IPMVP—Adherent Evaluation of Ductless Multi-Split Air-Source Heat Pump Retrofits in an Electrically Heated Rowhouse Complex In a Cold Climate

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ABSTRACT

Air-source heat pumps (ASHPs) are a promising retrofit technology for electrically heated buildings but there is currently a limited amount of measurement and verification (M&V) results documenting real-world energy savings. This study applied the International Performance Measurement and Verification Protocol (IPMVP) to evaluate the energy savings of ductless multi-split ASHP retrofits in an electrically heated rowhouse complex located in Brantford, Ontario, Canada. Normalized energy savings calculations were conducted in two rowhouses and estimated an energy savings of 19 and 32% on the total electricity bills for the heating season when compared to electric baseboards. Cooling mode savings estimates were also conducted but were not IPMVP-adherent because of study constraints. In a direct comparison of a retrofitted and non-retrofitted unit, it was estimated that the heat pumps consumed 5x less energy than the window shaker air-conditioners during the cooling season to provide a comparable level of cooling. Interviews with tenants were very positive. They appreciated the energy savings, quiet operation, ease-of-use, improved thermal comfort and the addition of cooling to their units. The business case for ductless multi-split ASHPs will vary across jurisdictions but for the specific study units and jurisdiction, it was estimated that the simple payback of the retrofits is on the same scale of the estimated ASHP lifetimes (approximately 15 years). However, the business case may improve with other variants of ASHP technology, like lower-cost mini-splits or larger-scale variable refrigerant flow (VRF) systems. The authors acknowledge that this was a case study. Results are dependent on tenant behaviors and other installation-specific details. Greater or lower energy savings are possible in other buildings. A larger body of IPMVP-adherent M&V results from real-world retrofits would help bring consensus on the achievable energy savings of ASHP retrofits.

INTRODUCTION

Electric heating is common in many jurisdictions. In Ontario, Canada, it has been estimated that approximately 24% of multi-unit residential building (MURB) units are heated with electric resistance heating like baseboards or packaged thermal air-conditioners (PTAC) [1]. Electric resistance heating is robust and long-lived, but it is also energy-intensive when compared to other heating options. In Ontario, electric resistance heating is several times more costly than natural gas options and, given the context of rising electricity rates, this makes heating with electric resistance increasingly unaffordable. Furthermore, many electrically heated MURB units have either no cooling at all or they may rely on window shaker air-conditioners, which vary greatly in their efficiency and quality of installation. In the context of a warming climate, high-efficiency cooling options are also increasingly needed for health and safety.

Electrically driven heat pumps offer a potential solution. In heating mode, they achieve a high efficiency by supplementing electrical energy consumption with heat energy extracted from the air, ground or elsewhere. Air-source heat pumps (ASHPs), particularly ductless ASHPs, have great potential for retrofit applications in buildings previously heated with electric resistance because they are lower cost and typically straightforward to retrofit. There are many variants of air-source heat pump technology, including ductless mini-splits, ductless multi-splits, centrally ducted, mini-ducted and larger-scale variable refrigerant flow (VRF) options. There are also options for variable capacity inverter-driven compressors and modification to the refrigerant circuit than enhances heating performance in extremely cold conditions (making it a “cold-climate heat pump”). It follows that a prospective system owner has many options from which to choose.

The decision to move forward with any given retrofit ASHP option would depend on many factors, but chiefly among them is the projected energy savings. Rated efficiencies (termed the coefficient of performance (COP) or heating season performance factor (HSPF) in the context of ASHPs) for the more advanced options suggest that greater than three times the heating energy can be delivered for the same energy consumption as electric resistance heaters. However, performance ratings ought to be bolstered by measurement and verification (M&V) results that have determined the energy savings in actual buildings. Previous M&V results can demonstrate achievable savings to prospective system owners and help to estimate savings of future retrofits, as well as provide many other useful insights on performance.

Currently, a lack of M&V-based case studies of documenting energy savings of ASHP retrofits has been an important, but surmountable, barrier to more widespread adoption of the technology [1]. Different approaches to M&V have been taken in previous work. Researchers in [2] and [3] estimated the efficiency of ductless heat pump retrofits using single-point temperature and air-flow measurements on indoor blowers, as well as other measurements. However, there may be a wide-distribution of temperatures and air flows across the blower cross-section and any single point may not be well-representative of the average values. It follows that this approach could be a useful high-level check of performance but is not a robust strategy for determining efficiency. The researchers' electricity bill analysis would provide a better estimate of savings, but it was not IPMVP-adherent. Researchers in [4] used indoor fan power consumption measurements as a proxy for air flow in a real-world evaluation of ductless ASHPs. However, their results were inconsistent with manufacturer air flow rates and overall, their approach is not easily replicable in the field (their field monitoring protocol is summarized in [5]).

To the author's knowledge, there have be few (if any) available M&V case studies of ASHPs in the literature that utilize the International Performance Measurement and Verification Protocol (IPMVP). IPMVP Option C evaluates the savings of an energy conservation measure (ECM) using the ECM's impact on whole-building energy consumption. IPMVP Option C is well-suited to ASHP retrofits because the savings should be easily distinguishable at the whole-building level and also, because the focus of IPMVP C aligns well with the needs of adopters in that what ultimately matters is a reduced utility bill.

