Sustainable Technologies
EVALUATION PROGRAM

Energy Conservation & Efficiency

Evaluation of an Air-Source Heat Pump Water Heater

Water heating is the second largest source of energy consumption in Canadian residential buildings. With growing concerns towards energy conservation, high-efficiency approaches to water heating are emerging on the market. Heat pumps for residential water heating are gaining increasing interest, achieving efficiencies greater than conventional electric or natural gas water heating.

This study evaluated the performance of an air-source heat pump water heater (ASHPWH) in a cold climate. It investigated the standalone performance of the ASHPWH, as well as its impact on space heating and cooling. Experimental data showed that the water heater met the performance claims of the manufacturer. Simulated performance shows that while this device does increase the heating load of a building, it has a net decrease in overall energy consumption due to savings associated with water heating and space cooling.

This study has shown that the ASHPWH can payback within ten years, compared to all-electric alternatives. However, natural gas remains to be the most cost effective method of water heating. A greenhouse gas (GHG) analysis shows that an ASHPWH has the lowest associated GHG emissions, compared to electric or natural gas alternatives. Simulations show that this technology is capable of energy savings in a Canadian climate, however greater savings are expected in climates with hot summers.

Basic heat pump technology is already commonplace in nearly every home, it's just typically used for cooling rather than heating. For example, a refrigerator uses heat pump technology for cooling, rejecting heat energy from inside the refrigerator to the ambient space surrounding it. Whereas a refrigerator can only "pump" heat in one direction, a "heat pump" is reversible and can be used for both heating and cooling.
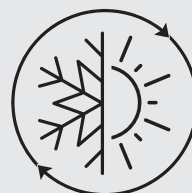
Air-source heat pump water heaters (ASHPWHs) are electrically-powered devices that extract heat energy from ambient indoor air to provide domestic hot water. They have an efficiency that is more than twice that of a conventional water heater, and provide cooling to the surrounding space. The benefits of cooling are clear in warm climates but less so in cold climates with long heating seasons. However, most ASHPWHs can also operate purely as an electric resistance water heater and can be switched-over seasonally so as to not increase the heating load if desired.

BACKGROUND

Residential buildings accounts for 17% of secondary energy use in Canada (Natural Resources Canada, 2015), with space heating and water heating dominating this sector, accounting for 62% and 20% of energy end-use, respectively (Natural Resources Canada, 2015). By fuel type, natural gas and electricity make up 67% and 25% of residential water heating, respectively (Natural Resources Canada, 2015). In 2014, buildings and electricity contributed to 12% and 11% of Canada's greenhouse gas (GHG) emissions (Environment and Climate Change Canada, 2016). Clearly, these are important sectors for carbon emission and energy consumption reduction so as to meet Canada's COP21 commitments.

Heat Pumps

Heat pumps are a highly efficient method of space heating, cooling, and water heating, that can address energy conservation needs. Air-source heat pumps (ASHPs) or ground-source heat pumps (GSHPs) are electrically driven devices used for space heating and cooling. These types of heat pumps can achieve efficiencies that are 3 to 5 times greater than that of conventional heating and cooling alternatives by transferring heat energy between a building and the ambient outside air or the ground, rather than just releasing energy that is contained in a fuel.
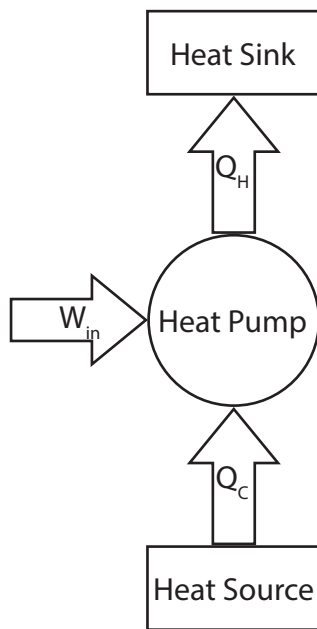
Figure 1. A heat pump transfers energy from a heat source (Q_C) to a heat sink (Q_H) using work or electrical energy (W_{in}). Note that the heat source can actually be *colder* than the heat sink.

