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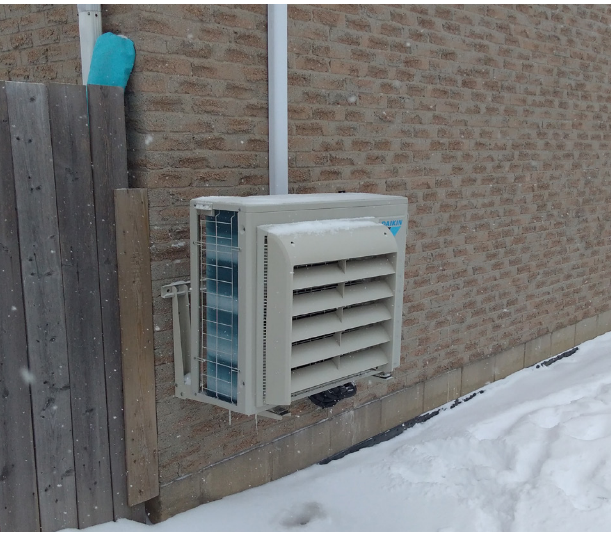

Assessment of Multi-split Ductless Air-source Heat Pump Retrofits in an Ontario Rowhouse: Heating and Cooling

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THE SUSTAINABLE TECHNOLOGIES EVALUATION PROGRAM

The Sustainable Technologies Evaluation Program (STEP) is a multi-agency initiative developed to support broader implementation of sustainable technologies and practices within a Canadian context. STEP works to achieve this overarching objective by:

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- Assessing technology implementation barriers and opportunities;
- Developing supporting tools, guidelines and policies;
- Delivering education and training programs;
- Advocating for effective sustainable technologies; and
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EXECUTIVE SUMMARY

Electric baseboards are the main heating source for 24% of Ontario multi-unit residential (MURB) and rowhouse units. Heat pump retrofits are a significant conservation opportunity in this sector. Heat pumps extract heat energy from the air, ground or elsewhere and can drastically reduce heating energy consumption. Various options are available. Multi-split ductless air-source heat pumps have a single outdoor fan coil connected to multiple indoor fan coils and are ideal for retrofit applications. This study evaluated ductless multi-split heat pump retrofits in a Brantford, ON, rowhouse over the 2017-18 heating season and 2018 cooling season.

Figure A. Multi-split ductless heat pump outdoor coil with exterior connections to indoor fan coils.

Study Site and Installation

Six rowhouse units participated in the study. Four received ductless multi-split heat pump retrofits (Units 1 to 4) and two were controls (Units 5 and 6) that were not retrofitted. Heat pumps were donated by Daikin and Mitsubishi. Indoor fan coils were wall-mounted and refrigerant lines were predominately run on the exterior, creating a simple retrofit.

Figure B. Wall-mounted indoor fan coils were selected for this retrofit. Ceiling- and floor-mounted fan coils are also available.

"If I had to continue paying heat for that (electric baseboard heater), I would probably would be shopping for (another place to live) next year."

-Unit 3 Tenant

Instrumentation and Data Analysis

A remote monitoring package was installed in the study units to evaluate energy savings according to the widely-used International Performance Measurement and Verification Protocol (IPMVP) Option C. Energy measurements were used to develop regression models of baseline and post-retrofit energy consumption and the models were used to estimate savings for a typical year.

" ... it was quiet. You didn't even know it was on, it's like, 'Are you sure that's on' "

-Unit 2 Tenant

Heating Mode Results

Heat pumps were used to heat and cool the rowhouse units for the majority of the monitoring period, starting November 2017 and finishing August 2018. Baseline heating data was obtained by turning off the heat pumps for several weeks and reverting back to the baseboards. Tenant interviews captured the tenant's experience with the technology and ensured a fair comparison. Regression models in heating mode for Unit 3 are shown in Figure C. Models were only possible for Unit 3 and 4. Normalized heating mode energy savings for a typical heating season are in Figure D. Unit 3 and 4 total electricity consumption was reduced by 32% and 19%, respectively. Note that the differences in energy savings between the two units is due to factors that could not be carefully controlled within the study and *not* because one heat performed better than the other.

Q. "How happy are you that you received the heat pump retrofit? "

A. "Very happy.

" -Unit 4 Tenant

Cooling Mode Results

Cooling energy consumption of a control unit (Unit 6) and a retrofitted unit (Unit 1) were compared. The heat pump was estimated to save 1,148 kWh/year in cooling mode when compared to window shakers. If the heat pump introduced cooling where there was none before, the additional consumption was estimated at 316 kWh/year and this increase is relatively small in comparison to the heating energy savings.

Cost Savings

Average annual savings for the units were estimated at $868 including both heating and cooling mode operation. Average annual heating mode savings were estimated at $624, and cooling mode, at $244. There are also a number of non-energy benefits that were not quantified, including: increases in property values; increases in marketability of the units, tenant retention and overall satisfaction; and improved health, safety and comfort of tenants.

"... it's nice and clean (looking). Like there is no wires, you know what I mean?"

-Unit 2 Tenant

Installed Costs

Estimated installed system costs are shown in Table A, neglecting any rebates or incentives. Potential system owners are encouraged to consider the impact of incentives (for example, Save On Energy in Ontario) for their application and context. Single-port (i.e. *mini-split*) heat pump installed costs are shown as well for comparison. Actual installed costs will vary. Table A includes equipment and installation costs but neglects other costs which may push total installed cost towards $14,000 for 3- and 4-port heat pumps. Costs are expected to come down as uptake increases, and for applications where equipment can be purchased in bulk.

Table A. Estimated installed costs.

Heat Pump Type	Estimated Installed Cost
2-ton single-port cold-climate	$4,400
2-ton 3-port cold-climate	$10,600
3-ton 4-port conventional	$10,700

This study also explored a rental model. Rental amounts were prepared by Cricket Energy and are summarized in Section 12.

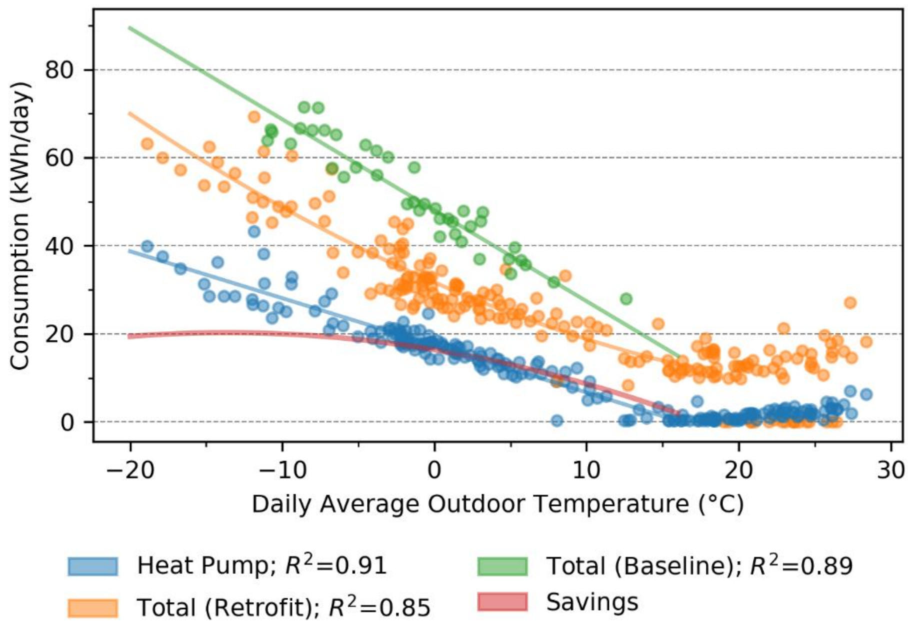

Figure C. A comparison of the regression models of whole-house baseline and post-retrofit energy consumption shows that the heat pump saves a notable amount of energy when compared with baseboards.

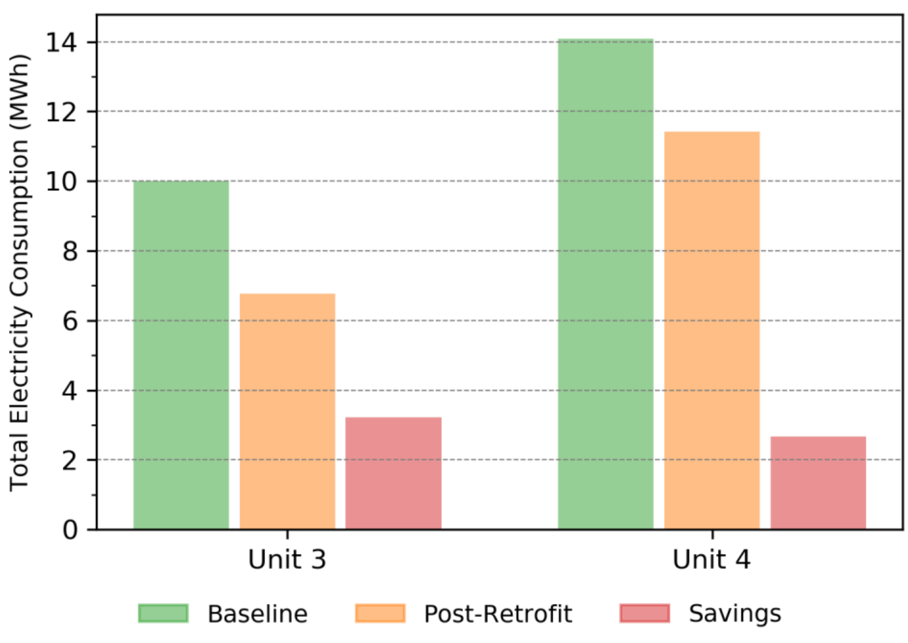

Figure D. Regression models of building energy consumption were used to estimate energy consumption and savings for a typical *heating season*. Unit 3 was estimated to save 3.228 MWh/year (32%) during a heating season as a result of the heat pump retrofit and Unit 4 was estimated to save 2.661 MWh/year (19%).

In reference to the installation process: "There were no issues. See, I work out of town. I'm gone in the morning. You guys come in and do what you have to do and you were pretty much done with it the time I come back. No issues."

-Unit 3 Tenant

Real-world Considerations

Real-world factors may have affected savings. These factors included higher return temperatures, compressor cycling, set-point changes and parasitic heat losses from outdoor runs of refrigerant piping. Some of these factors can be mitigated through tenant education or system design.

Tenant Interviews

Tenants appreciated the energy savings, the simplicity of the retrofit process, the user-friendliness of the remote controls and the increased thermal comfort over electric baseboards. Tenant feedback is highlighted throughout this summary.

Q. " Did you find that the heat pump had any issues providing sufficient heat to keep your unit comfortable? For example, in December we had that really bad cold snap. It was like down to -20° C."

A. "It did more than enough."

-Unit 2 Tenant

Conclusion

The heat pumps were a reliable, efficient and comfortable source of heating and cooling, and were highly appreciated by the tenants. However, the installed costs are large compared to business-as-usual and this makes the business case more challenging. A full business case assessment should evaluate heating and cooling mode savings, as well as non-energy benefits and any applicable incentives. Looking only at energy savings, and neglecting incentives, it is estimated that the simple payback of multi-split ASHPs for these rowhouse units could be on the same scale as the estimated lifetime of the equipment (15 years).

Having multiple indoor fan coils provided tenants with a high degree of thermal comfort but a lower installed cost may be important for many applications. A ductless *mini-split* heat pump (with a single port) installed in the main living space may strike a more economical balance between comfort, energy savings and installed costs. Baseboards may even be left in place for other areas of the home. For larger MURBs, variable refrigerant flow (VRF) ASHP systems may also help to bring the per-unit installed costs down. These approaches should be evaluated in future work.

Lastly, the researchers acknowledge that the energy savings calculations in this study are dependent on the behaviours and preferences of the study tenants themselves as well as other installation-specific details. It follows that the results should be understood as a case study. Other units may have greater or lower savings if they undertake a heat pump retrofit, depending on the occupants and other installation-specific details. Additional IPMVP-adherent studies would be helpful towards building further confidence in heat pump retrofit energy savings estimates.

"… Honestly, who wouldn't want to convert from those (baseboard) heaters to something far better, right?"

-Unit 1 Tenant

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1.0 INTRODUCTION

A recent study by The Atmospheric Fund (TAF) estimated that there are 405,000 electrically-heated units in multi-unit residential buildings (MURBs) and rowhouses within Ontario. TAF estimated that this comprises 24% of all MURB and rowhouse units, and nearly of these units use electric-resistance baseboards.[1]

There is a large opportunity to drastically reduce the carbon emissions associated with electric resistance space heating within the sector, while also saving energy and improving the lives of tenants, and there is a commercially-available, easy-to-retrofit and cost-effective technology to help realize that potential: ductless air-source heat pumps (ASHPs).

The basic components of a *mini-split* ductless ASHP are depicted in Figure 1-1.[2] There is an outdoor fan coil that can be mounted on an exterior wall or sit on a stand or pad, and an indoor fan coil. Most of the mechanical components of the refrigerant circuit are housed in the outdoor fan coil. Refrigerant lines connect the fan coils through a small building penetration. A *multi-split* ductless ASHP has multiple indoor fan coils connected to the same outdoor fan coil and can easily distribute heat throughout a whole building rather than just a single zone.

Figure 1-1. Components of a ductless *mini-split* ASHP.

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[1] The Atmospheric Fund. "Pumping Energy Savings: Ontario EMURB Characterization Study," February 2016.

[2] Image courtesy of Mitsubishi.

ASHPs function on the same principle as refrigerators and air-conditioners, in that a vapour-compression cycle is used to "pump" heat between two locations, in this case, the building interior and the outdoor ambient air. However, unlike air-conditioners, ASHPs provide cooling in the summer *and* heating in the winter.

Commercially available ductless ASHPs are available in North America from major manufacturers like Daikin, Mitsubishi, LG and Fujitsu. Modern inverter-driven cold climate heat pumps incorporate advanced design features that allow them to function down to -25 °C outdoor ambient temperatures and beyond, and achieve seasonal heating coefficients of performance (COPs) that approach and surpass 3.0 according to standardized performance rating tests. This is the key benefit of ASHPs; performance ratings suggest that roughly three times the heat energy output can be provided for the same energy input when compared with electric resistance heating.

The technology has large potential carbon savings, is commercially-available, significantly reduces utility bills, is straightforward to retrofit and is simple to operate - and yet, is generally not deployed in the Canadian MURB and rowhouse sector which can benefit most from the technology. A key barrier is the lack of compelling case studies to assuage the concerns of building owners that perceive the technology as new, and therefore, risky.

This study sought to address that barrier via long-term performance monitoring of real-world ductless ASHP retrofits in a rowhouse located in Brantford, ON, for the 2017/2018 heating season and the 2018 cooling season.

2.0 SITE

The study took place in a rowhouse complex operated by Jama Property Management and located in Brantford, ON (Figure 2-1). The complex consists of 36 units total, all of which are heated using electric baseboards. They are 2- and 3-bedroom (Figure 2-2 and Figure 2-3), two-storey rowhouses with an unfinished full basement, ranging in size from approximately 1500 ft^2 to 1900 ft^2. Units are suite-metered.

Figure 2-1. Rowhouse complex under study in this project.

Electric baseboards are used in various rooms throughout the units and are controlled by individual thermostats. Some thermostats are on walls and some are attached directly to the baseboards themselves. This creates different heating zones within the rowhouse units. Electric baseboards are powered by dedicated circuits from the service panels, with one circuit powering multiple baseboards. Many units also use window shaker air conditioners. The units all have electric hot water tanks.

