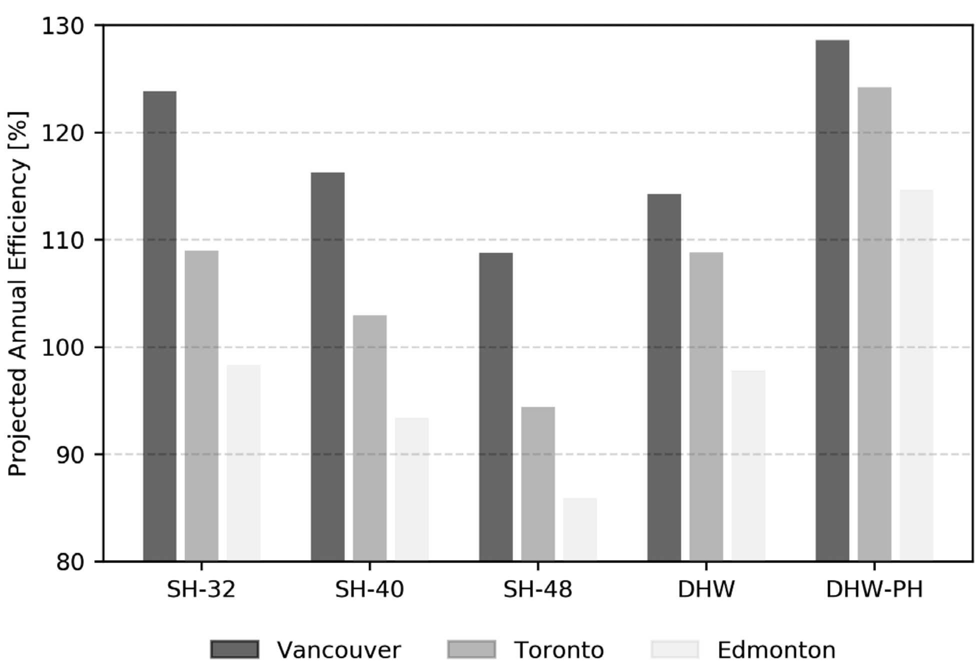

Figure 10. Projected annual efficiencies (based on HHV).

The projected gas, cost, and carbon reductions for the different locations and applications are given in Figures 11 to 13. The standout application is again DHW preheating.

The estimated annual savings for DHW preheating applications in Toronto was approximately $1,500, and for Vancouver, $2,400. This included utility savings only and did not include any other rebates, incentives or carbon pricing, all of which could significantly promote the business case. It also does not include losses from cycling, which could be substantial if not accounted for in the system design and control.

The Canadian distributor suggested that the incremental capital cost of the heating-only GHP is currently $14,500 (CAD) when compared to a similarly-sized high-efficiency boiler. There are many factors to consider when implementing a retrofit but, at a high-level, given the incremental capital cost and projected savings, a simple payback under 10 years seems feasible for certain applications. This should be confirmed in real-world installations.

When it was not used for testing, the GHP operated to meet the heating and cooling requirements of the ASH Lab. It operated without issue for the study period, which included both extreme cold and hot temperatures. It did