This study used IPMVP Option C to evaluate multi-split ductless ASHP retrofits in an electrically heated rowhouse complex located in Brantford, Ontario, Canada. Six units were included in the study. Four were retrofitted (Units 1 to 4) and two were incorporates as controls (Units 5 and 6). A wireless cloud-based monitoring system was deployed in each unit to monitor indoor temperature, outdoor temperature, heat pump energy consumption and whole-house energy consumption. Sensors were verified at the Archetype Sustainable House (ASH) Lab in Vaughan, Ontario, prior to deployment. Whole-house submeters were also compared against manual utility meter readings throughout the monitoring period and found to agree to within 2%. Data was collected from November 2017 to August 2018.

Rowhouses were 2- or 3-bedroom units with two stories, two bathrooms and a full basement. They ranged in size from approximately 1,500 to 1,800 ft2 (Figure 1). Prior to the retrofits, electric baseboards provided heating throughout the rowhouses, each controlled by an individual thermostat installed on the wall or packaged into the baseboard itself. Ductless multi-splits were selected for the retrofits because it seemed to be the simplest option that could effectively replace an entire baseboard heating system. A ductless multi-split ASHP system consists of a single outdoor fan coil (i.e., a "condenser" like that in an A/C system) connected to multiple indoor fan coils using small diameter refrigerant piping that can be run on the exterior of a building (Figure 2) or tight spaces within a building. Small building penetrations then connect the refrigerant lines to indoor fan coils. In this study, ductless wall-mounted indoor fan coils were used (Figure 3) but other form factors are also available. Installations took a team of two people approximately two days per rowhouse unit and there was no need for any interior finish work. The retrofit process was straightforward and reported to be non-invasive by tenants.

Heat pumps were donated by Mitsubishi and Daikin. Both 3- and 4-port multi-splits were used. Systems were sized using HOT2000™ (an energy simulation and design tool for low-rise residential buildings) and designed such that the main floor living space and each bedroom received an indoor fan coil. System capacities ranged from 2- to 3-tons nominal. All heat pumps were inverter-driven variable capacity models. The benefit of variable capacity heat pumps is that they can modulate their capacity down to very low levels rather than turn off entirely. This makes the system more efficient, in part because losses associated with start-up are greatly diminished. Both cold-climate and conventional heat pump models were included. Cold-climate models can continue operating when outdoor temperature drops below -25°C, while conventional models can typically no longer provide heating when the outdoor temperature is below -15°C and back-up heating must be used.

Heat pumps were installed in November 2017 by a GreenON approved contractor. GreenON was an Ontario incentive program for energy efficiency measures but is now discontinued. The installation was overseen by a Senior Project Manager from project partner Cricket Energy and reviewed by representatives from each manufacturer. No errors or faults were detected on start-up. In late February 2018, one of the manufacturer representatives identified that building penetrations had not been insulated by the contractor. This was fixed in early March 2018, after data had been collected for more than 3 months, but this is not believed to have impacted the energy savings estimates within the study because of the approach taken for baseline data collection.

Baseline data was collected by disabling heat pumps and reverting back to the baseboards for a several week period in January and February. Baseline data was collected with the unsealed penetrations, like most of the post-retrofit data, and the baseline and retrofit periods therefore formed a fair comparison.