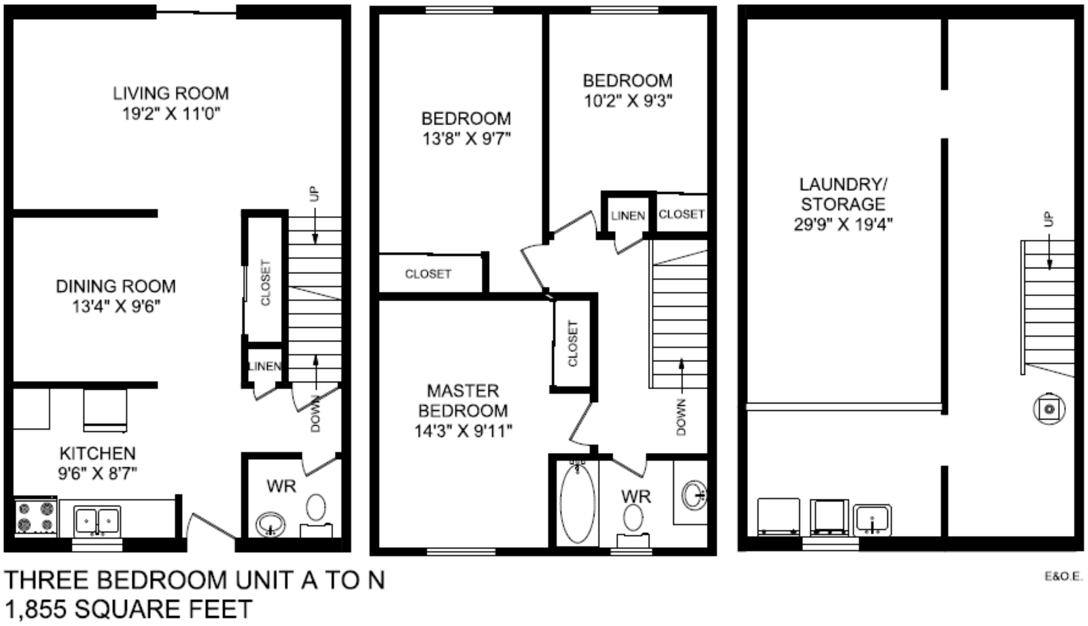

Figure 2-2. Example layout for a 3-bedroom unit in the rowhouse complex.

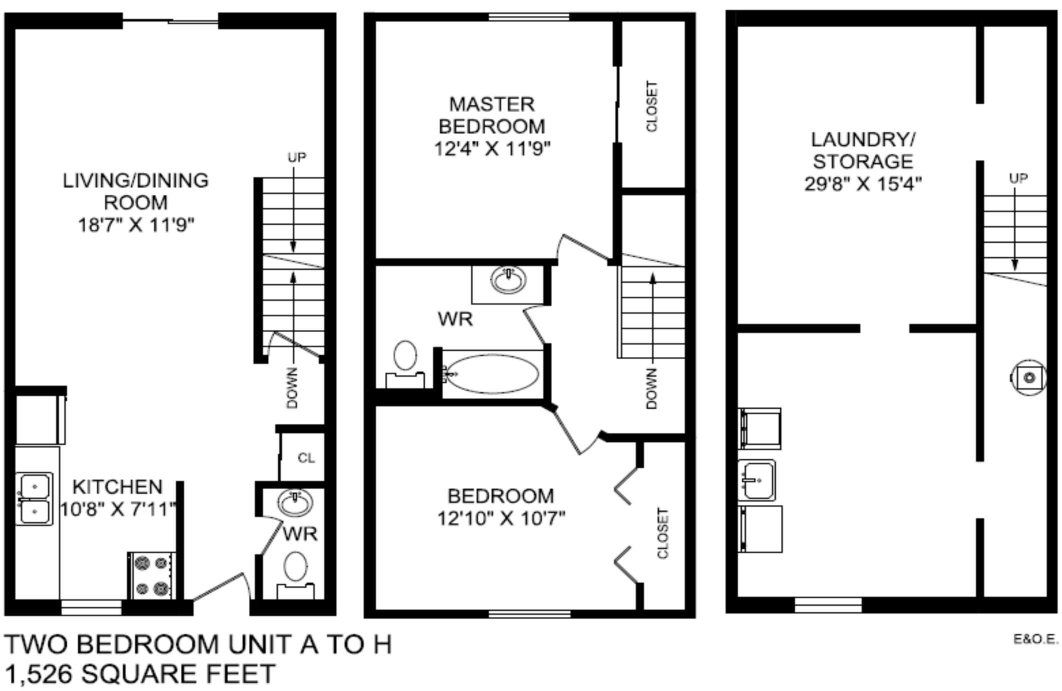

Figure 2-3. Example layout for a 2-bedroom unit in the rowhouse complex.

3.0 RETROFITS

In November 2017, four rowhouse units in the complex received a ductless multi-split ASHP retrofit and an additional two rowhouse units were selected as controls and were instrumented with sensors but not retrofitted with a heat pump. An overview of the retrofits is provided in Table 3-1.

Table 3-1. Overview of rowhouse units and heat pumps.

#	Bedrooms	Type	Placement in Row	Heat Pump Manufacturer	Model	Zone IV HSPF [kBtu/h]/kW kW/kW
1	3	Retrofit	End	Daikin	4MXS36NMVJU (Conventional)	12.2 (3.6)
2	2	Retrofit	End	Mitsubishi	MXZ3C24NAHZ2 (Cold-climate)	10.0 (2.9)
3	2	Retrofit	Mid	Daikin	3MXL24QMVJU (Cold-climate)	12.5 (3.7)
4	3	Retrofit	Mid	Mitsubishi	MXZ4C36NA (Conventional)	11.0 (3.2)
5	2	Control	Mid	N/A	N/A	N/A
6	3	Control	Mid	N/A	N/A	N/A

The four retrofitted rowhouse units included two 2-bedroom rowhouse units and two 3-bedroom rowhouse units. Each of the units selected for a retrofit was modelled in HOT2000 to determine the heating loads. Multi-split ductless heat pumps were sized and selected such that there was one indoor fan coil on the first floor in the main living space, and one in each bedroom. It follows that both 3- and 4-port multi-split heat pumps were considered in the study.

Heat pumps were donated by Daikin and Mitsubishi. The 2-bedroom units used a cold-climate version of the technology that is able to continue to extract useful heat energy from outside air down to -25 °C, and beyond. The 3-bedroom units used the conventional version, which has a manufacturer specified lower operational limit of -15 °C. In practice, they appeared to continue operating down to -18 °C.

Refrigerant lines were run primarily on the exterior of the building. For the interior rowhouse units, the outdoor coil (on the rear of the house) was connected to the front bedroom by routing the refrigerant lines through the basement ceiling and then on the exterior at the front of the house. Routing of the refrigerant lines to each of the individual indoor fan coils is depicted in Figure 3-1 to Figure 3-4. All indoor fan coils were wall-mounted (Figure 3-5).

Figure 3-1. Outdoor coil and refrigerant line set for the Mitsubishi heat pump mounted in a 2-bedroom rowhouse end unit.

Figure 3-2. Outdoor coil and refrigerant line set for the Daikin heat pump mounted in a 3-bedroom rowhouse end unit.

Figure 3-3. (Left) Outdoor coil and refrigerant line set for the Daikin heat pump mounted in the 2-bedroom rowhouse unit. (Right) Refrigerant line set was run through the basement and then on the exterior at the front of the house to reach the front bedroom.

Figure 3-4. Outdoor coil and refrigerant line set for the Mitsubishi heat pump installed in a 3-bedroom rowhouse unit.

Figure 3-5. All indoor fan coils were wall-mounted with the return near the ceiling.

The installation was supervised by a Senior Project Manager from Cricket Energy and installed by a GreenON approved installation contractor. Heat pumps were commissioned according to manufacturer instructions. No fault codes or other issues/failures were noted on start-up. A representative from Daikin reviewed the Daikin heat pump installations in November 2017 and a representative from Mitsubishi reviewed the Mitsubishi heat pump installations in February 2018.

The Mitsubishi representative made two important observations. Firstly, he suggested that routing the refrigerant lines behind the outdoor coil (Figure 3-6) introduces some parasitic losses because convective heat loss from the line set would increase. In this installation, the contractor had decided to route the refrigerant lines behind the outdoor coil because it would improve the appearance of the installation.

The Mitsubishi representative also noted that the building penetrations for the refrigerant line set were not insulated, leaving an open pathway for cold air through the building envelope (Figure 3-7). This was the case for all units. The unsealed building penetrations affected the initial period of post-retrofit data collection and all the baseline data (the heat pumps were turned off temporarily in early 2018 to collect baseline data with the electric baseboards). The building penetrations were sealed during the first week of March 2018.

To estimate the impact of the penetrations on the collected data, Figure 3-8 plots the heat pump energy consumption data from Unit 3 before and after the penetrations were sealed. The lack of sealing of the penetrations appears to have no discernable impact on the heat pump energy consumption, likely because the buildings are already leaky. It follows that no data was rejected from the study due to the unsealed penetrations.

Figure 3-6. Refrigerant line sets were routed behind the outdoor coil for the sake of appearance but this would have also introduced parasitic heat loss from the lines.

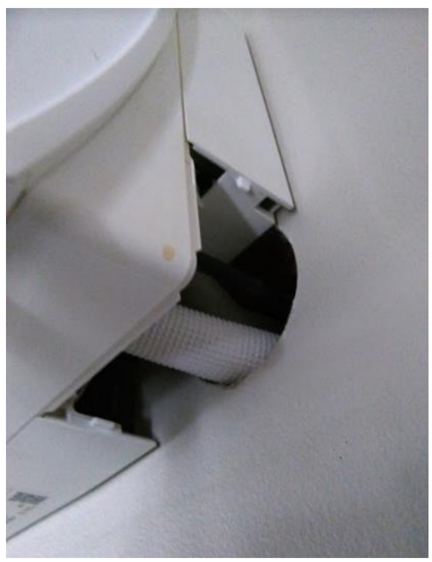

Figure 3-7. When the plastic cover was removed it was clear that the building penetrations had not been sealed by the contractor. This affected all of the baseline period and part of the retrofit period but is not believed to be a source of error since Figure 3-8 shows that the lack of sealing did not impact heat pump energy consumption.

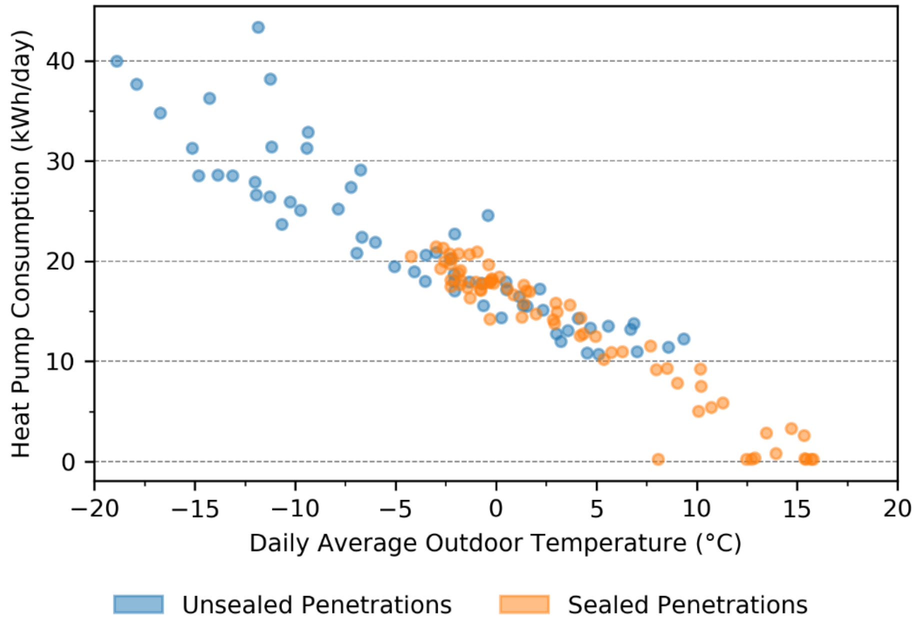

Figure 3-8. Unsealed building penetrations did not appear to impact the heat pump energy consumption.

4.0 CONTROL

It was important to maintain the thermal comfort of the tenants. Many tenants prefer a warmer bathroom but it was not feasible to install fan coils in the bathrooms. To ensure thermal comfort, power to the electric baseboards was left on in the bathrooms and the tenants were left with the opportunity to use them or not use them. Bathroom baseboards were not on dedicated circuits so this meant that power to all other baseboards was also left enabled.

It was anticipated that the conventional heat pumps would not operate in extremely cold conditions. Tenants in these units were told to turn their baseboard thermostats on during extreme cold but set at a lower set-point than the heat pump thermostats. They were told that otherwise baseboards should be off. This would allow the baseboards to act as back-up if the heat pump was not able to meet the set-point. Instructions were provided to the tenants over the phone and through an FAQ document.

Relying on the tenants to turn on or off the baseboard thermostats was not ideal. However, the research team could not find a better cost-effective controls solution. Wired thermostat options or wireless relays for the baseboards were possible but deemed not cost-effective given the fact that there were multiple indoor fan coils and installation costs were already considerable.

Those with cold-climate heat pumps were instructed to leave all baseboards off (except bathroom baseboards, which were used at their discretion) because they would not be required as back-up. All heat pumps were controlled by the tenants using the provided remote control.

5.0 INSTRUMENTATION

Electrical submeters were installed for each unit. The whole-house submeter provided ease-of-access to the data and it also collected data at a high-resolution (10 minutes) such that the data could be aggregated and analyzed at different timescales. In addition to the whole-house electrical submeters, submeters were also installed for the heat pumps and the baseboards. An outdoor temperature and relative humidity (RH) sensor was installed at the complex and a single indoor RH/temperature sensor was installed on the wall at chest-height in the main living space of each rowhouse unit.

The instrumentation package used energy meters from AccuEnergy and wireless sensors from Monnit. Energy meters were installed by an electrician directly adjacent to the service panel in the unfinished basement (Figure 5-1 and Figure 5-2). Retrofitted units used three energy meters (whole-house, heat pump and baseboards) and control units used two energy meters (because there was no heat pump). Pulse outputs from the energy meters were read by an Alta wireless pulse counter from Monnit. Wireless Alta sensors from Monnit were also used for indoor (Figure 5-3) and outdoor temperature/RH (Figure 5-4). The logging interval was 10 minutes.[3]

Figure 5-1. Electrical submetering boxes were installed adjacent to the main service panel.

[3] Note that this does not mean the energy/power measurements were instantaneous. The energy meters output a pulse every time a certain quantity of energy was measured. The pulse counters then logged the number of pulses that occurred in a 10-minute interval.

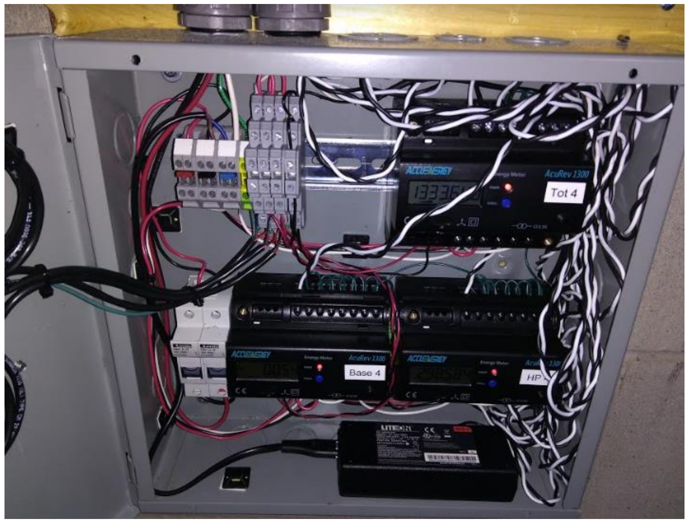

Figure 5-2. Close-up of a submetering box in a retrofitted rowhouse unit.