Heat Pump Water Heaters

The conventional approach to heating water with electricity is with an electric resistance water heater, where one unit of electrical energy can produce – at most – one unit of heat energy. In contrast, an air-source heat pump water heater (ASHPWH), pictured in Figure 2, can produce more than two units of heat energy for every unit of electrical energy because it

transfers heat from the ambient indoor air into the water. An ASHPWH is single-packaged, simple to install and can provide space cooling and dehumidification to the space in which it is installed – a potential advantage in the summer and disadvantage in the winter. This problem can be addressed by choosing to install an ASHPWH in an unconditioned space – such as a garage, or by seasonally switching-over the controls of the unit to operate it as a conventional hot water heater in the winter and as an ASHPWH in the summer.

Figure 2. The A.O.Smith ASHPWH installed in the basement of the test site.

Similar to the energy efficiency ratio (EER) for air conditioners, the coefficient of performance (COP) is a helpful metric used to measure the performance of a heat pump. The COP is a ratio of the energy delivered by the heat pump over the energy consumed by the heat pump. An electric resistance heater could – at most – have a COP of 1, since it can't convert more than 100% of its electrical energy consumption into heat energy. Since heat pumps *transfer* heat from one place to another, they can achieve COPs that may be as great as 5. The COP of a heat pump depends on many things; chiefly among them is the temperature of its heat source and heat sink. Figure 1 shows the basics of heat pump operation, and Equation 1 shows the definition of the COP in heating mode.

In Equation 1, Q_H is the energy transferred to the heat sink, Q_C is the energy extracted from the heat source, and W_{in} is the work or electrical energy used by the heat pump. T_C and T_H are the temperatures of the heat source and heat sink respec-

tively. The COP of a heat pump has a theoretical ideal limit, defined by the temperatures T_C and T_H. This ideal case is derived from what is known as the Carnot Cycle. Understanding the basics behind the relationship between T_C, T_H, and COP is important – the COP of a heat pump decreases with increasing T_H, and increases with increasing T_C.

$$COP_{heating} = \frac{Q_H}{W_{in}} = \frac{Q_H}{Q_H - Q_C} \xrightarrow{\substack{Ideal \\ limit}} \frac{T_H}{T_H - T_C} \quad (1)$$

Various ASHPWHs are available on the market today. While these devices have higher initial costs than conventional water heaters, they have shown to be cost effective in mild climates (Natural Resources Canada, 2012). Since these devices transfer heat from their surroundings, they remove heat from the indoor space in which they are located, leading to increased space heating loads and decreased space cooling loads. This leads to various interesting potential applications. For example, an application may be multi-unit residential buildings that have difficulty maintaining indoor temperatures below a maximum threshold in the summer months. The Toronto Municipal Code, Chapter 629 – 38 Heating and Air Conditioning, maintains that residential properties must maintain indoor temperatures below 26°C between June 2nd and September 14th (City of Toronto, 2015). Due to their inherent space cooling effect, ASHPWHs could aid in maintaining a building's temperature below a maximum threshold, promoting the safety and well-being of residents while cutting the summertime water heating energy costs by a half.

A previous study has investigated the impact of an ASHPWH on the space conditioning needs of a home over a two-week period, showing no impact on winter heating loads, but a substantial reduction of summer cooling loads (CMHC, 2014). Another study simulated the operation of an ASHPWH in different Canadian cities, and found that the greatest energy savings could be achieved when the ASHPWH was installed in an unconditioned space, minimizing the impact on the heating load of the building (Kegel, Tamasauskas, Sunye, & Giguere, 2017).

Figure 3. The Archetype Sustainable House A (left) and House B (right).

This study investigates the performance of an ASHPWH in a cold climate. The unit was installed in the basement of the LEED™ Platinum Archetype Sustainable House at the Living City Campus in Vaughan, Ontario. The performance of the device was verified with the manufacturer's claims, and its operation potential was extrapolated over the course of a year.