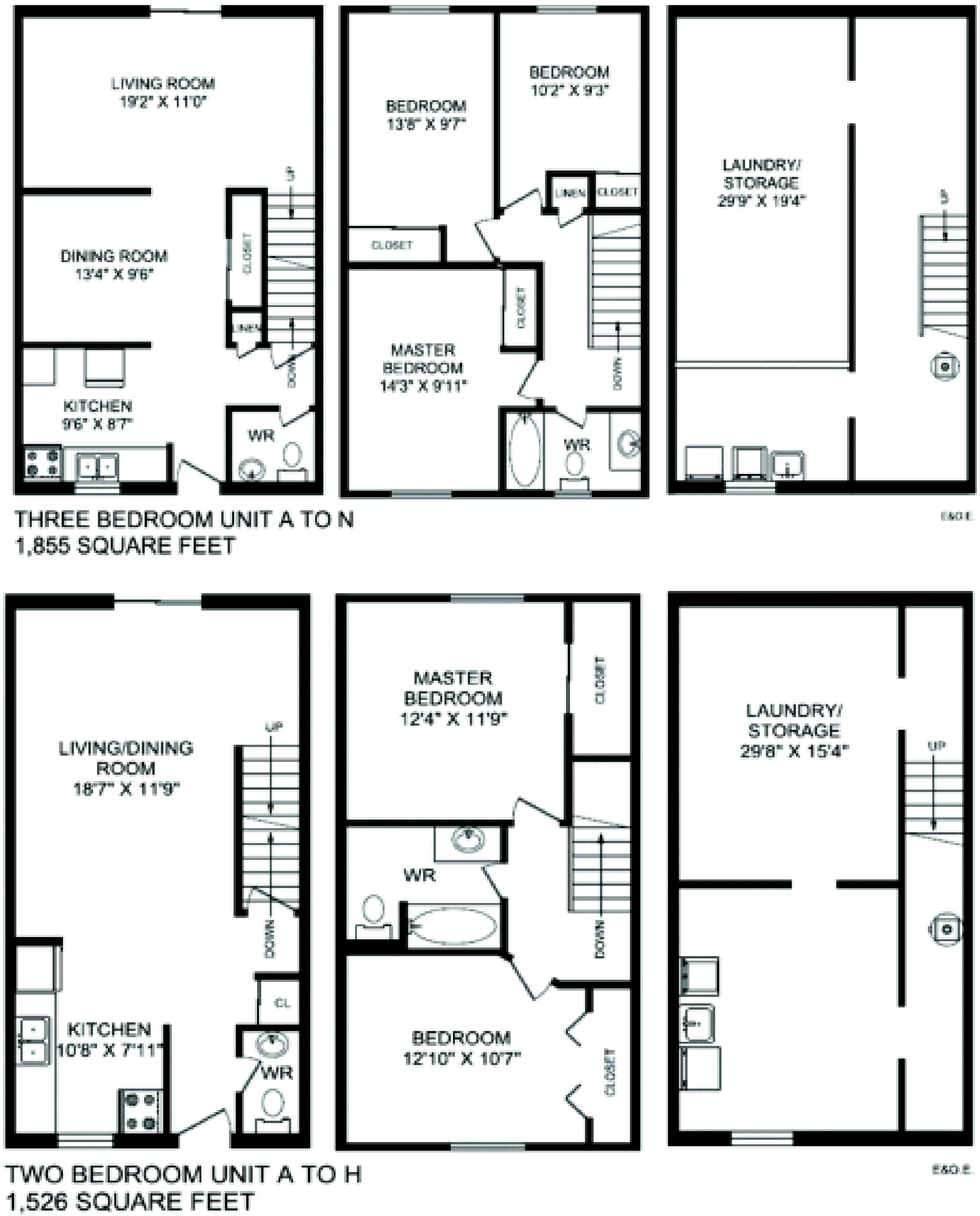

Figure 1. Layout of units

Time periods for retrofit and baseline monitoring periods are shown in Table 1. Utility data from the previous year was not used because this preceded the study period in which interviews and site visits could ensure a fair comparison between baseline and retrofit monitoring periods. Monitoring periods were staggered in this way (i.e., retrofit-baseline-retrofit) to ensure that both the retrofit

Figure 2.
Outdoor refrigerant lines connecting condenser and indoor fan coils

Figure 3. Wall-mounted indoor fan coils were used but ceiling- and floor-mounted options are also available

Table 1.
Monitoring Periods

Time Period	Data Collection
Nov 20, 2017 to Jan 18, 2018	Heat pumps used for heating. Baseboards used in bathrooms at discretion of tenants. Baseboards in Unit 4 (with a conventional heat pump) used as back-up heating when required.
Jan 20, 2018 to Mar 1, 2018	Heat pumps disabled. Baseboards used for heating.
Mar 3, 2018 to Aug 1, 2018	Heat pumps used for heating or cooling. Baseboards used in bathrooms at discretion of tenants and for back-up in Unit 4. Monitoring was discontinued after August 1st but heat pumps were left in place to be used by tenants moving forward.

and baseline monitoring periods covered a sufficient spread of outdoor ambient temperatures.

IPMVP-adherent normalized energy savings calculations were performed for Unit 3 and 4 only. Unit 1 and 2 were removed from consideration because the baseline and retrofit data did not form a fair comparison. In Unit 1, the tenant turned on a baseboard heater in the basement at a constant level and left it on for much of the heating season across both the baseline and retrofit monitoring periods. The heater did not need to be on, and it created artifacts in the energy data that made it impossible to obtain a good regression model of energy consumption. In Unit 2, the tenant selectively provided heating to a spare bedroom based on whether foster kittens were being kept in the room. It turned out that when heat pumps were enabled, the room was kept very warm but when baseboards were enabled, the room was left unheated.

MODELLING AND COMPARISON

In accordance with IPMVP Option C, whole-house energy consumption data was used to develop regression models of energy consumption for both the baseline and retrofit monitoring periods. Unit 3 tenants were relatively consistent in their daily energy usage in that the outdoor temperature was the primary factor causing any difference in energy consumption. The Unit 3 models were therefore based on the daily energy consumption with the average daily outdoor temperature used as the independent variable. Unit 4 showed marked differences in its energy consumption between weekdays and weekends. Energy models for Unit 4 were instead based on weekly aggregated energy consumption using heating degree-days (HDDs) as the independent variable. Daily average outdoor temperature was used first, where possible, because it creates simpler and more intuitive representation of energy consumption. The authors note that different days with same outdoor temperature can have a different distribution of temperatures, and that this could cause scatter in the energy consumption data. These effects are taken into account given the statistical nature of the analysis, which uses regression modeling across multiple days.