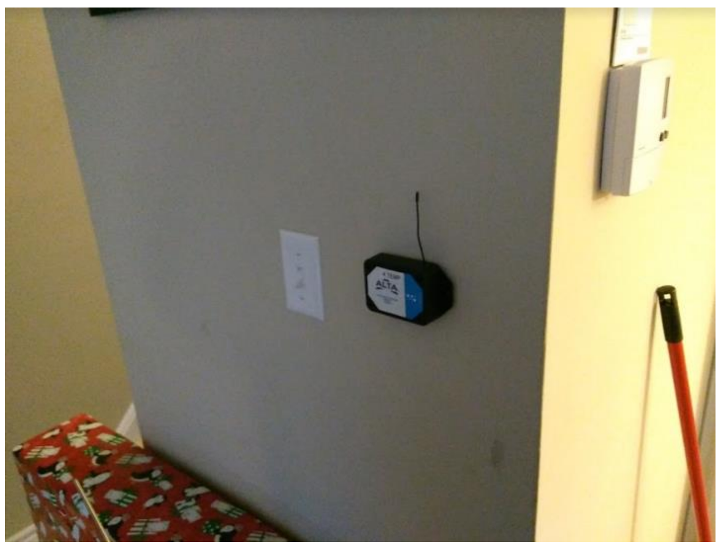

Figure 5-3. Wireless temperature sensors were installed in the main living space of each rowhouse.

Figure 5-4. An outdoor RH/temperature sensor with radiation shield was installed in the complex.

Data was wirelessly transmitted from each sensor to an Alta cellular gateway from Monnit and then to an online monitoring portal where data was downloaded or viewed in near real-time. The overall monitoring system is depicted in Figure 5-5 and sensors are summarized in Table 5-1.

Table 5-1. Overview of sensors used in the study.

Sensing Point	Sensor Manufacturer and Model
Whole-house Energy Consumption	AcuRev 1300 series pulse output energy meter from AccuEnergy connected to a single channel wireless Alta pulse counter from Monnit
Heat Pump Energy Consumption	AcuRev 1300 series pulse output energy meter from AccuEnergy connected to a single channel wireless Alta pulse counter from Monnit
Baseboard Energy Consumption	AcuRev 1300 series pulse output energy meter connected to a single channel wireless Alta pulse counter from Monnit
Indoor Temperature and RH	Alta wireless temperature and RH sensor
Outdoor Temperature and RH	Alta industrial wireless temperature and RH sensor installed with radiation shield

Sensors were installed on November 19th 2017 and fully commissioned on December 14th 2017. During the commissioning procedure, it was found that all baseboard current transducers (CTs) had been installed incorrectly by the electrician. Baseboard CTs were re-installed on December 14th. However, two undiagnosed errors persisted on the baseboard energy meters for Unit 3 and 4 throughout the monitoring period and the baseboard data was not available for these units.

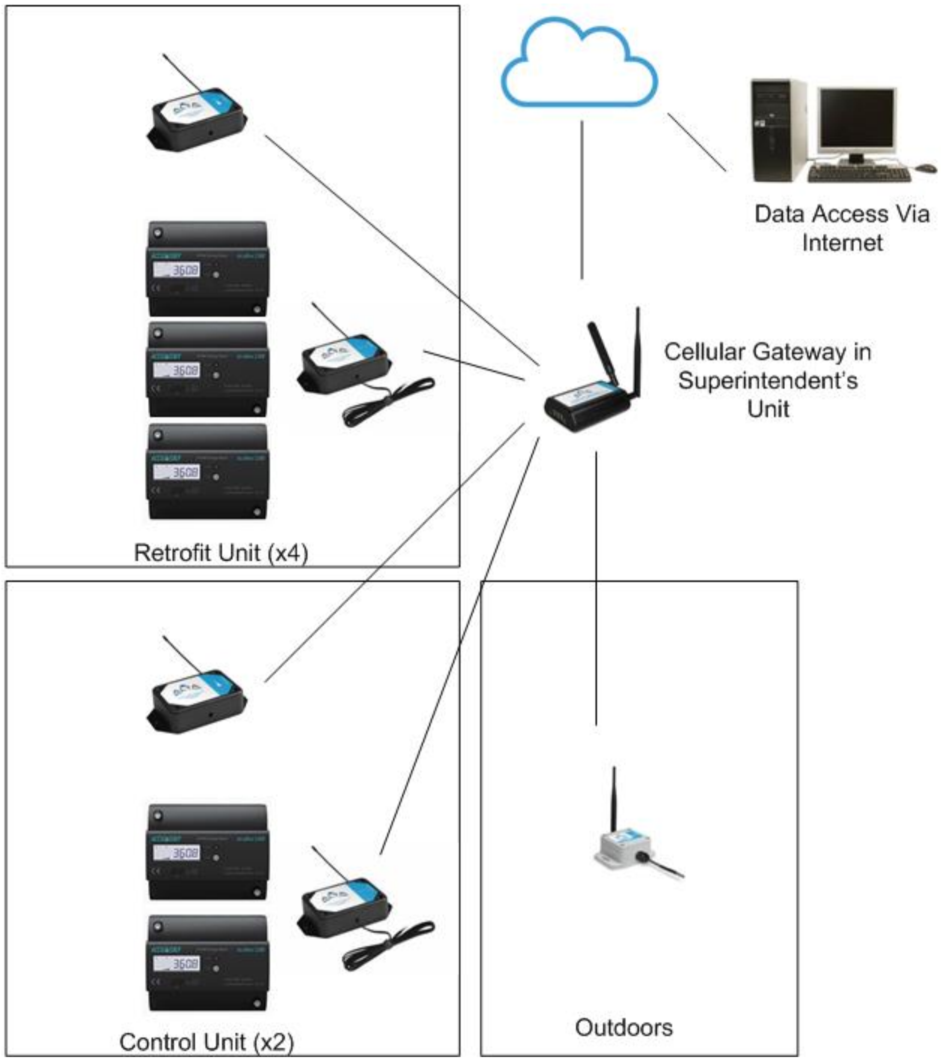

Figure 5-5. Schematic of monitoring package used for the complex.

Sensors readings were verified prior to field deployment. However, the analysis hinged heavily on the whole-house energy meters and additional data integrity checks were warranted. At various points throughout the monitoring period, the energy measurements from the whole-house energy meters were compared against manual readings from the utility meter for the rowhouse units. Table 5-2 compares the energy monitoring results from this study against the utility meter near the beginning and end of the study. It shows good agreement between the energy monitoring data and the utility meter readings.

Table 5-2. Data integrity check on whole-house energy meters.

	Utility Meter Reading 1		Utility Meter Reading 2				
Unit	**Date and Time**	**Reading**	**Date and Time**	**Reading**	**Utility Meter Energy (kWh)**	**Submeter Energy (kWh)**	**% Difference**
1	12/13/2017 3:28 pm	117760	3/2/2018 4:00 pm	125116	7356	7207	2.0
2	12/13/2017 9:12 am	125743	5/30/2018 10:31 am	134440	8697	8556	1.7
3	12/13/2017 9:22 am	98374	5/30/2018 10:28 am	104546	6172	6033	2.3
4	12/13/2017 9:10 am	109645	5/30/2018 10:25 am	119359	9714	9513	2.1
5	12/13/2017 3:33 pm	51255	5/30/2018 10:30 am	55227	3972	3947	0.6
6	12/20/2017 12:47 pm	132819	5/30/2018 10:30 am	141587	8768	8755	0.2

6.0 INTERVIEWS

Tenant interviews were performed in November, March and June. This was done in partnership with the TRCA's Sustainable Neighbourhood Retrofit Action Plan (SNAP) team. SNAP was the main point of contact for the tenants throughout the monitoring period. The purpose of the interviews was to collect information about tenant experience with the heat pumps and also about their energy behaviours, such that the baseline and heat pump monitoring periods could be fairly compared. Interview results ae summarized in Section 15.0 and 16.0 .

7.0 MONITORING PERIODS

Data collection commenced on November 20th 2017 for all units except Unit 1 because it had an issue with the power meter that was not rectified until December 13th 2017. Data collection was completed on August 1st 2018 for all units. Heat pumps operated from November 20th to January 18th in all units. Heat pumps were disabled for all units at the breaker panel on January 19th 2018 with the aim of collecting baseline energy consumption data for the electric baseboards. Heat pumps were turned back on in Unit 1 on February 7th, 2018. They were turned back on February 11th in Unit 2. Heat pumps were turned back on March 2nd 2018 in Unit 3 and Unit 4. Once turned back on, heat pumps were then left on for the remainder of the monitoring period. Within this report, the *retrofit monitoring period* describes the period of time in which the heat pumps were on and *baseline monitoring period* describes when they were turned off and the electric baseboards were used. Retrofit and baseline monitoring periods are illustrated in Figure 7-1.

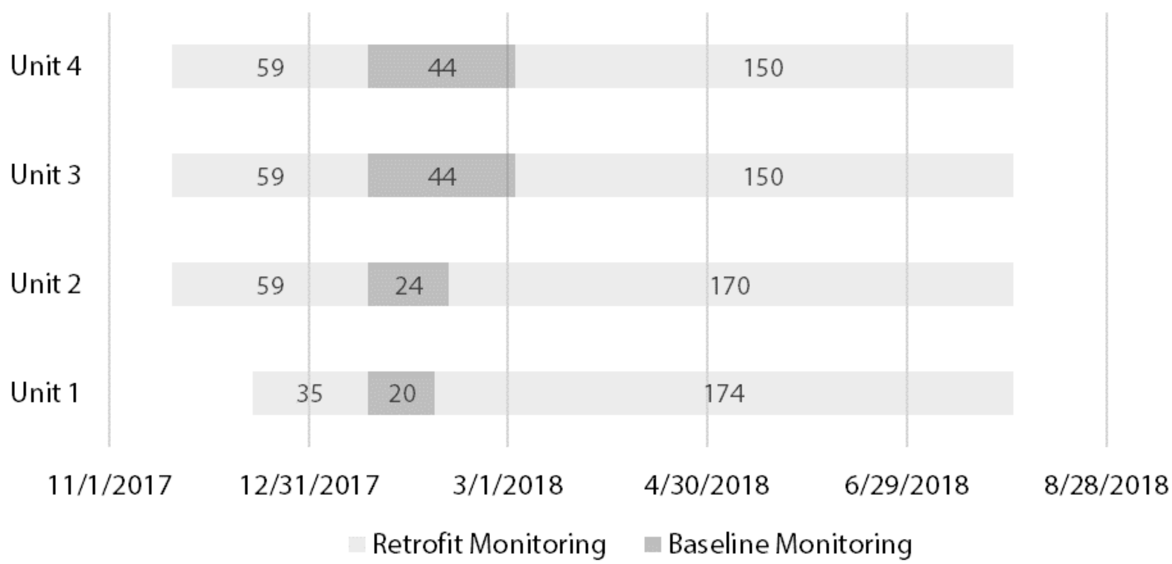

Figure 7-1. Baseline monitoring was achieved by disabling the heat pumps for a period of time during the heating season. Data labels indicate the number of days in each time period. Note that baseline data collection according to this approach was only collected for heating mode operation.

The Unit 1 heat pump was turned back on early at the request of the tenant. The Unit 2 heat pump was turned back on early because the initial retrofit monitoring period data was not valid for comparison against the baseline monitoring period due to a significant change in their energy consumption. It was turned back on in an attempt to collect data additional retrofit monitoring period data. However, while energy savings was demonstrated, both Unit 1 and Unit 2 yielded incomplete datasets for an accurate calculation. The analysis instead focused on Unit 3 and 4.

Note that the retrofit and baseline monitoring periods are different lengths and also, that this *did not* bias the calculation of energy savings. Savings was calculated by comparing regression models of energy consumption rather than a direct comparison of actual energy consumption during the monitoring periods. It follows that there were two requirements regarding the length of the monitoring period: (1) that it encompassed a sufficient range of outdoor temperatures to define the model and (2) that there were enough data points to keep uncertainties within acceptable limits. Section 11.0 plots the monitoring data from each monitoring period and presents the calculated energy savings. It demonstrates that both requirements were met because the data from both periods span a range from very cold to mild temperatures, and also that uncertainties of the models are reasonable.

8.0 DATA LOSS AND OMISSIONS

Data was aggregated into daily totals or averages for analysis. For 95% of the days considered within the study, data loss for each sensing point was less than 1%. For the remaining days, data loss was 6% at most. All baseboard data was erroneous for Unit 3 and Unit 4, and Unit 6 did not log any baseboard energy consumption because the occupants used electric space heaters instead of the baseboards (despite the fact that baseboards were functional).

Data from certain time periods from Unit 1 and Unit 2 was omitted from the study. In Unit 1, the tenant turned on an electric baseboard starting Jan 2nd 2018 and left it on until March 24th 2018. It is believed that this was a baseboard heater that was in the basement and not controlled by a thermostat, but rather, by a dial which could be set to high, medium, low, etc. The baseboard load was substantial at 38 kWh/day. It started before the baseline monitoring period and ended after the baseline monitoring period. It affected all the baseline data and much of the heat pump data. There was no straightforward method to correct the data and a direct comparison between baseline and post-retrofit data would be misleading – this large load did not actually *need* to be on constantly to meet the heating requirements of the unit. It was not possible to rectify the issue and the affected data affected was rejected from the study. This left some retrofit monitoring period energy consumption data and no baseline data for Unit 1.

In Unit 2, data taken up until Jan 18th 2018 was rejected from the study. During that time, the tenant had been fostering kittens in a spare room and used the heat pump to keep the room very warm. When the baseboards were used during the baseline data collection, the kittens were no longer there. The tenant turned off the electric baseboard in that room and used a towel to seal the opening at the bottom of the door to save energy. It follows that the energy consumption during the first post-retrofit monitoring period would have been artificially high and it was rejected from the study. In the end, there wasn't sufficient baseline or post-retrofit data to perform the analysis for this unit.

9.0 MAINTENANCE

The heat pump user guides recommend cleaning of the heat pump filters every *two weeks* – which is notably more often than with standard air handler filters. The tenants were provided with a user guide with the cleaning instructions but the research team did not verbally instruct them to clean the filters every two weeks at the beginning of the study.

The team visited the site in June 2018 to document the state of the filters, then clean them and discuss the filter cleaning process with the tenants prior to the cooling season. The team walked through the user guide cleaning instructions with the tenants and showed them a video explaining the process. The tenants also observed while one of the research team members cleaned their filters.

It follows that the tenants had clear guidance and instructions on filter cleaning for the cooling season but not for the heating season. However, only in Unit 2 did clogged filters appear to present an issue. Unit 2 had two occupants that were smokers. They also had pets. Figure 9-1 shows the main floor filter of Unit 2 after it had been operating for roughly 6 months without being cleaned. It was heavily soiled. However, it should be noted that the soiled filters in Unit 2 *did not impact the study* because, as discussed in Section 8.0 , Unit 2 data had to be disregarded anyway and energy savings was not calculated for this unit.

Figure 9-1. The Unit 2 filter was heavily soiled after 6 months of operation without a cleaning. The upper left part of the filter had been cleaned to illustrate what a clean filter ought to look like.

There are concerns regarding uncleaned filters. Firstly, if they are clogged, it restricts the air flowing over the coil and degrades efficiency. Secondly, it could lead to air quality and maintenance issues – especially in the summertime where the fan coils will be moist from condensate. The coils themselves may end up requiring a more in-depth clean that the tenant cannot do themselves.