STUDY SITE

The performance evaluation of the ASHPWH took place at the Archetype Sustainable House (ASH), pictured in Figure 3. These two semi-detached houses, referred to as House A and B, serve as testing facilities for various sustainable technologies primarily intended for residential applications. Both houses are 3-storey, south facing buildings with similar floor areas, internal volumes, and levels of insulation (R-30 above grade, R-20 below). For this study, the ASHPWH was installed in the basement of House B.

The ASH and surrounding testing facilities feature an advanced monitoring and data acquisition (DAQ) system comprised of several hundred measurement points. The existing monitoring infrastructure makes the site ideal for examining the real-world performance of energy efficient HVAC equipment.

Table 1. ASHPWH specifications.

Feature	Value
Model	A.O.Smith SHPT-50
Capacity	190 L
Height	1.6 m
Diameter	0.56 m
Energy factor (heat pump mode)	2.78
Energy factor (hybrid mode)	2.75
Energy factor (electric mode)	0.89

Water Heater Under Test

The unit investigated in this experiment, pictured in Figure 2, was an A.O.Smith SHPT-50 ASHPWH. Table 1 summarizes the manufacturer's specifications for the ASHPWH used in this experiment, including its rated energy factor (EF) in each mode of operation. The energy factor is similar to the COP, but specific to water heaters; it is a ratio of energy delivered to the hot water, and the energy consumed by the water heater.

The water heater has a heat pump integrated directly on top of its water tank, and removes heat from the space in which it is installed. The water heater has a 190 L (50 gal) tank, and can have its set point adjusted between 35°C and 60°C. The ASHPWH has three modes of operation: heat pump, hybrid, and electric mode. In heat pump mode, the unit tries to maximize the utilization of the heat pump, with minimal use of the backup electric element. Electric mode only uses the electric heating elements to heat the water. Hybrid mode primarily uses the heat pump, but will turn on the electric heaters at times of high demand.

APPROACH

The study involved the experimental characterization of the ASHPWH performance, along with high-level calculations investigating the savings of the unit in potential applications in a Canadian climate on a seasonal basis.

Experimental Design

This experiment utilized the existing DAQ system at the ASH. Flow rates and temperatures of inlet and outlet water streams were measured, along with the water temperature at six heights throughout the tank. The power consumed by the heat pump and electric heater were measured separately in order to distinguish between the two through different modes of operation. The temperature and humidity of the surrounding space was monitored and controlled using space heaters, humidifiers and dehumidifiers. A custom LabVIEW-enabled thermostat and humidistat were used to maintain ambient conditions within ± 1˚C and ± 1% RH.

The ASHPWH was tested under four different temperature and humidity conditions in order to characterize the unit over a range of operating conditions. A standard water-draw profile was applied based on the IEA Annex 42. This automated draw profile was implemented for two-day periods, consuming 150 and 250 litres of hot water on the first and second day respectively, using *LabVIEW*-controlled solenoid valves. A local well was used as the water supply, with supply temperatures ranging from 4˚C in March, to 15˚C in September. The experimental conditions, along with the real-world situations that they are intended to represent, are listed below:

1.   19.7˚C and 50% RH. Used to validate operation against manufacturer's performance claim.

2.   15˚C and 70% RH. Representative of a cold and damp space, such as the basement in an older house.

3.   20˚C and 35% RH. Winter comfort zone.

4.   25˚C and 50% RH. Summer comfort zone.

Table 2. Seasonal energy balance calculation assumptions.

Assumption	Value Assumed	Notes
Water usage	225 L/day	Typical for Ontario residents (Environment Canada, 2011).
Hot water percentage of total	39.6%	Based on findings for water consumption in Canada (Aguilar, White, & Ryan, 2005)
Heating season water-use fraction	2/3	Based on the length of the heating season in Canada
Cost of electricity	16.8 ¢/kWh	Current estimated time-averaged price of electricity in Ontario (IESO, 2016).