Figures 4 and 5 show the models for Unit 3 and 4. Unit 3 baseline and retrofit models are defined in Equations 1 and 2. Heat pump energy consumption model for Unit 3 during the retrofit monitoring period is shown in Equation 3. Unit 4 baseline and retrofit models are shown in Equations 4 and 5. The heat pump energy consumption model for Unit 4 during the retrofit monitoring period is shown in Equation 6. Table 2 provides additional model parameters. Note that polynomial, rather than a linear, regression was used for the Unit 3 retrofit energy model because it provided a better fit. The physical justification for a non-linear model is that the heat pump efficiency is temperature-dependent and the baseline and retrofit models ought to converge at extremely cold temperatures as the coefficient of performance approaches 1.0. The Unit 3 models are applicable to days with a daily average temperature less than or equal to 16°C. This is the temperature observed within the study at which the

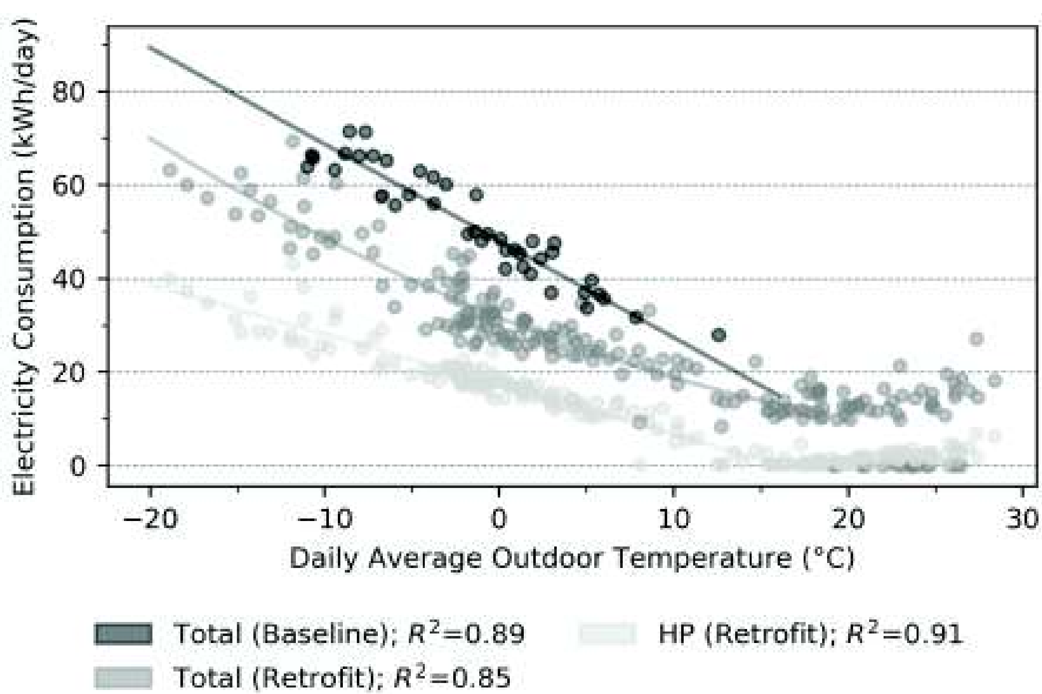

Figure 4. Unit 3 baseline and retrofit models

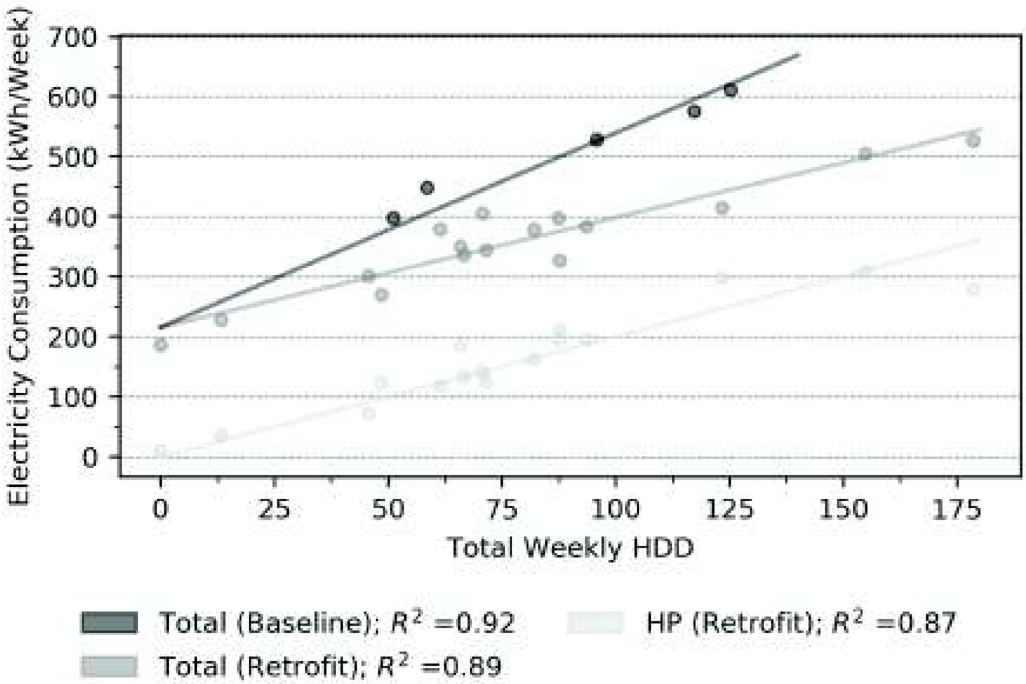

Figure 5. Unit 4 baseline and retrofit models

heat pump no longer consumed energy. The Unit 4 models are applicable to days with daily average temperatures below 11°C. This was the building balance temperature used to determine HDDs, and it was empirically determined as the temperature at which the Unit 4 heat pump no longer consumed energy. HDDs were determined using hourly aggregated outdoor temperature data from the monitoring package.

$$B_{Unit3}(T_o) = -2.065 \cdot T_o + 48.04 \qquad \text{Eq (1)}$$

$$R_{Unit3}(T_o) = 0.02082 \cdot T_o^2 - 1.497 \cdot T_o + 31.67 \qquad \text{Eq (2)}$$

$$H_{Unit3}(T_o) = -0.0001926 \cdot T_o^2 - 1.071 \cdot T_o + 17.40 \qquad \text{Eq (3)}$$

$$B_{Unit4}(HDD) = 3.235 \cdot HDD + 216.3 \qquad \text{Eq (4)}$$

$$R_{Unit4}(HDD) = 1.827 \cdot HDD + 215.9 \qquad \text{Eq (5)}$$

$$H_{Unit4}(HDD) = 2.007 \cdot HDD \qquad \text{Eq (6)}$$

Normalized savings was calculated by applying the models to a typical meteorological year (TMY) weather data file. The Canadian Weather Data for