The state of the filters after 6 months of operation for Unit 3 is shown in Figure 9-2, and for Unit 4, in Figure 9-3. Energy savings calculations were performed for these two units only. A light layer of dust was observed on the filters and it is not believed to have impacted airflow during the heating season. It's also the case that the majority of the cold weather data was taken within two months of the install and the filters would have been even cleaner than what is depicted in the figures.

Figure 9-2. The Unit 3 filters showed a minimal amount of dust after 6 months of operation and this is not believed to have impacted the energy savings calculations for this unit.

It is the opinion of the research team that the manufacturer recommendations around filter cleaning could be improved for the MURB and rowhouse context. Based on the state of the filters within this study, biweekly cleaning is likely to be unnecessarily onerous for some tenants and may make the heat pumps appear to require more maintenance than is necessary.


Figure 9-3. The Unit 4 filters showed a minimal amount of dust after 6 months of operation and this is not believed to have impacted the energy savings calculations for this unit.

10.0 ANALYSIS

10.1 Heating Mode Energy Savings

Energy savings are not directly measurable. They are the difference between the actual post-retrofit energy consumption and the energy consumption that *would have occurred* had the retrofit not taken place. This necessarily means that energy savings are an estimate because the calculation procedure needs to make assumptions about something that did not actually happen. The framework within which these assumptions are made is described in the International Performance Measurement and Verification Protocol (IPMVP).

Since the constraints on different measurement and verification (M & V) initiatives will vary, the IPMVP gives four different options. Different options may be selected depending on the availability and quality of data, the resources available for the evaluation and the energy conservation measure (ECM) being studied. Options include:

- **Option A: Retrofit-isolation: Key Parameter Measurement.** Savings are determined through measurement of a single key-parameter. *Eg. The energy savings of outdoor lighting upgrades could be determined by power measurements of a sample of light fixtures pre- and post-ECM.*
- **Option B: Retrofit-isolation: All Parameter Measurement.** Savings are determined through measurement of multiple parameters. *Eg. The energy savings of a chiller upgrade could be determined using measurements of power consumption, temperature and flow, pre- and post-ECM.*
- **Option C: Whole Facility.** Savings are determined by evaluating the change in energy of the entire building, often using utility bills. *Eg. Option C is well-suited to evaluating ECMs that will save a significant portion of the building's energy consumption*.
- **Option D: Calibrated Simulation.** Savings are determined by generating a calibrated building energy simulation. The simulation is used to compare the ECM(s) against baseline systems. *Eg. Option D is well-suited to applications where baseline data is limited or where the client wants to know the relative impact of different ECMs implemented as part of a multi-faceted energy management program.*

Energy savings were demonstrated for Unit 1 and 2 but there was insufficient data to calculate an accurate value. Heating mode energy savings calculations adherent with IPMVP Option C were only completed for Unit 3 and 4. Within the calculation procedure, experimental data from both the baseline and retrofit monitoring periods was used to generate regression models of the rowhouse units. Slightly different approaches were used for Unit 3 and Unit 4.

The regression models for Unit 3 described the total *daily* energy consumption of the rowhouse units as a function of *daily* average outdoor temperature. Daily aggregation based on average outdoor temperature was performed because it created a simple and intuitive representation of the unit's energy consumption. Daily aggregation worked well in Unit 3 because, on a day-to-day basis, energy consumption did not vary due to factors other than outdoor temperature. In other words, the occupants were relatively consistent with how they used energy. However, this was not the case with Unit 4.

In Unit 4, it was not possible to generate regression models that accurately represented the *daily* energy consumption. Unit 4 had two working adults and a child and there were clear differences between weekend (when occupancy would be higher) and weekday (when occupancy would be lower) energy consumption. Improved regression models were achieved when Unit 4 was instead analyzed using weekly aggregation, with heating degree days as the independent variable. The main impact of weekly aggregation was a higher uncertainty in the energy savings estimate.

10.1.1 Unit 3: Daily Aggregation

Regression models were created for both the baseline and the retrofit monitoring periods. The models represented the total energy consumption for the unit as a function of the daily average outdoor temperature. Models were applied to a typical meteorological year (TMY) from Toronto[4]. Toronto TMY data was selected to generate results that were more widely applicable - although the results would not be notably different from those obtain using TMY data for Brantford. Normalized energy savings was calculated as the difference between the total energy consumption of Unit 3 for the Toronto TMY when using the baseline monitoring period regression model and that when using the retrofit monitoring period regression model. Important considerations for the IPMVP-adherent normalized energy savings calculations are presented in Appendix A. Parameters used in the normalized energy savings calculations are presented in Table 10-1. Note that it may also be helpful to move ahead and refer to Figure 11-1 for a clearer idea of the data and regression modelling in this context.

[4] Regression models were evaluated using typical meteorological (TMY) climate data from the Canadian Weather Year for Energy Calculations (CWEC) database for Toronto. The specific data file was: CAN_ON_TORONTO-CITY-CENTRE_6158359_CWEC.epw

Table 10-1. Parameters for IPMVP-adherent normalized energy savings calculation for Unit 3.

Parameter	Unit	Symbol	Description
Total whole-house energy consumption for a heating season when using electric baseboards	kWh	$B_{Unit\ 3,tot}$	This is the total energy consumption of Unit 3 for a Toronto TMY heating season if it uses electric baseboards as the heating source.
Baseline monitoring period whole-house energy consumption model	kWh/day	$B_{Unit\ 3}(T_k)$	This function defines the baseline energy consumption of Unit 3 as a function of the average daily outdoor temperature. It is derived from regression analysis of the whole-building submeter data collected during the *baseline* monitoring period.
Heating mode balance point of the house	˚C	T_{bh}	This is the temperature beyond which active heating is not required to meet the indoor temperature set-points. It was evaluated empirically in this study as the lowest daily average outdoor temperature at which the heat pump energy consumption goes to zero. For Unit 3 it was 16ºC.
Lowest daily average temperature of the heating season	˚C	T_l	This temperature depends on the weather data used. It sets the lower bound of the summations used below. For the Toronto TMY weather data it is -16ºC.
Outdoor temperature	˚C	T_k	The Toronto TMY weather data was used to generate a frequency histogram. The histogram described the number of days occurring within given 1ºC-wide temperature bins during the heating season. "T_k" is the daily average outdoor temperature associate with a given bin. For example, $T_{2.5}$ is 2.5 ºC and it is used to define a bin that spans from 2 to 3 ºC. The subscript is required because bins are discrete rather than continuous.
Number of days	days	n_k	This is the number of days during a Toronto TMY heating season, that occur within a 1 ºC wide temperature defined by the subscript "k." For example, $n_{2.5}$ is the number of days during a Toronto TMY heating season where the daily average outdoor temperature fell between 2 to 3 ºC.

Total whole-house energy consumption for a retrofitted unit during the heating season	kWh	$R_{Unit\ 3,tot}$	This is the total energy consumption of Unit 3 for the Toronto TMY heating season once it has been retrofitted with a heat pump.
Retrofit monitoring period energy consumption model	kWh/day	$R_{Unit\ 3}(T_k)$	This function defines the retrofit monitoring period energy model that is derived from regression analysis of the submeter data collected during the retrofit monitoring period.
Total normalized energy savings	kWh	$S_{Unit\ 3,tot}$	This is the difference between the modelled energy consumption for both the baseline and reporting periods.

Total baseline period energy consumption was calculated by applying the regression model, determined during the baseline monitoring period, to the Toronto TMY heating season (Equation 1). This equation multiplies the kWh per day energy consumption associated with a given outdoor temperature by the number of days that occur for that outdoor temperature. It then sums the results across all outdoor temperatures to determine the total energy consumption.

$$B_{Unit\ 3,tot} = \sum_{k=T_l}^{T_{bh}} B(T_k) \cdot n_k \qquad \text{Equation 1}$$

Total reporting period[5] energy consumption is calculated by applying the linear regression model, determined during the retrofit monitoring period, to the Toronto TMY heating season (Equation 2).

$$R_{Unit\ 3,tot} = \sum_{k=T_l}^{T_{bh}} R(T_k) \cdot n_k \qquad \text{Equation 2}$$

Total normalized energy savings is the difference between the total reporting period energy consumption and total baseline energy consumption (Equation 3).

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[5] "Reporting period" is term used in the IPMVP that describes the span of time over which the post-retrofit energy consumption is determined. In this study, the baseline and post-retrofit models were analyzed for a Toronto TMY. The Toronto TMY would then be both the reporting period and the baseline period according to IPMVP terminology.

$$S_{Unit\ 3,tot} = B_{Unit\ 3,tot} - R_{Unit\ 3,tot}$$ Equation 3

For the sake of clarity, a sample calculation is provided in Appendix B.

10.1.2 Unit 4: Weekly Aggregation

Unit 4 energy consumption data was aggregated into weekly totals using heating degree days. Weekly total heating degree days were determined by summing hourly degree days. Hourly degree days were calculated as the difference between the building balance point (determined from the heat pump consumption data) and the average outdoor temperature for a given hour as measured on-site.

Heating degree days for the Toronto TMY were calculated on an hourly basis and then aggregated into weekly sums. Normalized energy savings were obtained by applying the regression models, expressing total weekly energy consumption as a function of total weekly heating degree days, to the weekly aggregated Toronto TMY weather data.

Table 10-2. Parameters for IPMVP-adherent normalized energy savings calculation for Unit 4.

Parameter	Unit	Symbol	Description
Total whole-house energy consumption for a heating season when using electric baseboards	kWh	$B_{Unit\ 4,tot}$	This is the total energy consumption of Unit 4 during a Toronto TMY heating season when using electric baseboards.
Baseline monitoring period whole-rowhouse energy consumption model	kWh /week	$B_{Unit\ 4}(\mathrm{HDD}_i)$	This function defines the weekly total baseline energy consumption as a function of the weekly total heating degree days. It is derived from regression analysis of the whole-building submeter data collected during the *baseline* monitoring period.
Weekly total heating degree days	˚C-day	HDD_i	This is the heating degree days of the i^{th} week within the Toronto TMY weather data.
Total whole-house energy consumption for a retrofitted unit during the heating season	kWh	$R_{Unit\ 4,tot}$	This is the total energy consumption for Unit 4 with the heat pump retrofit during a Toronto TMY heating season.

Retrofit monitoring period whole-house energy consumption model	kWh /week	$R_{Unit\ 4}(\mathrm{HDD}_i)$	This function defines weekly whole-house total energy consumption for the retrofit monitoring period as a function of the weekly total heating degree days. It is derived from regression analysis of the whole-building submeter data collected during the retrofit monitoring period.
Total normalized energy savings	kWh	$S_{Unit\ 4,tot}$	This is the difference between the modelled energy consumption for both the baseline and reporting periods.

The total whole-house baseline energy consumption for a Toronto TMY was evaluated on a weekly basis for the heating season. This is shown in Equation 4. The heating season comprised all weeks where the total heating degree days were greater than zero.

$$B_{Unit\ 4,tot} = \sum_{i=1}^{52} \begin{Bmatrix} B_{Unit\ 4}(\mathrm{HDD}_i); for\ HDD_i > 0 \\ 0;\ for\ HDD_i = 0 \end{Bmatrix} \qquad \text{Equation 4}$$

The total whole-house post-retrofit energy consumption for a Toronto TMY was evaluated on a weekly basis and then summed for all weeks in the year. This is shown in Equation 5.

$$R_{Unit\ 4,tot} = \sum_{i=1}^{52} \begin{Bmatrix} R_{Unit\ 4}(\mathrm{HDD}_i); for\ HDD_i > 0 \\ 0;\ for\ HDD_i = 0 \end{Bmatrix} \qquad \text{Equation 5}$$

Savings is the difference between the baseline whole-house energy consumption and the retrofit whole-house energy consumption.

$$S_{Unit\ 4,tot} = B_{Unit\ 4,tot} - R_{Unit\ 4,tot} \qquad \text{Equation 6}$$

10.2 Cooling Mode Energy Savings

In *heating* mode, energy savings were calculated by comparing the whole-house energy consumption using the heat pump against the whole-house energy consumption using the electric baseboards. This was a simple procedure because it was possible to revert back to the pre-existing baseboard system in each unit by disabling the heat pump at the breaker panel. It was much less straightforward to revert to a baseline *cooling* system. It follows that, in cooling mode, the heat pumps were left to operate and were not disabled at any point.

Estimations of cooling mode energy savings are complicated by the uncertainty surrounding what the heat pump is replacing. Firstly, there is the variation in the efficiency of different window-based air-conditioning systems and there is also variation in the quality of the installation of those systems. Secondly, there is the wide range of tenant behaviours and preferences.

To simplify the cooling analysis, and to create more generalized results, this study considered the three scenarios outlined in Table 10-3. The scenarios assume that the heat pump will either (i) not be used in cooling mode, (ii) replace inefficient window shakers (reducing energy consumption compared to a base case) or (iii) introduce cooling where there was none prior (increasing cooling season energy consumption compared to a base case).

Table 10-3. Scenarios for estimating impact of heat pump cooling on energy consumption.

	Scenario	Effect on Overall Savings Calculations
1	The tenant does not use the heat pump, or any air conditioner, to provide air conditioning.	The total energy savings benefit of the heat pump is determined entirely by heating mode savings.
2	The heat pump retrofit replaces inefficient window shaker air conditioners.	There are cooling mode energy savings in addition to the heating mode energy savings.
3	The heat pump retrofit introduces cooling where there was no prior cooling.	The heat pump represents an additional electrical load in cooling mode and this lowers overall energy savings but improves comfort.

To estimate the cooling mode energy savings or increases, the cooling energy consumption of a control unit (Unit 6) and a retrofitted unit (Unit 1) were compared. Unit 6 was selected because it was the only control unit that used air-conditioning. Unit 1 was selected because it was the closest comparable unit to Unit 6. They are both 3-bedroom units, however, Unit 1 is an end unit and, based on the indoor temperatures, appeared to be using more cooling than Unit 6. It follows that the calculations are likely conservative estimates.

The energy consumption of the Unit 1 heat pump was directly measured and the cooling energy consumption of Unit 6 was determined from the temperature-dependent portion of its total energy consumption. Linear regression models were created for both curves. A savings curve was calculated as the difference between the two cooling energy consumption curves. It expressed the kWh/day savings as a function of the daily average outdoor temperature.

To determine the *total energy savings* for a typical year for Scenario 2, the energy savings curve was applied to the Toronto TMY weather data. To determine the *total additional consumption* for a typical year in Scenario 3, the heat pump energy consumption curve was applied to the Toronto TMY weather data. Note that this approach formulated best estimates based on the available data within the study, and is not be fully representative of all possible cases. Humidity was not taken into account because this is a high-level comparison. Also note that this approach *was not IPMVP-adherent* because the baseline data was not taken in the same rowhouse unit as post-retrofit data.

Table 10-4. Parameters used to estimate cooling energy savings associated with the heat pump.

Parameter	Unit	Symbol	Description
Total cooling mode savings	kWh	$S_{cool,tot}$	This is the estimated savings associated with the heat pump during a Toronto TMY cooling season when it is replacing window shaker air-conditioners. It was determined by evaluating the difference in the cooling energy consumption of retrofitted Unit 1 and control Unit 6.
Cooling mode energy savings model	kWh/day	$S_{cool}(T_k)$	This function models kWh/day savings as a function of the average daily outdoor temperature. It was determined by evaluating the difference in the cooling energy consumption of Unit 1 and Unit 6.
Cooling mode balance point of the house	˚C	T_{bc}	This is the temperature at which active cooling is required to maintain indoor set-points. It was empirically determined in this study as the temperature at which the heat pump turns on in cooling mode.
Highest daily average outdoor temperature in heating season	˚C	T_h	This is the highest average daily outdoor temperature that occurs in the weather data used to calculate savings. It is the upper limit of the summation calculations used to determine cooling mode energy savings.
Daily average outdoor temperature	˚C	T_k	See Table 10-1.
Number of days	days	n_k	See Table 10-1.
Heat pump energy consumption	kWh	$H_{cool,tot}$	This is the total heat pump energy consumption during the cooling season.
Heat pump energy consumption model	kWh/day	$H_{cool}(T_k)$	This function describes the kWh/day energy consumption of the heat pump as a function of the daily average outdoor temperature. It is based on data collected from Unit 1.