Seasonal Energy Balance

The operation of the ASHPWH was compared to that of conventional electric and gas water heaters using simplified, seasonal energy balances. This calculation procedure accounts for the heating and cooling energy consumed by the house along with the energy required to produce hot water, and whether that energy is extracted from the building.

While this approach neglects the detailed operation of the system on a short time-scale, it can help indicate potential benefits that may warrant further investigation. The intent of these calculations is to provide a general idea as to how much the ASHPWH may impact the space heating and cooling loads of buildings. General calculation assumptions are summarized in Table 2. The seasonal energy balance was used to compare the ASHPWH to conventional electric and natural gas alternatives, the details of which are described in Tables 3 and 4, respectively.

Both the all-electric and natural gas cases investigated in this analysis were applied to two different housing scenarios. The first scenario considered a family home with four occupants and a total floor area of 345 m² (3714 ft²), the same area as the Archetype House A. The second housing scenario assumed an apartment building with two occupants and a floor area

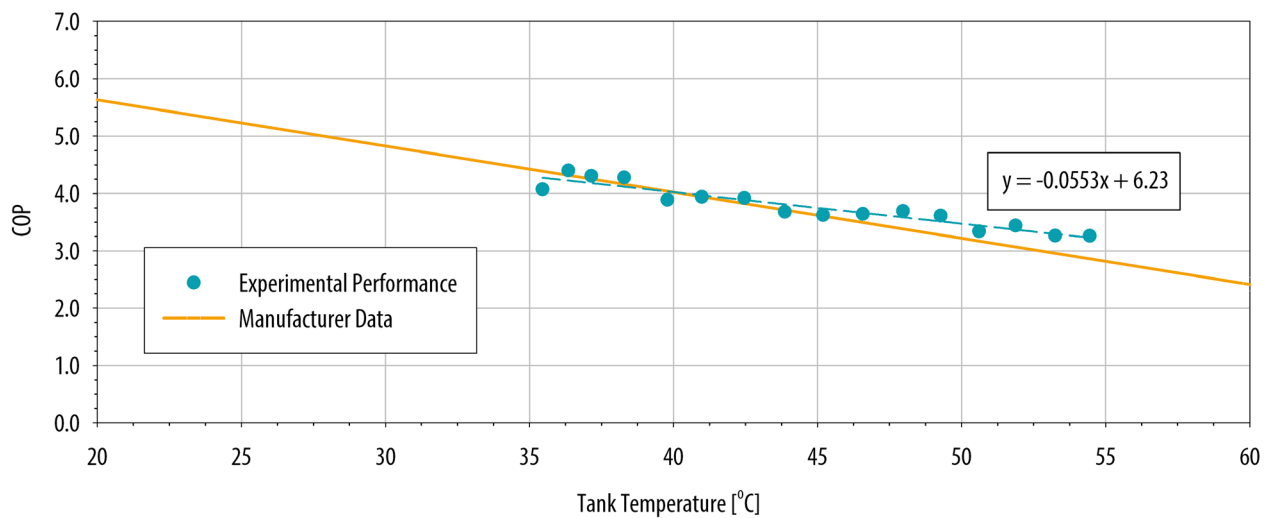Table 3. All-electric case summary for seasonal energy balance calculations.

Case	Water heater type	Space heating system	Space cooling system
Conventional electric baseline	Electric resistance (EF = 0.95)	Electric resistance (equivalent COP = 1)	Air conditioning (equivalent COP = 3)
Conventional electric-ASHPWH	ASHPWH (EF = 2.78)	Electric resistance (equivalent COP = 1)	Air conditioning (equivalent COP = 3)
Efficient electric baseline	Electric resistance (EF = 0.95)	ASHP (COP = 3.35)	ASHP (COP = 5.19)
Efficient electric-ASHPWH	ASHPWH (EF = 2.78)	ASHP (COP = 3.35)	ASHP (COP = 5.19)

Table 4. Natural gas case summary for seasonal energy balance calculations.