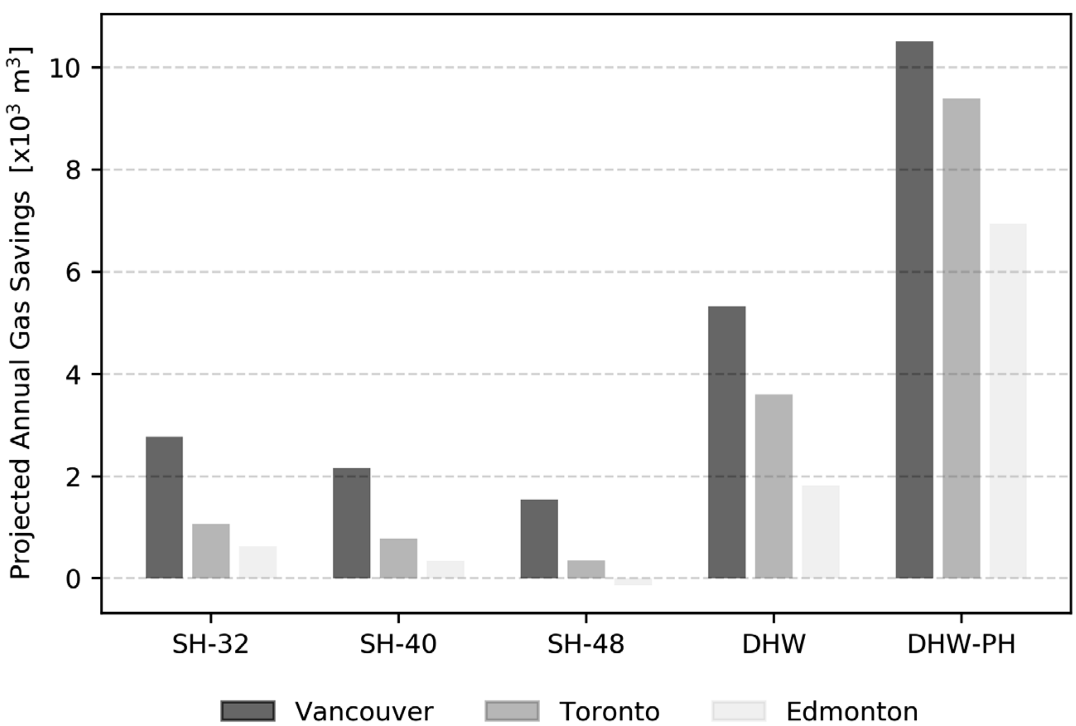

Figure 11. Projected annual gas savings.

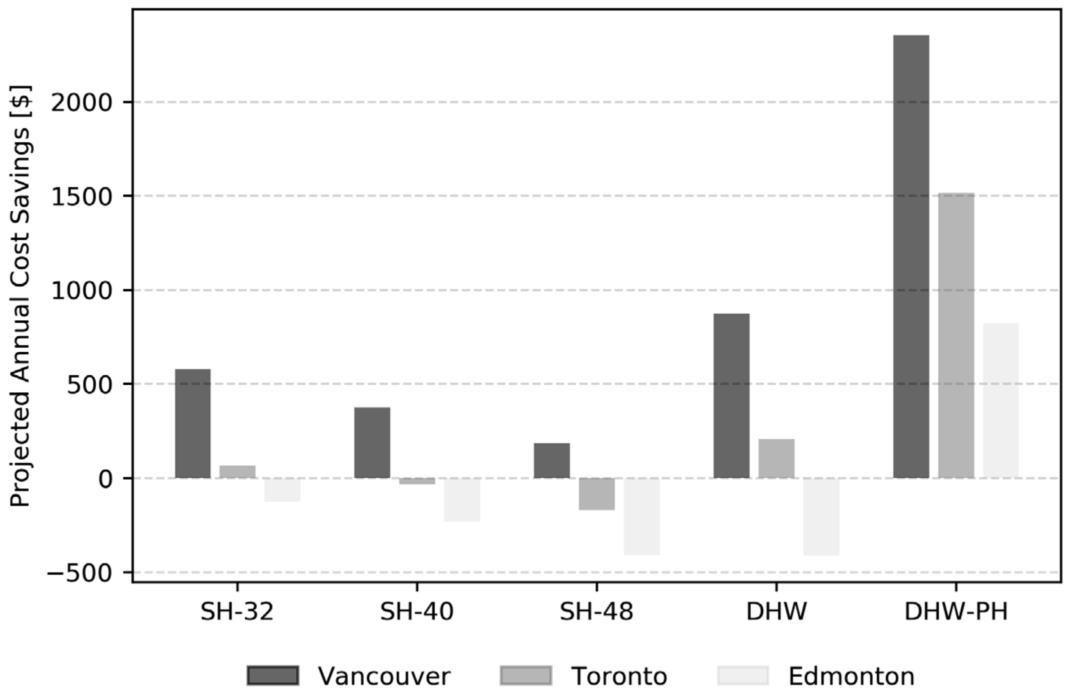

Figure 12. Projected cost savings.