The total cooling energy savings was determined by multiplying the kWh/day energy savings for a given average outdoor temperature with the number of days occurring at that temperature during a Toronto TMY. This is shown in Equation 7.

$$S_{cool,tot} = \sum_{k=T_{bc}}^{T_h} S_{cool}(T_k) \cdot n_k \qquad \text{Equation 7}$$

The heat pump energy consumption was determined by multiplying the kWh/day energy consumption for a given outdoor temperature with the number of days occurring at that temperature during a Toronto TMY. This is shown in Equation 8.

$$H_{cool,tot} = \sum_{k=T_{bc}}^{T_h} H_{cool}(T_k) \cdot n_k \qquad \text{Equation 8}$$

11.0 ENERGY SAVINGS

11.1 Heating Mode

11.1.3 Unit 3

Total whole-building energy consumption data for Unit 3 during both the baseline and the retrofit monitoring periods is plotted in Figure 11-1 alongside regression model curves. The energy savings curve is the difference between the baseline and retrofit regression models. Figure 11-1 demonstrates that the heat pump is no longer needed for heating, and the energy savings is zero, when the average daily outdoor temperature surpasses 16 ˚C. This is the building balance point. Note that the average indoor temperatures during the baseline and retrofit monitoring periods are approximately comparable. During the baseline monitoring period, it was 21.5 ˚C, and during the retrofit monitoring period, it was 21.9 ˚C. The regression models are explicitly defined in Table 11-1. More detailed regression statistics and uncertainty calculations are shown in Appendix C.

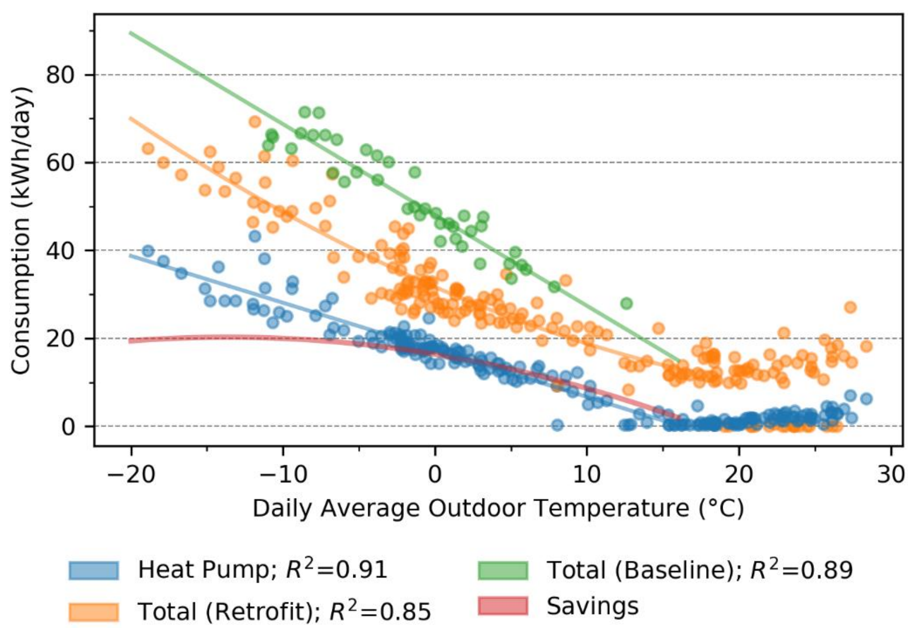

Figure 11-1. A comparison of the regression models of baseline and post-retrofit energy consumption shows that the heat pump saves a notable amount of energy when compared with the electric baseboards.

The regression models were used alongside Toronto TMY weather data to determine the overall energy consumption for the baseline and post-retrofit case, as well as the savings. This is summarized in Table 11-2. B_{tot}, R_{tot}, S_{tot} and H_{tot}, are the total baseline energy consumption, post-retrofit energy consumption, energy savings, and heat pump energy consumption, for a Toronto TMY heating season. For this unit, the heating season encompasses those days where the average outdoor temperature is less than or equal to 16 °C. Uncertainties are reported for a 95% confidence interval.

Table 11-1. Regression models for Unit 3.

Description	Equation	R^2	Range
Baseline monitoring period whole-house energy consumption (kWh/day)	$B_{Unit\ 3}(T_o) = -2.065 \cdot T_o + 48.04$	0.89	$-18 \le T_o \le 16.0$
Retrofit monitoring period whole-house energy consumption (kWh/day)	$R_{Unit\ 3}(T_o) = 0.02082 \cdot T_o{}^2 - 1.497 \cdot T_o + 31.67$	0.85	$-18 \le T_o \le 16.0$
Heat Pump energy consumption (kWh/day)	$H_{Unit\ 3}(T_o) = -0.0001926 \cdot T_o{}^2 - 1.071 \cdot T_o + 17.40$	0.91	$-18 \le T_o \le 16.0$

Table 11-2. Energy consumption and savings of Unit 3 for a Toronto TMY heating season.

B_{tot}	R_{tot}	S_{tot}	H_{tot}
kWh/year	*kWh/year*	*kWh/year*	*kWh/year*
10,002 ± 127	6,775 ± 153	3,228 ± 197	3,282 ± 83

11.1.4 Unit 4

Daily aggregated total energy consumption for Unit 4 during both the baseline and the retrofit period showed a high degree of scatter. This was related to how the occupants consume energy for the other large loads in the house, and how that varies with the schedules of the occupants on a daily basis. To developed improved models, energy consumption data was instead aggregated on a weekly basis according to heating degree days. This is shown in Figure 11-2. Note that the average indoor temperature during the baseline monitoring period was 23.2 °C and during the retrofit monitoring period, it was 22.2 °C. Also note that the measurements indicated the heat pump is no longer needed for heating when the average daily outdoor temperature surpassed 11 °C. This is a relatively low value and it is due to high internal heat gains within the rowhouse unit.

The regression models are shown in Table 11-3. They were used alongside Toronto TMY weather data to determine the overall energy consumption for the baseline and post-retrofit case, as well as the savings, during a typical heating season. This is summarized in Table 11-4. For this unit, note that the heating season encompasses those weeks where the total heating degree days (based on an 11 °C building balance point) are greater than zero. Uncertainties are reported for a 95% confidence interval.

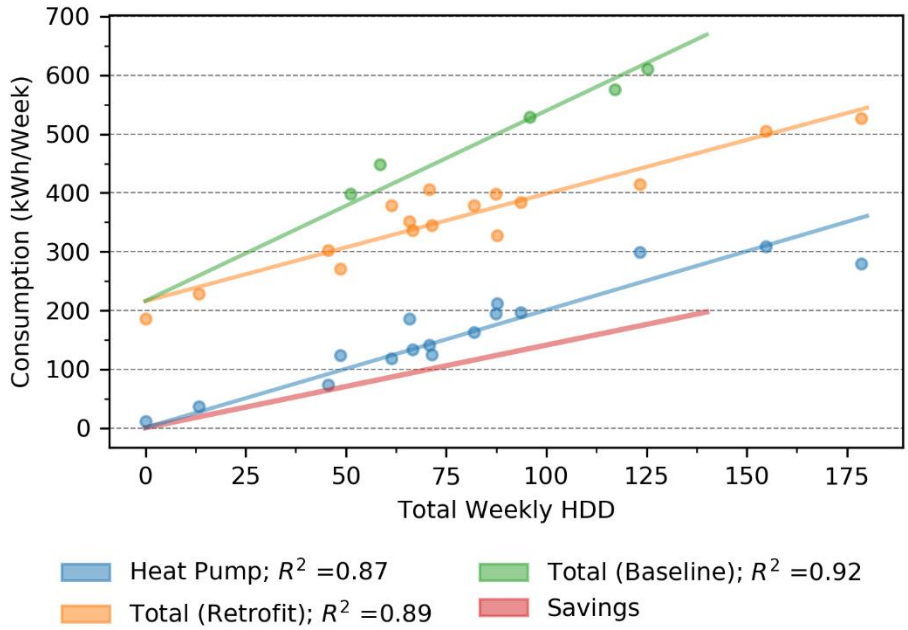

Figure 11-2. Linear regression models are shown where each data point represents one week of data. Linear regression models used weekly aggregated data because tenant behaviour is more constant on a week-to-week basis rather than a day-to-day basis.

Table 11-3. Linear regression models for Unit 4.

Description	Equation	R^2	Range
Baseline monitoring period weekly energy consumption (kWh/week)	$B_{Unit\ 4}(HDD) = 3.235 \cdot HDD + 216.3$	0.92	HDD > 0
Retrofit monitoring period weekly energy consumption (kWh/week)	$R_{Unit\ 4}(HDD) = 1.827 \cdot HDD + 215.9$	0.89	HDD > 0
Heat pump energy consumption (kWh/week)	$H_{Unit\ 4}(HDD) = 2.007 \cdot HDD$	0.87	HDD > 0

Table 11-4. Energy consumption and savings of Unit 4 for a Toronto TMY heating season.

B_{tot}	R_{tot}	S_{tot}	H_{tot}
kWh/year	*kWh/year*	*kWh/year*	*kWh/year*
14,085 ± 570	11,424 ± 392	2,661 ± 815	3,777 ± 427

11.1.5 Heating Mode Summary

Figure 11-3 shows the results from both units. The magnitudes of the energy savings are near each other. However, as a fraction of the total consumption, the relative energy savings in Unit 3 is much higher than that in Unit 4. This is because Unit 4 has a higher baseload. Figure 11-1 shows that when there is no heating or cooling load, the energy consumption of Unit 3 is on the scale of 10 kWh/day. Figure 11-2 demonstrates the weekly energy consumption in Unit 4 is 216 kWh/week, or 31 kWh/day, when there are no heating degree-days.

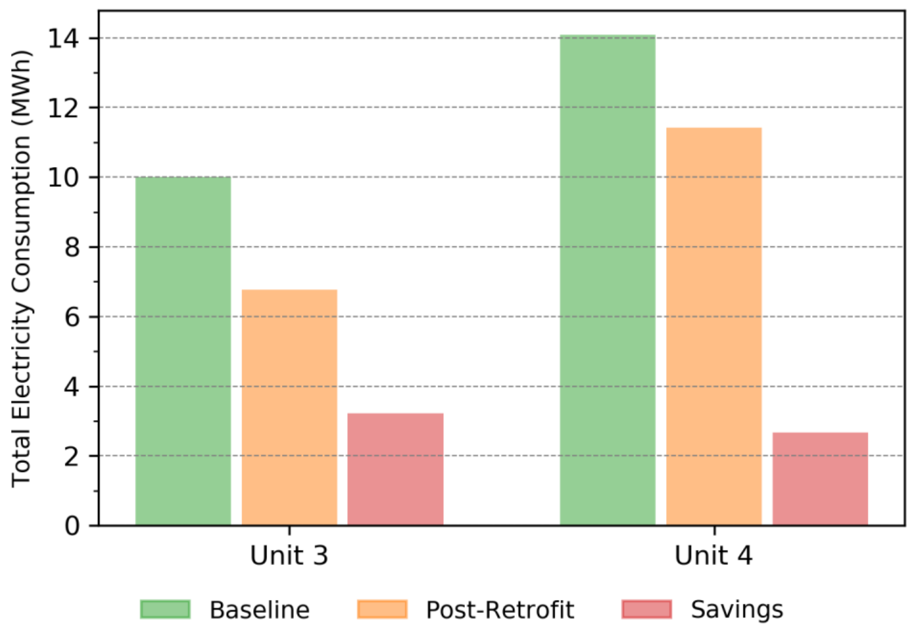

Figure 11-3. Regression models of building energy consumption were used to estimate energy consumption and savings for a typical *heating season*. Unit 3 was estimated to save 3.228 MWh/year (32%) during a heating season as a result of the heat pump retrofit and Unit 4 was estimated to save 2.661 MWh/year (19%).

It follows that the baseload in Unit 4 is about three times greater than that in Unit 3. This baseload was a source of internal gain and it explains why the building balance point temperature in Unit 4 was lower than that in Unit 3 (11 °C vs. 16 °C); i.e the higher internal heat gains in Unit 4 are sufficient to maintain it's internal set-point temperature at colder outdoor temperatures. The lower balance point reduced the opportunity for energy savings in Unit 4 because less heating was required from the heat pump and the heat pump operated less under warm outdoor conditions when its efficiency is highest.

It's clear from the difference in balance point temperature that the differences in energy savings between Unit 3 and Unit 4 should not be attributed to one heat pump being "better" than the other. There are a number of factors affecting energy consumption and savings, and these factors have not been controlled within this study. Other factors are listed in Section 13.0

11.2 Cooling Mode

The energy consumption of the Unit 1 heat pump was directly measured and the cooling energy consumption of Unit 6 was determined from the temperature-dependent portion of its total energy consumption (i.e. a constant baseload was removed). Figure 11-4 shows a comparison between the units. In each case, data points span the same period of time. During June and July, Unit 1 had an average indoor temperature of 21.5 °C and Unit 6, 22.6 °C. Furthermore, Unit 1 was an end unit while unit 6 was a middle unit, resulting in a larger cooling load for Unit 1 with all other factors being equal. It is very likely that the Unit 1 heat pump was actually providing more cooling than the Unit 6 window shakers. Furthermore, the heat pump was able to do this while consuming much less energy.

Note that energy consumption is plotted as a function of the daily *average* outdoor temperature. It follows that the daytime highs and overnight lows are averaged into a single number. This is why cooling energy consumption begins past a daily average outdoor temperature of 18˚C which might otherwise be thought of as a low temperature to require cooling.

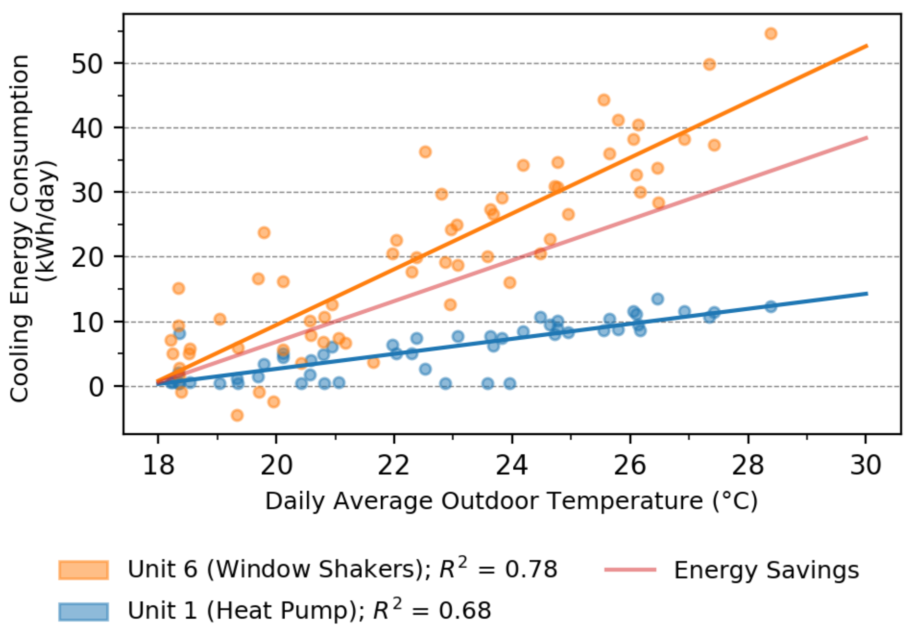

Figure 11-4. For roughly comparable rowhouse units, the window shaker air conditioners consume much more energy than the heat pump system.