Case	Water heater type	Space heating system	Space cooling system
Natural gas baseline	Natural Gas (EF = 0.8)[a]	Natural gas (efficiency = 0.95)	Air conditioning (equivalent COP = 3)
Natural gas-ASHPWH	ASHPWH (EF = 2.78)	Natural gas (efficiency = 0.95)	Air conditioning (equivalent COP = 3)

a. A high-efficiency natural gas water heater (Union Gas, 2017)

Figure 4. Experimentally determined COP of the ASHPWH compared to water tank temperature.

of 92.9 m^2 (1000 ft^2). An annual heating energy intensity of 50 kWh/m^2*year was assumed for both scenarios, and the cooling load was assumed to be 10% of the annual heating load.

Natural gas prices are highly variable; over the past 10 years, the natural gas commodity price has ranged from 9.176 to 43.123 ¢/m^3, plus additional ancillary charges that totaled 19.2 ¢/m^3 in January 2017 (Ontario Energy Board, 2016). Because of such variability, a sensitivity analysis on natural gas price was performed. Since natural gas is currently much cheaper than electricity, it is of interest to find the natural gas price at which an ASHPWH becomes a more cost-effective option.

FINDINGS

Experimental Findings

Experimental results showed agreement with the manufacturer's performance claims. Figure 4 compares the actual performance of the ASHPWH with the manufacturer-provided performance curve. The plot shows the COP of the ASHPWH as a function of water tank temperature.

The downwards trend is expected based on the definition of COP for heating defined in Equation 1 – with a fixed heat source temperature (T_C), the COP of the heat pump will decrease with increasing heat sink temperature (T_H). Note the heat source is the ambient air and the heat sink is the water in the tank. The results of the trials at the conditions matching those provided of the manufacturer, 19.7°C and 50% RH, show good agreement with performance claims.

The ASHPWH showed reductions in power consumption while operating in heat pump mode compared to both electric and hybrid modes Table 5 summarizes the energy consumption of the water heater in different modes of operation,

under different ambient conditions. In all cases, the water heater consumed the least amount of energy when operating in heat pump mode. This is to be expected, since heat pump operation has a COP (and EF) greater than 1, and can therefore heat the water tank using less electricity than conventional electric water heating.

Table 5. ASHPWH two-day electricity consumption in different modes of operation.

Test Condition	Electricity Consumption (kWh)		
	Electric	Heat Pump	Hybrid
15°C & 70% RH	9.34	3.56	5.05
20°C & 35% RH	-	3.98	4.19
25°C & 50% RH	7.66	3.60	-

Between all three modes of operation and the ambient conditions investigated, no significant differences in maintained tank temperature were found; the ASHPWH consistently delivered hot water between 45 - 55°C.

Seasonal Energy Balance Findings

A simple cost analysis shows that the ASHPWH can reduce overall electricity costs for a home in multiple scenarios using all-electric space heating, cooling, and water heating. Potential savings associated with the all-electric scenarios are summarized in Table 7. These results show greater potential for savings in homes that use high-efficiency methods of space heating and cooling. Note that since a fixed electricity price of 16.8¢/kWh was used for calculations, the *cost* savings percentage is equal to *electricity consumption* savings percentage.

When an ASHP is used for space heating and cooling, it is essentially "purchasing" heating or cooling energy at a price between 3:1 and 5:1 due to its high COP. When both an ASHP and ASHP-WH are used in a home, the heat energy transferred to the water

by the ASHPWH has already been "purchased" at a cheaper rate. Therefore, greater savings are possible in the efficient electric case – essentially getting more use out of an efficient ASHP.

Table 8 highlights the specific energy end-use areas in which annual costs change when replacing a conventional water heater with an ASHPWH. It shows the cost reductions associated with high-efficiency water heating and cooling load reductions far outweigh the negative impacts of an increased heating load, resulting in a net decrease in annual electricity costs.