Table 2.
Model Parameters

Model	Independent Variable	Dependent Variable	# Points	Range	Coefficient of Determination (R^2)	Standard Error of Estimate
Unit 3 Baseline Whole-house	Daily Average Outdoor Temperature (°C)	Daily Whole-house Energy Consumption (kWh/day)	41 days	$-18^oC < T_o < 16^oC$	0.89	3.95 kWh/day
Unit 3 Retrofit Whole-house	Daily Average Outdoor Temperature (°C)	Daily Whole-house Energy Consumption (kWh/day)	133 days	$-18^oC < T_o < 16^oC$	0.85	4.86 kWh/day
Unit 3 Retrofit Heat Pump	Daily Average Outdoor Temperature (°C)	Daily Whole-house Energy Consumption (kWh/day)	133 days	$-18^oC < T_o < 16^oC$	0.91	2.62 kWh/day
Unit 4 Baseline Whole-house	Weekly Aggregated Degree-Days (°C-day)	Weekly Whole-house Energy Consumption (kWh/week)	5 weeks	HDD > 0	0.92	29.5 kWh/week
Unit 4 Retrofit Whole-house	Weekly Aggregated Degree-Days (°C-day)	Weekly Whole-house Energy Consumption (kWh/week)	16 weeks	HDD > 0	0.89	30.1 kWh/week
Unit 4 Retrofit Heat Pump	Weekly Aggregated Degree-Days (°C-day)	Weekly Whole-house Energy Consumption (kWh/week)	16 weeks	HDD > 0	0.87	32.8 kWh/week

Energy Calculations (CWEC) data base was used. (The specific data file was CAN_ON_TORONTO-CITY-CENTRE_6158359_CWEC.epw.) Toronto weather data was used to put the results in the context of Canada's most populous city. For Unit 3, the weather data was aggregated to determine the daily average temperature for each day within the TMY. The daily average temperature for each day was then substituted into Equations 1 to 3 to calculate energy consumption for each model. Results were then summed across the year. The same basic approach was used for Unit 4, except that the TMY data file was used to calculate weekly HDDs. Results are provided in Figure 6 and Table 3. Uncertainty calculation are in accordance with Statistics and Uncertainty for IPMVP (EVO 10100 1:2014).

In heating mode, it was possible to collect baseline data simply by reverting to the pre-existing baseboards. This approach would have been less straightforward in cooling mode. Cooling mode was instead evaluated by comparing the temperature-dependent energy consumption of a retrofitted and (otherwise