Energy savings and consumption were determined by applying the curves in Figure 11-4 to the Toronto TMY weather data. Results are shown in Table 11-5. An uncertainty analysis was not conducted on these results because, in this case, the baseline and retrofit data are from different units and the analysis is intended to be a higher level comparison. Note that these are best estimates based on the available data within the study, and are not fully representative of all possible cases. In general, the data suggests that a heat pump system is much more energy efficient than window shaker air-conditioners. It also suggests that even if a heat pump retrofit adds cooling to a unit without prior cooling, the increase in energy consumption is relatively small even if it is very heavily used as was the case in Unit 1.

Table 11-5. Scenarios for estimating impact of heat pump cooling on energy consumption.

	Scenario	Effect on Overall Savings Calculations	Estimated Overall Savings for Unit 3	Estimated Overall Savings for Unit 4
1	The tenant does not use the heat pump, or any air conditioner, to provide air conditioning.	No change	3,228 kWh/year	2,661 kWh/year
2	The heat pump retrofit replaces inefficient window shaker air conditioners.	Saves an additional 1,148 kWh/year	4,376 kWh/year	3,809 kWh/year
3	The heat pump retrofit introduces cooling where there was no prior cooling.	Adds a load of 316 kWh/year	2,912 kWh/year	2,345 kWh/year

12.0 COST SAVINGS

12.1 Savings

Electricity costs were estimated from the 2017 Long-term Energy Plan (LTEP) forecasted average monthly electricity bill from 2017 to 2032. For simplicity, future cash flows were not discounted. The estimated per unit electricity cost was 0.212 $/kWh.

The annual total energy savings of Unit 3 and Unit 4 are summarized in Table 12-1. The table also assumes a cooling mode energy savings. Values are likely higher than the actual Unit 3 or 4 cooling energy savings because these two units used their heat pump relatively sparingly during the summer; however, it is included to generalize the results.

Table 12-1. Summary of total energy and cost savings using Toronto TMY weather data.

	Heating energy savings (kWh/year)	Cooling energy savings (kWh/year)	Total energy savings (kWh/year)	Cost savings heating ($/year)	Cost savings cooling ($/year)	Cost savings total ($/year)	Total 15-yr cost savings ($)
Unit 3	3,228	1,148	4,376	684	243	928	13,916
Unit 4	2,661	1,148	3,809	564	243	808	12,113
Average	**2,945**	**1,148**	**4,093**	**624**	**243**	**868**	**13,014**

In the context of a warming climate, it is also useful to evaluate energy savings using recent weather data. Table 12-2 shows results on an annual basis for Unit 3 using actual weather data from 2013 to 2017 for Toronto.[6] On average, the results are equal to those obtained using the TMY weather data.

Table 12-2. Energy and cost savings results for Unit 3 using actual weather data from 2013 to 2017.

Weather Data Year	Heating energy savings (kWh/year)	Cooling energy savings (kWh/year)	Total energy savings (kWh/year)	Cost savings ($/year)
2013	3,181	1,203	4,384	929
2014	3,294	949	4,243	900
2015	3,056	1,195	4,251	901
2016	2,975	1,886	4,861	1,031
2017	3,005	1,159	4,164	883
Average	**3,102**	**1,278**	**4,381**	**929**

This study has estimated the normalized cost savings in heating and cooling mode but did not evaluate the full business case because there are also a number of non-energy benefits that are

[6] Data is from climate.gc.ca for "Toronto City".

difficult to quantify. These should also be considered in a business case assessment where applicable. Non-energy benefits may include:

- increases in property values;
- marketability of the units;
- tenant retention;
- tenant satisfaction;
- tenant comfort; and,
- improved health and safety (i.e. risks of heat exhaustion in summer).

12.2 Installed Costs

Estimated installed system costs, prepared by Cricket Energy, are shown in Table 12-3. Costs are shown including a 5-year warranty. Single-port (i.e. mini-split) heat pump installed costs are shown as well for comparison. Actual installed costs will vary. Note that Table 12-3 includes equipment and installation costs but neglects certain soft costs like distributor mark up or sales commissions, which may push total installed cost towards $14,000 retail for the 3- and 4-port multi-split heat pumps. However, costs are expected to come down as uptake increases, and for applications where equipment can be installed and purchased in bulk. Table 12-3 also neglects incentives. Potential system owners are encouraged to consider the impact of incentives (for example, Save On Energy in Ontario) for their application and context.

Table 12-3. Estimated installed system costs.

System	Suite	Equipment Cost	Installed Cost
2-ton 1-port cold-climate	N/A	-	$4,400
2-ton 3-port cold-climate	Unit 3	$4,800 to $5,600	$9,800 to $10,600
3-ton 4-port conventional	Unit 4	$4,500 to $5,200	$10,00 to 10,700

Estimated rental amounts were prepared by Cricket Energy using their standard business practices and include two scenarios and three terms. In Scenario 1 (Table 12-4) only the capital equipment is financed and the property manager/owner would be responsible for contracting for the installation, while in Scenario 2 (Table 12-5) the total installed cost is financed and the project is managed by Cricket Energy. In both scenarios, Cricket Energy would be responsible for all warranty service for the term of the agreement.

Table 12-4. Monthly costs for Scenario 1: Equipment Cost Only.

System	Suite	5 yr Term Rental ($/mo.)	10 yr Term Rental ($/mo.)	15 yr Term Rental ($/mo.)
2-ton 3-port cold-climate	Unit 3	114.99	84.99	71.49
3-ton 4-port conventional	Unit 4	104.99	76.49	66.49

Table 12-5. Monthly costs for Scenario 2: Total Installed Cost.

System	Suite	5 yr Term Rental ($/mo.)	10 yr Term Rental ($/mo.)	15 yr Term Rental ($/mo.)
2-ton 3-port cold-climate	Unit 3	207.98	148.98	121.48
3-ton 4-port conventional	Unit 4	206.98	146.48	121.48

12.3 Cost-effective Retrofits

A business case assessment for multi-split ASHP retrofits needs to consider both heating and cooling mode operation, as well as non-energy benefits and any applicable incentives. In cases where the only factor considered is the energy savings, it estimated that the ductless multi-split system may pay back within its estimated lifetime of 15 years without incentives – although it does depend somewhat on the behaviour and preferences of the occupants.

In the MURB and rowhouse sector, and especially in a low-income context, a lower installed cost system may be key. A ductless *mini-split* heat pump (with a single port) installed in the main living space may strike a more economical balance between energy savings, cost savings and installed costs. In this scenario, electric baseboards may be left in place for other areas of the home. A ductless mini-split would provide lower normalized cost savings overall, and would not provide comparable thermal comfort to the multi-split, but it would have much lower installed costs and likely a quicker payback.

The cost premium paid for a *cold-climate* version of the mini-split heat pump is small (this is not the case for the multi-splits) and the research team suggests that using the cold-climate variation of a mini-split would simplify the controls interaction with the living room baseboard in that it could simply be turned off rather than stay in place as back-up. This would also ensure that tenants do not inadvertently use their living room electric baseboard.

For larger MURBs, variable refrigerant flow (VRF) ASHP systems may also help to bring the per-unit installed costs down because the system has centralized primary heat pump components. While initiatives like TowerWise in Toronto are exploring energy retrofits in the high-rise MURB sector, MURBs that are 3-stories and under may be understudied in Ontario. Both building types may be ideal candidates for VRF ASHPs.

13.0 REAL-WORLD CONSIDERATIONS

There are numerous differences between the testing completed in this work and the standards to which heat pump capacities and efficiencies are rated.[7] This is a very important distinction. To be clear, this study *did not* attempt to replicate the methodologies or measurements of standardized testing. It would not have been feasible given that the units are occupied by actual tenants and the testing environment is not a carefully controlled laboratory. Rather, within this study, heat pumps were installed in actual housing units, with actual tenants and the actual energy savings was determined (as well as the corresponding uncertainties) according to the widely-accepted IPMVP framework for energy conservation measures.

A key strength of standardized laboratory testing procedures is that they produce a performance rating that is replicable across different laboratories such that the ratings of one heat pump model can be fairly compared against those of another. This study does not intend in any way to cast doubt on the validity or accuracy of standardized COP, HSPF, EER, SEER or capacity ratings.

However, there is no standardized rating that predicts the annual energy savings when a heat pump is installed in a specific building and energy savings is a key piece of information that a prospective system owner wants to know. It could be estimated based on the expected efficiency values from the standardized ratings but without actually measuring whether or not those energy savings were achieved, the quality of the estimates will be uncertain. This why it is important to directly calculate energy savings based on energy measurements in units that have been retrofitted and ideally, data for many units would be available to build further confidence in the results.

The researchers acknowledge that the energy savings measurements in this study are dependent on the behaviours and preferences of the study tenants themselves as well as other installations-specific details. This is both a strength and a drawback. The drawback is that different units will have different tenants and energy savings will therefore not be perfectly replicable between different units. The strength is that the calculated energy savings is much closer to a measurement than it is to an estimate in that calculations are based on an accepted framework that uses actual energy measurements in specific real-world units.

It follows that the results of this study should be understood as a case study. The calculated energy savings apply to the specific study units only. Without a much larger sample size, extrapolation of energy savings to other units would be based on speculation. Other units may have greater or lower savings if they undertake a heat pump retrofit, depending on the occupants and other installation-specific details.

[7] Relevant standards include CAN/CSA-C656-05, AHRI 210/240 and AHRI 1230. Note that AHRI 210/240 covers mini-split systems (single-port) and AHRI 1230 covers multi-split systems.

This section of the report summarizes some of the important details regarding the specific study units and how they may have deviated from some of the assumptions within standardized testing. The authors speculate that these deviations resulted in lower energy savings for the units considered in this study when compared to what might have been estimated based on rated heat pump efficiencies.[8] However, the test setup was not designed to quantify the impact of each of these considerations and their potential impact on performance is only discussed at a high level.

13.1 Refrigerant Lines Run On Exterior Walls

A major advantage of multi-split ductless air-source heat pumps is that the retrofit is minimally invasive. This is in part because the refrigerant lines can be run on the exterior of the building. However, this introduces parasitic heat losses, even when refrigerant lines were insulated and installed behind a casing. Refrigerant lines were also run behind the outdoor unit to improve the appearance of the retrofit. This would also have increased parasitic heat losses due to convection.

13.2 High Return Temperatures

The standards evaluate the heat pump performance when the return temperature to the heat pump is 21.0 ˚C. Performance degrades as return temperatures increase. Figure 13-1 plots manufacturer results regarding the effect of heat pump return temperature on COP for a ductless heat pump (a different model than those used in this study).[9] In this example, an increase in return temperature of 10˚F (5.6ºC) from 65 to 75˚F decreased COP by roughly 0.75 (or 20%).

Average indoor temperatures for units in this study were frequently higher than 21 ˚C, sometimes notably higher. Indoor temperatures for Unit 3 and Unit 4 were typically around 22 ˚C. However, the return temperature to the heat pump would be greater than the temperatures measured by the indoor sensor due to thermal stratification within the room. The indoor temperature sensor is at

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[8] An excerpt from a soon-to-be-released companion report titled “Barriers and Opportunities: Information, Knowledge and Capacity Gaps limiting Air-Source Heat Pump Retrofits in Public Spaces,” by Susan Morrissey Wyse and Ian McVey of the Ontario Climate Consortium is relevant here:

“Interviews revealed varying perceptions of how successful air-source heat pump retrofits are in practice. For some organizations, the business case has already been made (i.e. heat pumps are seen to be a cost-effective option with additional benefits for residents), while for others there was a concern that some challenges have been understated by the organizations promoting the technology (e.g. issues operating within cold-climate or rebound effects) and that a subtlety has been missing in the information provided, which has ultimately done a disservice to the uptake of the technology. Ensuring that “real-world considerations” are factored into studies and case studies is therefore vital.”*

* Rebound effects is a term to describe where a reduction in expected energy savings occurs due to changes in occupants’ behaviour.

[9] Williamson, James and Robb Aldrich. “Field Performance of Inverter-Driven Heat Pumps in Cold Climates.” U.S. Department of Energy: Energy Efficiency and Renewable Energy. 2015.

thermostat-level while the return air intake is at the ceiling. Spot checks taken during this study suggest that the temperature entering the return of the heat pump could be on the scale of 2 ˚C higher than what was being logged by the temperature sensor installed at thermostat-level.

Within the study, tenants were asked to maintain the indoor temperature of the unit according to their own comfort level. The main request from the research team was that they be consistent about the indoor temperature set-points between the baseline and retrofit monitoring periods so as to form a fair comparison. The relatively similar indoor temperature between the baseline and retrofit monitoring periods shows that the tenants complied.

Manufacturers do offer options where indoor temperature set-points can be limited to specified upper and lower limits. However, tenants may always provide additional heat using space heaters, circumventing restrictions. Tenant education is likely the ideal approach for achieving moderate indoor temperatures that would promote heat pump efficiency.

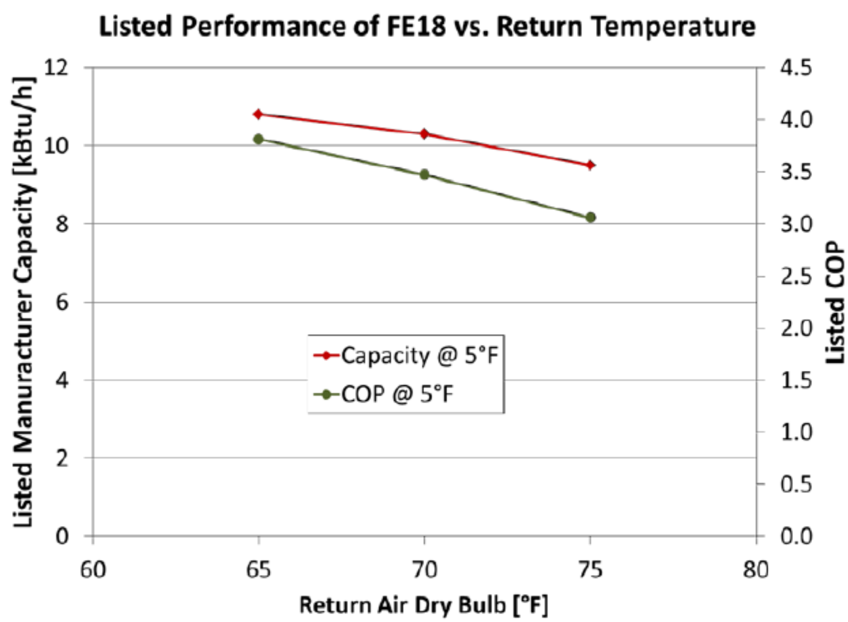

Figure 13-1. Example of the effect of return temperature on heat pump COP. Note that these results are *not* from this study.

13.3 Changes in Thermostat Set-points

None of the tenants reported using the setback features of their heat pumps but some did report occasionally turning the heat pump off entirely. For example, in one case the indoor unit was installed in front of the dining room table and the tenant turned it off during dinner because they were next to the airflow. In other cases, there was disagreement between different occupants within the unit about the thermostat set-point. For example, during the interview, the tenant in Unit 4 said:

"I would turn it up and then he would go and turn it back down… I just turn it up and hide the remote so he can't turn it down.

Frequent changes in the thermostat set-point, as suggested in the above quote, could degrade efficiency.

13.4 Cycling

Variable capacity heat pumps tend to operate more efficiently at lower compressor capacities. A key benefit of a variable speed heat pump is that is can operate at very low capacities for long periods of time rather than cycling on-and-off. This promotes efficiency. However, depending on the size of the heating load, the heat pump may still have too much capacity at its lowest compressor speed and would need to cycle on-and-off to avoid overheating the space. This type of cycling would degrade efficiency.