Compared to all-electric alternatives, an ASHPWH can payback within its lifetime based on current water heater and electricity prices. The simple payback of the ASHPWH was determined using the calculated savings. The payback analysis assumed an incremental water heater cost of $1,250 based on an electric water heater cost of $600, and the ASHPWH cost of $1,850 (SupplyHouse, 2017). Table 6 shows the simple paybacks for the all-electric cases (defined in Table 2). This shows that the ASHPWH should be expected to payback within its 10-year life-time for a variety of different use-cases.

Table 6. Simple payback of an ASHPWH in all-electric cases using $1,250 as the incremental cost

Case	Family Home	Apartment Unit
Conventional electric	3.3 years	7.0 years
Efficient electric	1.8 years	3.7 years

It should be noted that the payback will vary based on the incremental cost of the system. However, even in the case that shows the least savings, an apartment using electric resistance heating

and air conditioning, the ASHPWH would payback within its lifetime as long as the incremental cost remained below approximately $1,800.

Based on current natural gas and electricity prices, ASHP-WHs are not yet financially competitive when compared to conventional natural gas water heating. The current equivalent cost of natural gas is approximately 30 ¢/m³. At this price, an ASHPWH would cost a family-sized home approximately $174/year more to operate than a natural gas water heater. The ASHP-WH would increase both space heating costs and water heating costs and the savings associated with space cooling would not be sufficient to make up the losses.

Compared to natural gas, ASHPWH savings would not be achieved until gas prices surpass 88 ¢/m³. In the case of an apartment with a natural gas water heater, an ASHPWH would not achieve savings until natural gas prices reached $1.12/m3. Note that these results assumed a fixed electricity price of 16.8 ¢/kWh. These calculations show that if a home has an available natural gas connection, conventional water heating via natural gas remains to be the most cost effective option.

Calculations show approximately 18% GHG emission reductions when comparing the ASHPWH to a natural gas water heating. The emissions associated with using a natural gas water heater were estimated based on the volume of natural gas consumed in a year, multiplied by 1.879 kg CO_2e/m^3, the combustion emission factor of natural gas (Environment and Climate Change Canada, 2016). Emissions associated with using electricity to run the ASHPWH were estimated based on the emission factor of the

Table 7. Estimated annual costs and savings for both housing scenarios associated with all-electric cases. Note that these estimates are theoretical, based on a seasonal energy balance, accounting for all space-conditioning and water heating costs. Refer to Table 3 for the all-electric case summary.

Case	Family Home	Apartment Unit
Conventional electric baseline cost	$4,196.59	$1,403.90
Conventional electric-ASHPWH cost	$3,811.54	$1,226.09
Conventional electric savings	**$385.05**	**$117.81**
Efficient electric baseline	$2,122.92	$847.91
Efficient electric-ASHPWH	$1,430.18	$510.06
Efficient electric savings	**$692.75**	**$337.86**

Table 8. Changes in annual costs associated with water heating and space heating and cooling when the conventional water heater is replaced with the ASHPWH. Negative values indicate a reduction in cost.

Conventional electric case	Family Home	Apartment Unit
Change in space heating cost	$487.43	$243.71
Change in space cooling cost	-$81.24	-$25.90
Change in water heating cost	-$791.24	-$395.62
Efficient electric case		
Change in space heating cost	$145.50	$72.75
Change in space cooling cost	-$47.00	-$14.98
Change in water heating cost	-$791.24	-$395.62

Table 9. GHG emission comparison between natural gas water heater and ASHPWH, using natural gas for space heating and air conditioning for cooling in a family home.

	Natural gas baseline	Natural gas-ASHPWH
Electricity consumed (kWh)	575	2536
Natural gas consumed (m^3)	2538	2020
Total emissions (kg CO_2e/year)	4799	3923

Ontario electricity grid, assumed to be 0.050 kg CO_2e/kWh (Environment and Climate Change Canada, 2016). Emission savings occur because using electricity has lower associated emissions than natural gas.

Table 9 displays estimated emission reductions of 18% in the family home scenario under the natural gas case. The same emission reduction percentage is observed in the apartment scenario.