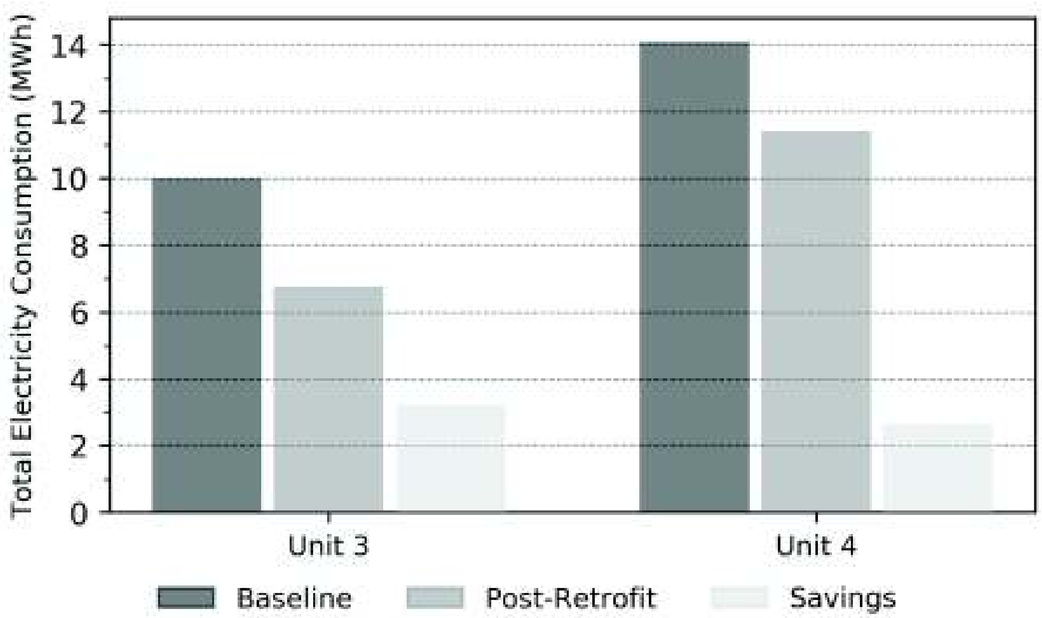

Figure 6. Heating season energy savings

Table 3. Heating Season Results

	Baseline Whole-house	Retrofit Whole-house	Savings Whole-house	Retrofit Heat Pump
Unit 3 (kWh/year)	10,002 ± 127	6,775 ± 153	3,228 ± 197	3,282 ± 83
Unit 4 (kWh/year)	14,085 ± 570	11,424 ± 392	2,661 ± 815	3,777 ± 427

comparable) non-retrofitted unit. It is believed that the comparison is fair and, if anything, conservative in regard to heat pump energy savings. The retrofitted unit was an end-unit (with greater heat gain) while the non-retrofitted unit was a middle-unit. Both were 3-bedroom units. Indoor temperature measurements showed that the heat pump was used to keep the retrofitted unit at slightly lower temperatures.

In the non-retrofitted unit, window shakers were seasonally installed and uninstalled by the tenant. Three were used in total. Cooling mode energy consumption for each is shown in Figure 7. Actual heat pump energy consumption was used for the retrofitted unit while the temperature dependent portion of the whole-building energy consumption was used for the non-retrofitted unit. These models were applied to the TMY weather data in the same way as the heating models to estimate the seasonal cooling energy consumption (Figure 8).

Note that because the cooling mode savings was determined from a comparison of two units, the results are not IPMVP-adherent. The results are also for a specific combination of window shakers, each with their own specific installation quality. The comparison is instructive but not definitive. For these units, the heat pumps consumed ~5x less energy to provide what is estimated to be a comparable degree of cooling versus the window shakers. This a very notable difference; greater than would be anticipated based on

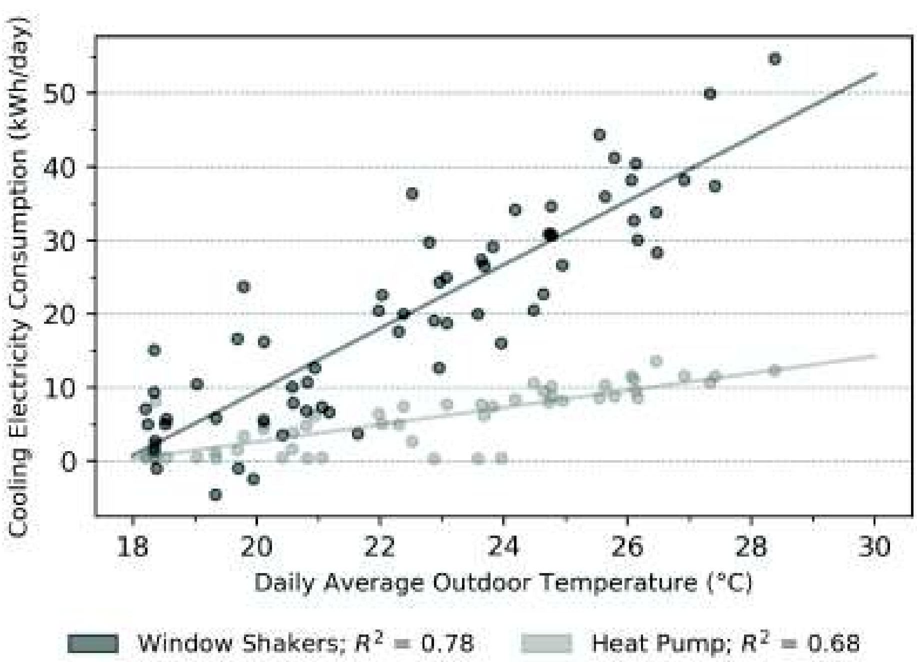

Figure 7. Cooling mode energy consumption models of heat pump versus window shakers