Figure 13-2 plots high-resolution power consumption data from Unit 3. The heat pump power consumption is plotted against the outdoor temperature for the 10-minute logging intervals. It shows that the heat pump rarely ever turns off entirely (i.e. power consumption does not go to zero). This suggests that the heat pump is able to modulate itself up or down to meet the load without having to cycle on or off. It also shows that tenant is not manually turning it off.

Figure 13-3 shows comparable data for Unit 4. Unit 4 is using a conventional heat pump (i.e. not a cold climate heat pump) but it actually continues to operate past its manufacturer-stated lower operating range of -15 ˚C outdoor temperature and does not shut itself off entirely until -18 ˚C. The magnitude of the power consumption suggests that it is still providing heating (i.e. the compressor is on) nearly right up until it shuts down. Above 0 ˚C, the heat pump is off part of the time. This may be the tenants turning it off or it may be that the heat pump needs to cycle on and off so as to not provide too much heating. Whatever the cause, this would affect the overall performance of the heat pump.

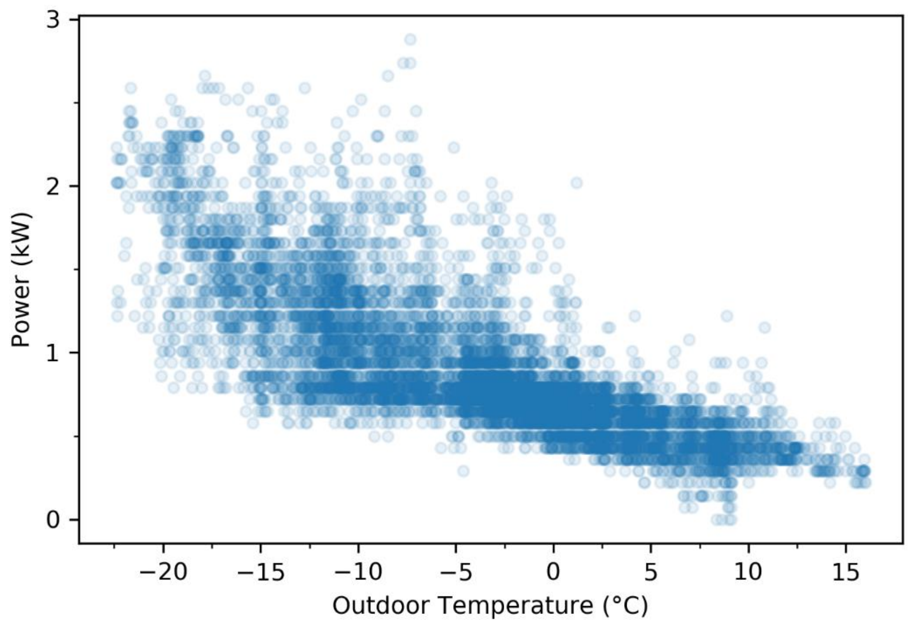

Figure 13-2. High resolution power consumption of the Unit 3 heat pump shows that the unit is able to modulate down to a low compressor speed to avoid turning off entirely.

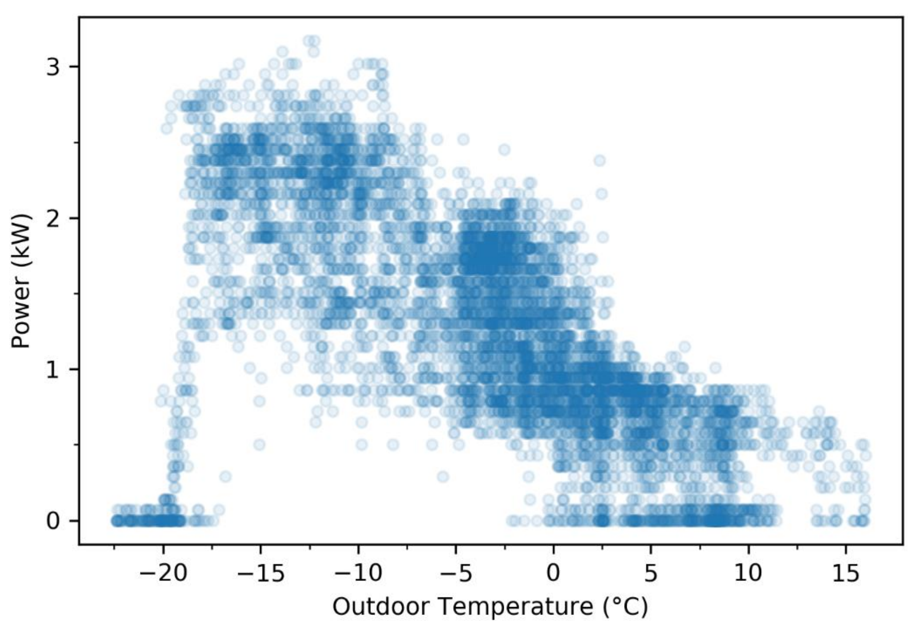

Figure 13-3. High resolution power consumption of Unit 4 as a function of the outdoor temperature. The unit shuts off entirely below -18 ˚C and appears to cycle on and off above 0 ˚C.

13.5 Defrost

An analysis of the defrost cycling behaviour of the heat pumps was not part of this study. Pulse outputs from the energy meters were collected at a 10-minute logging interval. This is likely longer than the length of a defrost cycle, making it difficult to find any signatures within the monitoring data to indicate how often the heat pump is defrosting.

13.6 Fan Speeds

All tenants reported that they did not adjust the fan speeds manually and just left the fan in "Auto" mode. However, fan powers were not measured individually in this study so it was not known whether fans consistently operated at high or low speeds. Previous work has demonstrated that fan speed can have a significant effect on efficiency. Figure 13-4[10] shows the effect of outdoor temperature, compressor capacity and fan speed on efficiency, with high fan speeds for a low compressor capacity yielding one of the most efficient configurations.

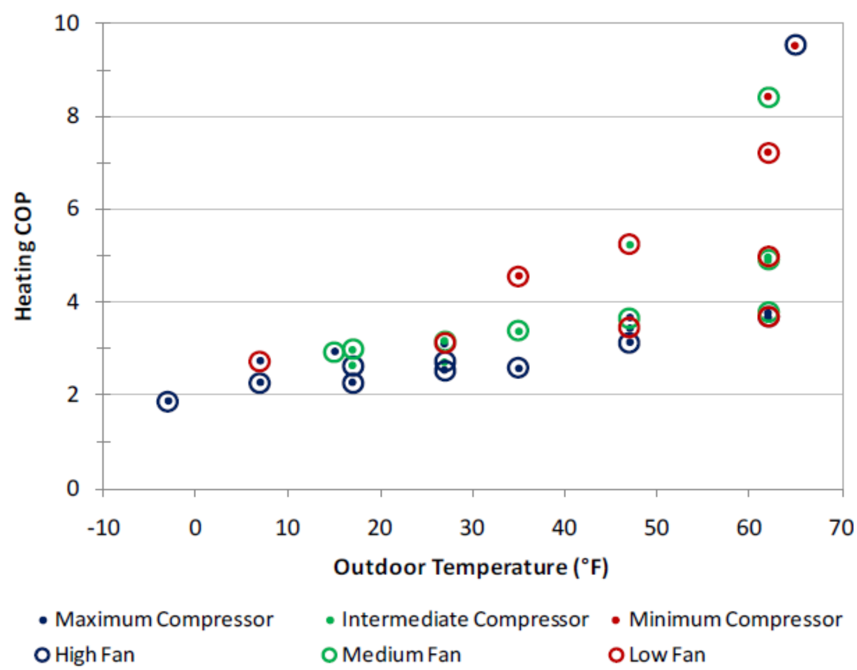

Figure 13-4. Previous research results displaying the effect of compressor capacity, outdoor temperature and fan speed on heat pump COP.

[10] Winkler, John. "Laboratory Test Report for Fujitsu 12RLS and Mitsubishi FE12NA Mini-Split Heat Pumps." U.S. Department of Energy: Energy Efficiency and Renewable Energy, Building Technologies Program, 2011.

14.0 CARBON SAVINGS

Carbon emission savings were calculated using two methods in order to identify a range of potential carbon savings, looking at two different types of emission factors (EFs). The first method, referred to as the *average* emission factor (AEF) method, used Ontario electricity grid EFs from the 2017 National Inventory Report[11] to calculate emissions associated with electricity consumption. This method of calculating emissions is widely used throughout Canada and used an emission factor of 43 g CO_2e/kWh. Note that this EF is very low compared to many other jurisdictions because the Ontario grid mix is relatively clean, having phased out the use of coal. As an example, the AEF for Alberta is 900 g CO_2e/kWh. Carbon emission savings in Alberta would therefore be much greater than those in Ontario.

The second calculation method used *marginal* emission factors (MEF), based on recent work developed by TAF aimed at better quantifying the way that changes in demand impact the electricity grid[12]. The AEF method accounts for all of the generation sources on the Ontario electricity grid and assumes that changes in grid demand impact all generators equally. In reality, only a small fraction of the total Ontario electricity supply would respond to a change in demand, and the MEF aims to relate emissions to only those generators that would ramp up or down in response to a change in demand.

The MEF method accounts for only generators that are "on the margin" at a given time. A generator on the margin means that its supply would increase or decrease in response to a change in demand. This method produces a higher EF than the AEF method because it neglects Ontario's low-carbon baseload electricity generation. The annual MEF for Ontario was calculated to be 158.8 g CO_2e/kWh. Since this number is higher than the AEF, it is possible that the MEF produces results that show savings of over 100%. This does not negate the results but merely reflects the fact that peak generators typically produce more emissions than those that make up the baseload.

Table 14-1 summarizes the estimated annual and lifetime emission savings for Units 3 and 4 when the heat pump is used only in heating mode, replacing electric baseboards. The baseline carbon emissions considered only the heating season for each respectively unit and not the entire year. Table 14-2 shows the estimated carbon savings for the case where the heat pump is used in both heating and cooling mode, replacing electric baseboards and a window shaker air-conditioner. Table 14-2 omits baseline carbon emissions because whole building energy models where not created for the whole

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[11] Environment and Climate Change Canada. National Inventory Report 1990-2015: Greenhouse Gas Sources and Sinks in Canada. April 2017.

[12] The Atmospheric Fund. A clearer view on Ontario's emissions: Practice guidelines for electricity emission factors. July 2017.

year, only in heating mode. Lifetime savings assumed a 15-year timespan. In reality, actual carbon emission savings would lie somewhere in between the values produced by these two methods.

While these savings may not be significant on their own, their impacts are much greater with increasing heat pump retrofit uptake. TAF estimates that the space heating consumption of all MURBs and rowhouses in Ontario to be 2,400 GWh/y[13]. Applying these electricity and carbon savings, even to a fraction of that load, could have a substantial impact on energy conservation and emission reductions.

A further consideration is that the electricity conservation through heat pump retrofits in electrically heated buildings may increase the grid capacity available for the electrification of transportation. This phenomenon would have a multiplier effect for carbon emissions when conserving electricity, but is currently understudied.

Table 14-1. Estimated annual and lifetime carbon emission savings for units 3 and 4 when the heat pump is used for heating only.

Unit	Baseline annual emissions (tCO_2eq/y)	AEF annual savings (tCO_2eq/y)	MEF annual savings (tCO_2eq/y)	AEF lifetime savings (tCO_2eq)	MEF lifetime savings (tCO_2eq)
3	0.43	0.14	0.51	2.08	7.69
4	0.61	0.11	0.42	1.72	6.34

Table 14-2. Estimated annual and lifetime carbon emission savings for units 3 and 4 when the heat pump is used for both heating and cooling.

Unit	AEF annual savings (tCO_2eq/y)	MEF annual savings (tCO_2eq/y)	AEF lifetime savings (tCO_2eq)	MEF lifetime savings (tCO_2eq)
3	0.19	0.69	2.82	10.42
4	0.16	0.60	2.46	9.07

[13] The Atmospheric Fund. "Pumping Energy Savings: Ontario EMURB Market Characterization Study," February 2016.

15.0 TENANT INTERVIEWS

15.1 Overview

The responses of actual tenants who received the ASHP retrofits are vital in understanding some of the qualitative aspects to this study. Surveys help in understanding how the tenants use the technology and this helps improve the data analysis. They also provide necessary feedback that quantitative data alone cannot provide. This feedback provides useful information regarding aesthetics, comfort, usability, as well as overall impressions that can further aid in future ASHP policy, engineering, incentives, and so on.

In-person interviews were conducted with all tenants who had received the ASHP retrofits. The post-heating season interviews focused on the tenants' experience of using their heat pumps. They lasted an average of 30 minutes in length and were recorded and transcribed for analysis. Tenants answered 19 questions within 8 key categories:

- Electricity savings
- Aesthetics
- Usability
- Comfort
- Retrofit process
- Comparisons between reporting and baseline periods
- Suggestions for improvement
- Overall impressions

15.2 Electricity Savings

The project team wanted to gain an understanding of the electricity savings experienced by the tenants during the study period. Of the 4 tenants who received a retrofit, 3 noticed a significant decrease in their utility bills. Those units reported savings ranging from $75-150 dollars a month. The unit that did not notice much of a change noted there had been an issue with a breaker and initially some of the electric baseboard heating units had not been turned off (Unit 2). They had also not been tenants the previous winter and had no historic winter energy bills for their unit for comparison. It should be noted that the interviews provide insight into the tenant's *opinion* of the energy savings and is not a scientific evaluation of actual energy savings.

15.3 Aesthetics

Tenants were asked about their thoughts on the looks of the heat pump, on a range of 1 to 5, 5 being "looks good", 1 being "looks really bad". Answers ranged from 3 to 5. While no tenant thought the units looked "bad", all 4 did comment on the bulkiness of the units. The tenant who rated the unit a "3" felt it was *"...not stylish….(and) hard to arrange pictures around"*. Another tenant who rated the unit a "4" thought it could be sleeker/flatter to the wall but appreciated that it was high up, as the electric baseboards prevent things being placed right up to the wall. Another tenant liked that it was an all-encompassing unit, rather than having multiple baseboard heaters.

> *"You take the good with the bad. I don't mind that it's there, it is a little larger unit but in my opinion, the savings far offset (the looks), I don't care what it looks like."*

Note that manufacturers offer different form factors for the indoor fan coils, including floor-, wall- and ceiling-mounted.

15.4 Usability

Tenants were asked if they had any issues using their heat pump. No major issues were reported and feedback was positive, including comments that it was *"easy to use"* and *"quiet"*. One tenant did report that it "*blows down onto the furniture"* but that the air flow can be redirected. Another tenant did experience some noise issues with one of the heat pump fan coils, but it stated that it wasn't a deal-breaker for them. Others found it very quiet.

> *" ...it was quiet. You didn't even know it was on, it's like, "Are you sure that's on?" "*

Tenants also commented on the remotes and the ease at which the remotes made adjusting comfort levels within their units.

> *"I enjoy having a remote. I thought it was a lot better than having to go up to the panel, because I'm short and could never reach, and trying to push buttons and program that way. I like the remote access a lot."*

15.5 Comfort

Tenants were asked how the heat pumps compared to electric baseboards with regards to providing comfortable temperatures throughout their homes. Of the 4 tenants that received retrofits, 3 reported that the heat pump was better than electric baseboards at providing comfortable temperatures in their homes over the heating season. Those tenants reported that the heat pumps provided more even heat distribution than their electric baseboard heaters. Two tenants did report their bathrooms being cold, however, they used the electric baseboard heating unit to heat that room. All tenants kept the fans running in auto mode, though some did make adjustments to the louvres to suit their comfort needs. Three of the tenants did not have any comfort issues during the cold spell (average daily temperatures down to -20 ˚C) that occurred during the study period. The tenant that noted an issue with thermal comfort had a conventional heat pump that could not operate in extremely cold conditions.