These reductions in GHG emissions occur because the fuel used for heating is changing from natural gas to electricity, and the Ontario electricity grid has a relatively low emission factor. When looking at the all-electric cases, the percent reduction in GHG emissions is equal to the percent reduction in electricity consumption, since the fuel type is the same for both cases.

According to a simple seasonal energy balance, the ASHPWH may be able to provide more cooling energy than is seasonally required by some housing units. The amount of cooling provided by the ASHPWH is directly proportional to the amount of hot water used in a home – for every unit of energy used to heat water, the ASHPWH removes 0.64 units of heat energy from the ambient indoor air, producing a cooling effect. In homes with larger hot water demands, a greater fraction of their space cooling requirements may be met by the unit, to the extent where the ASHPWH may even provide more cooling than necessary. However, it should be noted that the location of the ASHPWH matters as well since it may not be ducted, and it cools the ambient space directly surrounding it.
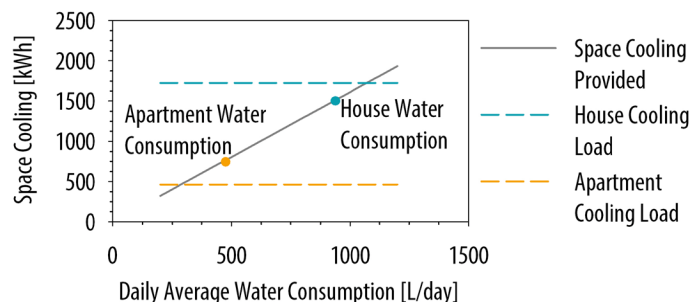

Figure 5. Space cooling provided by the ASHPWH as a function of daily water consumption. Water consumption above the dotted lines will meet the entire seasonal cooling load for the respective house size.

Figure 5 displays the seasonal space cooling provided by the ASHPWH as a function of total daily water consumption. The solid line shows the linear relationship between water consump-

tion and the space cooling provided by the ASHPWH. The dashed lines indicate the seasonal space cooling loads of the apartment and family home scenarios, and can be used to determine how much water consumption would be required to meet their respective cooling loads. For example, the apartment investigated in these calculations will have its entire seasonal cooling load met by the ASHPWH when daily water consumption is greater than 300 L/day.

Seasonal energy balances show that the ASHPWH provides 84% of the cooling load for the family home investigated, and surpasses the cooling requirement of the apartment by over one half. It should be noted that this analysis relied on a high-level energy balances that neglected daily and hourly variations. Additionally, experimental work has shown a much more reduced cooling effect than a seasonal energy balance estimates, and highlights the importance of ducting the ASHPWH such that it's cooling effect is distributed throughout the building (CMHC, 2014). Nonetheless, the potential for space cooling is clear, warranting long-term experimental testing.

CONCLUSIONS

The performance of an air-source heat pump water heater was evaluated, specifically with regards to its impact on the energy consumption and cost associated with water heating, space heating and space cooling. The performance of the ASHPWH under test was experimentally verified with the manufacturer performance curve. A high-level seasonal energy balance was then used to estimate the impact of the ASPHWH on space conditioning and water heating, and determine the costs associated with replacing conventional electric and gas water heaters.

Because the ASHPWH is able remove unwanted heat energy from the ambient space in the cooling season, and then use it to heat water at an enhanced efficiency, it consumes less energy and therefore costs less than conventional all-electric household scenarios. It is expected that replacing an electric water heater with an ASHPWH would payback within the device's lifetime, as long as the home is already heated and cooled using electricity. However, at this time natural gas water heating remains to be most cost-effective means of water heating. These results make a good case for the replacement of electric water heaters in homes that do not have a natural gas connection, even in colder climates, along with other niche applications.

For a more detailed analysis of the A.O. Smith ASHPWH, the Master's thesis titled *Heat Pump Water Heater for Cold Climate – Canada* may be accessed from the Ryerson University Database.

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