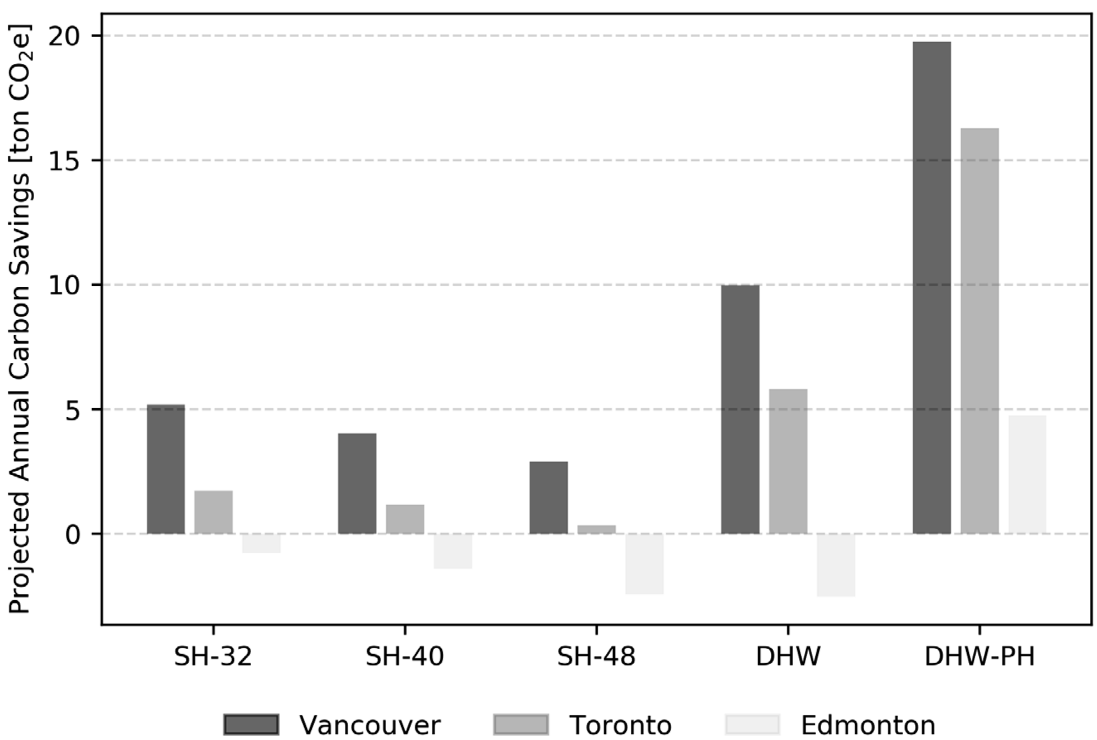

Figure 13. Projected carbon savings.

not require any special expertise over-and-above that required for the installation of any hydronic natural gas heating system.

Cooling mode performance was evaluated as well. The low-efficiency (approximately 60%) would result in substantially greater carbon emissions when compared to high-efficiency electric cooling and in most cases for the jurisdictions considered, it would also increase utility costs for cooling. It is, therefore, the opinion of the authors that, as a low-carbon technology, heating-only models are preferred.

CONCLUSIONS

This study evaluated an air-source GHP for different applications in a cold-climate. The analysis projected annual gas heating efficiencies up to 128%. The study concluded that the best application for the GHP is DHW preheating for a larger boiler. In ideal conditions, DHW preheat applications in Vancouver were projected to save up to 20 tons CO_2e and $2,400 in natural gas per year, feasibly bringing the simple payback for the technology in this application and location below 10 years. Savings for other applications and locations were lower and, in some cases, cost increases were projected. The authors caution that calculations represent the upper limit of potential performance and detailed modelling is required to estimate the performance in specific buildings. While GHPs are a very promising technology, the performance varies greatly with location and application and this must be taken into account when considering the technology. Future work should consider detailed modelling in representative buildings and more detailed assessments of actual installations. A full report of this work is available at Toronto and Region Conservation Authority (TRCA) [8].

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