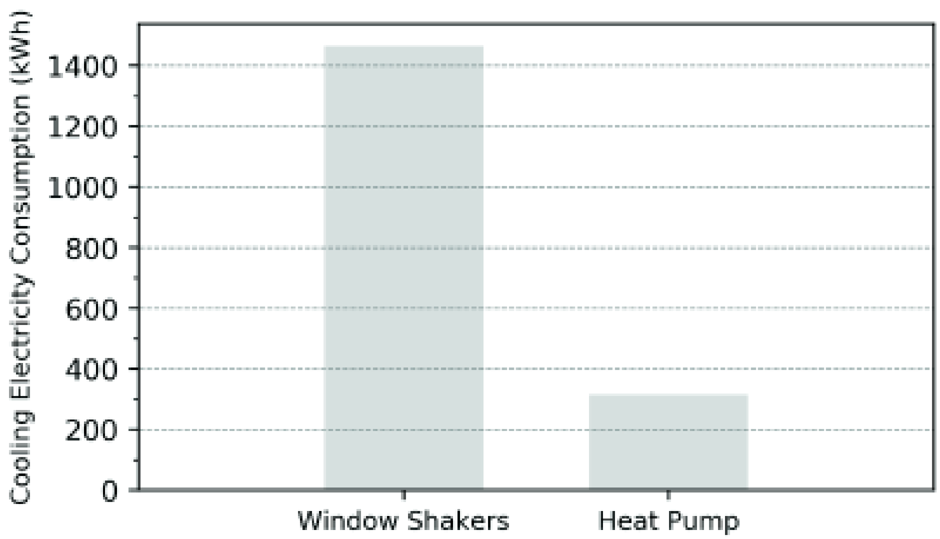

Figure 8. Cooling season energy consumption of heat pump versus window shakers

equipment efficiency alone. Another important finding is that the heat pump cooling energy consumption is low in general, and also low compared to the magnitude of the heating savings. Prospective system owners should therefore be less concerned about high electricity bills during the cooling season.

Several installation specific factors that would have impacted energy consumption were identified but could not be quantified within this study. These included higher return temperatures to the heat pump, long outdoor refrigerant runs, frequent set-point changes, and compressor cycling (either the result of tenant control or automatic control). Note that these factors were not extreme and would be considered normal use. Indoor temperature sensors measurements for Unit 3 and 4 were typically near 22°C, however, spot measurements showed that the temperature at the wall-mounted indoor fan coil return (near the ceiling) could be 1 to 2°C higher because of thermal stratification within the room. Efficiency is degraded as return temperature increases. The effect of other factors like fan and compressor speed have been examined elsewhere [6]. An important factor for Unit 4 was that internal heat gains were high and active heating was not needed for days with an average daily outdoor temperature greater than 1°C. Heat pumps are most efficient at warmer temperatures and the fact that the balance point of this unit was low meant that there was effectively less baseboard electricity that could be saved. Savings could have been greater in a different unit with a higher building balance point. This illustrates that it is important, insofar as is possible, to consider real-world operational factors when evaluating a prospective heat pump retrofit and adjust the expected performance and savings accordingly. This would be a challenge in a rental context because one set of tenants may have different behaviors and preferences than another.

Equipment was donated. However, installed costs for the system were estimated by project partner Cricket Energy to be greater than $10,000 and up to $14,000. Based on Ontario's most recent long-term energy plan, the average cost of electricity for the next 15 years was estimated at $0.212/kWh. It follows that annual heating mode savings was estimated at $684 and $564/year for Unit 3 and 4, respectively, and annual cooling mode savings at $243/year, yielding a total annual savings of approximately $850/year on average. Simple payback, including both heating and cooling mode savings, for these study units was therefore on the same scale of the estimated equipment lifetime of 15 years. Note that the authors acknowledge that this was a case study. Results are dependent on tenant behaviors and other installation-specific details. Greater or lower energy savings are possible in other buildings.

The multi-splits provided a high degree of thermal comfort. In applications where cost-effectiveness is the most important factor, the authors speculate that a ductless mini-split may actually be a better option. Ductless mini-splits only have a single-zone, but they are less than half the cost of a multi-split of comparable capacity. In these study units, a ductless mini-split installed on the main floor and electric baseboards left in-place for the bedrooms would likely have had a better business case. This would essentially be a hybrid system where the heat pump does most, but not all, of the heating. The mini-split would also still provide high-efficiency cooling. Multi-zone systems can also be accomplished using mini-split heat pumps. There would be multiple benefits to such an approach, including built-in redundancy, ease-of-troubleshooting and shorter refrigerant lines (with a resulting improvement in efficiency). The primary downside is that there would be additional outdoor fan coils that take up space and may affect the building aesthetics. Hybrid and multi-zone systems based on ductless mini-splits should be evaluated in future M&V studies.

On-site interviews with tenants were performed in November 2017, March 2018 and June 2019. The intent of the interviews was to capture the tenant's qualitative experience with the heat pumps and ensure that the baseline and retrofit periods formed a fair comparison. The tenant's experience was very positive. They found the heat pumps easy-to-use via the provided remote control. Their thermal comfort was improved, especially through the additional of cooling to their units. They did not dislike the appearance of the indoor fan coils and they highly appreciated the energy savings. Their comments complimented the quantitative data in that the heat pumps all operated according to their stated with range, with the cold-climate heat pumps operating across all temperatures experienced during the study period and the conventional heat pumps turning off entirely when daily average outdoor temperatures dropped below their stated operational range.

An interview was also conducted with the building owner. In this study, units were suite-metered with the electricity bill being paid by the tenants. This is not an ideal arrangement for energy efficiency retrofits because there is a split-incentive between the tenants and building owner. Tenants receive the energy savings benefit, but the building owner would pay for the retrofit and, depending on the arrangement with the tenants, any ongoing maintenance. The split-incentive was circumvented during the study period because the equipment was donated, and the research team coordinated the install. The building owner would not have undertaken the retrofit on their own. They participated in the study to provide value for their tenants while also exploring the potential for retrofits in bulk-metered buildings within their portfolio. From the owners' perspective, non-energy benefits of the technology are difficult to translate into a monetary value. Non-energy benefits include increased marketability of units as well as improved tenant satisfaction and well-being. The owner was not concerned about tenants leaving due to high utility costs because, from their perspective, a renter is best off staying in the same unit for as long as possible to avoid large increases in their rent when moving between different rental units. The split-incentive problem is a notable barrier but may be overcome in the future; for example, through grants, creative financing or legislated safe maximum limits on rental unit indoor temperatures, which would force building owners to explore options for high-efficiency cooling.

Lastly, this study did not seek to compare the performance of heat pumps from the different manufacturers. The study design would not be sufficient to draw such a comparison given the variability in tenant behaviors. However, the study did consider both cold-climate and conventional heat pumps and it is possible to comment further on that topic. Unit 3 used a 3-port cold-climate heat pump while Unit 4 used a 4-port conventional heat pump. As expected, the Unit 4 heat pump shut itself off when outdoor temperatures dropped below the heat pump's operational range. Tenants in Unit 4 were instructed to leave baseboard thermostats off during normal conditions but set them a couple degrees below the heat pump thermostat in extreme cold conditions such that they could operate as back-up heating. Relying on the tenants as part of the control strategy was not ideal but a suitable alternative approach could not be found at the time of the study. There were options for a 4-port cold-climate heat pump, but this had a significant increase in cost. Wireless relays or wired-in thermostats with back-up heating control were possible as well, but this would have added notable cost and would need to be replicated across all indoor fan coils. Back-up resistance heating integrated into the heat pump indoor fan coils themselves was not available from the manufacturers at the time of the study.

The research team came to the following conclusions in regard to cold-climate versus conventional heat pumps. Cold-climate heat pumps come with an added cost-premium. That cost-premium will vary with the type of heat pump, as well as the number of indoor fan coils in the case of ductless multi-split systems. If the climate is such that the outdoor temperature infrequently drops below the operational range of a conventional heat pump (-15°C for the heat pumps evaluated in this study) then the added cost of a cold-climate heat pump can likely be avoided. However, if heating is required in extreme cold temperatures then the options are to use a cold-climate heat pump or to use a conventional heat pump with back-up heating. Both options are feasible but the authors caution that automatic control of back-up heating in a ductless multi-split system would also add significant cost. The system owner may be satisfied with manual control of back-up by building occupants, as was done in this study, but the success of that strategy depends on the awareness of the building occupants in controlling the system effectively.

CONCLUSIONS

This study applied the IPMVP to evaluate the energy savings of ductless multi-split ASHP retrofits in an electrically heated rowhouse complex in a cold Canadian climate. Heating season energy savings were 19% to 32% of the total bill. In cooling mode, it was estimated that the heat pumps consumed 5x less energy than the window shaker air-conditioners. Interviews with tenants were very positive. They appreciated the energy savings, quiet operation, ease-of-use, improved thermal comfort and the addition of cooling to their units. It was estimated that the simple payback of the retrofits is on the same scale of the estimated ASHP lifetimes (approximately 15 years) for these specific units, neglecting incentives, carbon pricing or other subsidies. However, the business case would vary in different buildings and jurisdictions, and may improve with other variants of ASHP technology, like lower-cost mini-splits or larger-scale variable refrigerant flow (VRF) systems. Lastly, the authors acknowledge that this was a case study. Results are dependent on tenant behaviors and other installation-specific details. Greater or lower energy savings are possible in other buildings. Future work should include comparable studies in different buildings and consider different heat pump technologies. A larger body of IPMVP-adherent M&V results from real-world retrofits would help bring consensus on the achievable energy savings of ASHP retrofits. The research team suggests that hybrid systems based on ductless mini-splits and existing baseboard heating is a promising route to improved cost-effectiveness. A comprehensive project report is available from TRCA [7].

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