15.6 Retrofit Process

The tenants reported that the retrofit process was not intrusive in terms of the duration of the retrofit - *"...they did it pretty quick"*. In regards to the retrofit process, another tenant stated: *"There were no issues. See, I work out of town. I'm gone in the morning. You guys come in and do what you have to do and you were pretty much done with it the time I come back. No issues."*

15.7 Comparisons Between Reporting and Baseline Periods

Tenants that received the retrofit were asked if any of the electric baseboards were used during the study period. Two tenants did use their electric baseboard heaters to heat their bathrooms (one tenant used it only in the upstairs bathroom, while one had to use them in both bathrooms) during the study period. During the cold snap that occurred during the study period, only one tenant reported the electric baseboard heaters coming on to provide back-up heating for the heat pumps. This tenant had a conventional heat pump that could not function in extreme cold conditions.

Tenants were asked if there were any other factors that may have impacted their electricity consumption. The following activities were reported:

- Unit 2 reported fostering kittens in their spare room and had to keep the room warmer than normal;
- Unit 1 changed their front door part way through January;
- One unit reported being home more often over the Christmas holidays; and,
- Another unit reported changing the set points more often, as the remotes made it easier to adjust the temperature to their thermal preferences. No adjustments were made to take this in to account because it is a real phenomenon that would affect energy consumption of a heat pump retrofit.

Residents were also asked about the consistency of their electricity consumption on a day-to-day basis. All reported that their use was fairly consistent. Temperature set-point changes were made, as necessary, depending on who was home and/or the weather. Two tenants reported that their temperatures were set between 20-22 ˚C, with the other two tenants between 23-25 ˚C.

None of the residents programmed their thermostats and instead left them at a constant setpoint, adjusting the temperatures manually as necessary to suit their desired comfort levels. Two tenants reported setting temperatures higher than those set when using electric baseboards as the remotes make it easier to adjust the temperature. With regards to turning the heat pumps off completely, one tenant reported doing this when they weren't home while another reported that the heat pump stopped working during the cold spell and the electric baseboards were used. This was a conventional heat pump rather than a cold-climate one.

15.8 Suggestions for Improvement

Retrofit participants were asked if there was any additional information that could have been provided up-front about the heat pump that would have helped them to use it more effectively or otherwise improved their experience with it. One tenant recommended providing additional system information upfront so that they were better aware of the size and installation method of the system so that they were better prepared for the initial installation. Another recommended providing an explanation of how the heat would be distributed through their unit using the heat pump so they had a better idea of what to expect.

Tenants were also asked if they had any suggestions for manufacturers on how to improve their product. One tenant suggested a slimmer design, and extending the sensor range on the remote. Another tenant recommended lowering the temperature threshold that it operates at, because *"...it gets really cold that's when you need the heater the most. So it doesn't make sense for it to turn off when you need it most."* This tenant did not have a cold-climate heat pump which is able to continue operating in extremely cold conditions.

When asked if they had advice or tips for other tenants who might be receiving a heat pump retrofit, the following feedback was provided:

- shut off baseboards;
- keep it at a consistent temperature; and,
- implement any other conservation measures that you can before the new system is brought in to maximize savings.

15.9 Overall Impressions

Overall, tenants that received the heat pump retrofit were very happy with the system, stating that it was "easy to use", they saved money, and the inclusion of air conditioning was well appreciated.

> *"I feel a little bit better than I did with the electrical heaters. Even with the programmable stuff (thermostats) that they put in, I was confused with those. I was like, "Okay, _____. I don't know if this is on or off or what." I was confused, while with this one (heat pump) it was a lot easier. You had the remote. You saw what your temperature was at and you know you were good, right? I was appreciative of those (remotes)."*

> *"...it's nice and clean (looking). Like there is no wires, you know what I mean."*

Other comments included that they felt the heat pumps were cleaner and simpler to maintain and that the install was simple and less intrusive compared to other heating systems that require ductwork. With regards to other suggestions or feedback, one tenant suggested installing the outdoor units so that they were less noticeable and installing a housing unit for those adjacent to common areas, to prevent them from getting damaged.

Retrofit recipients were also asked whether they thought tenants in other buildings would have an issue paying a monthly rental fee to cover heat pump installations costs, potentially where the rental fee could be paid out of a portion of their electricity bill savings but the tenant would still save money overall. Overall, they didn't think others would have an issue with the rental fee, as long as it was "reasonable." One tenant suggested that education be provided to explain the system and potential savings, as well as to justify the rental fee.

> *"No, I would pay a rental fee. Just because you see the savings. (You) might not notice them right away, right? But you would definitely see the savings in the long run. Honestly, who wouldn't want to convert from those heaters to something far better, right?"*

> *"Winter months are always the worst (for bills)... But if these somehow ... If (they) got a grant or (they) did whatever (they) could to get these systems put into all these units, not only would (they) see a turnaround not happening all that often, (they'd) have a lot more tenants, more happier, more willing to want to pay their rent than finding ways to not pay their rent."*

> *"If I had to continue paying heat for that (electric baseboard heater), I probably would be shopping for (another place to live) next year."*

16.0 BUILDING OWNER INTERVIEW

16.1 Overview

The experience of the project site's building owner is key to understanding existing barriers and how widespread uptake can be fostered through the results of this study. Interviews help in the understanding of the building owner's perspective of the technology, how they approach retrofits and their decision-making process. The main purpose of the interview was to understand the building owner's needs and decision-making process such that the needs of building owners can be better identified (in terms of financing arrangements, policy support, subsidies, information, etc.) to move from a general interest in reducing energy usage/costs to ultimately implementing a heat pump retrofit. This feedback provides important knowledge that will inform recommendations of uptake as well as the planning and development of future studies.

A phone interview was conducted with the building owner of the heat pump retrofit site. However, it's important to note that this was a research study; the building owner was provided with *donated* equipment and the install was managed by the research team. It follows that the building owner did not go through a typical process for project implementation. The interviewed lasted for approximately 1 hour and was recorded and transcribed for analysis. Questions asked covered the following categories:

- Motivation to participate in the study;
- Thoughts on energy upgrades;
- Barriers to energy upgrades;
- The retrofit process and results to-date;
- Tenant education;
- Mobilizing the technology;
- Business case; and,
- The project process.

16.2 Motivation To Participate In The Study

The building owner was asked about their motivation to participate in the study. The driving factor was to deliver value to their tenants. From their standpoint, *"any opportunity that we can ...drive value toward them is a win for us"*. Knowing the cost burden that the electric baseboard heaters present tenants during the winter, there was a desire to see how the heat pumps would work.

16.3 Thoughts On Energy Upgrades

The building owner had considered energy efficiency improvements in the past. Some past measures that had been implemented were light bulb changes, adding insulation, and boiler replacements. Generally speaking, when the building owner approaches energy efficiency or any other improvements, cost and payback is the first metric they look at. The shorter the payback (for example

2 years), the more likely they are to implement. If it's longer, say 10 years, the project is unlikely to move ahead.

For projects that are in-between, other metrics (such as the amount of capital, aggregate dollar amount spent, potential disruption) are also considered. Information surrounding payback is typically obtained directly from the utilities, as they market programs targeting MURB owners. To-date, the building owner has not directly engaged a consultant to perform any cost feasibility studies or business cases on their behalf. They have engaged with some other third-party providers in the past, but no projects went ahead.

16.4 Barriers to Energy Upgrades

The building owner identified cost as the greatest barrier to implementing energy efficiency measures. Budget and equipment lifespan are factored into the decision making - for example, the costs of new boilers[14] and their anticipated lifespan are compared to the anticipated maintenance costs of the existing boiler over the same time frame.

> *"There's a lot of variables at play. And we do think about them a lot. I can't tell you what makes us eventually say, okay, let's replace. It's a little bit of (a) deliberate consideration and it's a little bit of a gut decision as well. And also, we operate month-to-month with a budget and if we're having a good month and it happens to go down that month, right. I might be more inclined to go ahead with the project. If we're having a bad month, I just might say, fix it. We can't afford the sixty grand outlay right now."*

From the building owner's perspective, the electric baseboard heaters are good enough for providing sufficient thermal comfort for tenants, however, the challenge is the operational costs. From a maintenance perspective, they are maintenance free, *"they're as good as you get"*.

16.5 Retrofit Process

At the time of the interview, the building owner had not yet seen data from the retrofit, and could not comment on how the retrofit had progressed so far. From speaking to the building superintendent, anecdotally they could report that tenants were pleased with their savings. One challenge encountered during the retrofit was the organization and planning of the install - the install took longer than originally planned. However, there was an understanding on the part of the building owner that it is a pilot project.

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[14] Note that the building owner owns other sites aside from this rowhouse.

In terms of aesthetics, the building owner *"wouldn't say (it's) pleasing, but I don't think it's that bad"*. Similar to feedback received from the tenants, the building owner felt it was not as clean as the electric baseboards and there is also the box outside.

The building owner is hoping that the project will answer the questions they have in terms of maintenance requirements and reliability, particularly because the equipment is expensive. With the existing electric baseboards, there is not a concern with them failing. In other properties, where utilities are included, heat pumps may be considered.

> *"Especially in this case because, in the case where we're driving the value for the savings, it's one thing if you have maintenance costs. But in this case where the tenant is driving the value and we're responsible for the maintenance costs... That's a very big consideration."*

16.6 Tenant Education

The building owner was asked about whether tenants have a good understanding of how their behaviour affects their energy consumption. Although the building owner does not interact with the tenants directly, on a portfolio-wide basis, for properties where utilities are included in rent, the building owner expressed that tenants may lack a good understanding of how their behaviour affects energy costs, or they may be less concerned about it. In buildings where there are submeters, more energy conservation measures are observed.

16.7 Mobilizing the Technology

The building owner was asked if they had heard of heat pumps before the study. Although they had seen them before, they had not heard of them by name or function, and thought this would be the same experience of other building owners operating at a comparable scale. It was expressed that the best way to encourage others to use this technology is through a cost-benefit analysis:

> *"I think it's really going to be a cost-benefit analysis. How much does it cost to switch over and how am I going to recoup that capital outlay and over what period of time? How much is my ongoing maintenance potentially going to be?"*

16.8 Business Case

The building owner was asked a number of questions to evaluate the business case from this specific technology from their perspective. Since the building owner does not pay the utility bills in this complex, from their perspective, the only mechanism available for them to recoup their investment for a heat pump retrofit is through an incentive or grant funding. For buildings where tenants pay the utilities, it would be difficult to implement complex-wide retrofits without any incentive or grant funding.[15]

Recently implemented provincial rent control measures act as a barrier to adjusting rental rates as a means to recoup energy efficiency investments. Improved tenant retention was not seen by the building owner in amounting in measurable cost savings that would justify the expenditure for a heat pump retrofit.

Although tenants may experience cost savings as a result of reducing heating costs because of the retrofit, there is concern that, because the heat pump also provides cooling which was not previously provided (although there may have been window units), any savings would be offset by added cooling costs.[16] With regards to quantifying tenant retention and associated administration costs within the business case, the building owner did not feel that hydro costs and hydro savings experienced during the heating season had a significant impact on tenant retention:

> *"I don't know. I don't think a tenant is going to stay because of a $100 savings of hydro for four months. It's a benefit to them, for sure, but I don't know if it's really a tenant retention issue. The biggest tenant retention issue is rising rent. Right? The longer you've been in... with the escalation of rent before rent control came in across the board, the longer you stay in your place, the better off you are."*

In terms of the potential for a rental ownership model to facilitate more heat pump retrofits, the building owner agreed that there is potential if a net benefit can be demonstrated to tenants. On-bill financing, a loan-repayment method that is incorporated into utility bills, was not seen by the building owner to be a viable tool to promote heat pump retrofits. From the building owners point of view, the

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[15] This is the "split-incentive problem." It is described in the following excerpt from a soon-to-be-released companion report titled "Barriers and Opportunities: Information, Knowledge and Capacity Gaps limiting Air-Source Heat Pump Retrofits in Public Spaces," by Susan Morrissey Wyse and Ian McVey of the Ontario Climate Consortium*:*

"A significant barrier that may discourage building owners from retrofits is the "split incentives" problem, which refers to situations where participants in an economic exchange have different goals or incentives. In the context of tenant-landlord relationships, a considerable challenge arises when the landlord provides the tenant with appliances, but the tenant is responsible for paying bills associated with these appliances. In this situation tenants and landlords have different goals: the landlord is seeking lower capital costs when purchasing appliances, while tenants are seeking lower energy bills. The landlord is incentivized to buy the cheapest appliance, but this may not be the most efficient option for residents. As investors in new technologies, building owners may not receive the benefits which accrue to their tenants when tenants pay for heating, cooling and utilities, and therefore may see little reason to invest. Studies have shown that, due to this barrier, energy efficiency expenditures are mainly undertaken in owner-occupied as opposed to renter-occupied dwellings. Research therefore suggests that the challenge of split-incentives between tenants and landlords can lead to underinvestment in energy efficiency expenditures."

[16] In this study, cooling mode electricity of the heat was shown to be very low and any additional electricity consumption from cooling mode operation was much less than heating mode savings.

challenge would be that tenants do not know how long they will be at the subject location or may go into default, and ultimately the contract would be the building owner's responsibility until the next tenant moved in.

> *"Whether we deliver heat by baseboard or by heat pump, we do have flexibility. So the question is would we take on an additional burden without having any benefit… We'd have to really understand the financial metrics before we comment on that."*

With regards to the benefits to the building owner for participating in this study, they get to deliver significant value to the tenants that did receive the benefits and are able to move the study forward in a way in which results could be used for another building if they are favourable.

In terms of the strength of the business case and deciding whether or not to proceed with a retrofit for both bulk and suite metered buildings, cost and relatively short paybacks were identified as the deciding factor. The building owner felt that they would need to understand what the process was and see that financial data that says what the actual costs are and this is what can be expected to be gained over a certain period of time.

17.0 RECOMMENDATIONS AND CONSIDERATIONS

Recommendations and considerations for potential adopters of ductless heat pump technology are listed below. A heat pump retrofit will involve many decision points. The information listed below is not intended to provide a firm recommendation on which way to choose, but rather, it highlights some of the important factors that should be considered with each decision.

1. **Back-up heating requirements: Cold climate vs. conventional heat pumps.** If appropriately sized, a *cold-climate* heat pump does not require back-up heating in Southern Ontario. The cold-climate heat pumps in this study continued heating during extremely cold conditions. A *conventional* heat pump will not provide heating once the outdoor temperature dips below a certain value. Depending on the local climate conditions, back-up heating may be required.

   Cold-climate heat pumps have an increased equipment cost but they also simplify controls since cold-climate heat pumps don't require back-up when appropriately-sized for the load. A conventional ASHP will need to be backed-up by the existing baseboards, or another source, during extreme cold conditions and controls are needed to coordinate that back-up. In this study, control of back-up for the conventional heat pumps was left up to the tenants. Tenants were instructed to turn baseboard thermostats on during extremely cold weather and set them below the heat pump thermostats. While this approach did appear to work sufficiently well in this study, it is not an ideal control strategy in a multi-unit context.

   To automate control of back-up heating for a conventional heat pump there will be an additional cost for wired-in thermostats or wireless relays. Furthermore, this cost will need to be replicated across all indoor fan coils. The additional cost of controls will reduce the cost savings from choosing a conventional heat pump. Control solutions should be an important consideration during the heat pump selection process.

2. **Multi-split vs. mini-split heat pumps.** For heat pumps of comparable capacity, a single-port mini-split heat pump is considerably less expensive than a multi-split heat pump. The main advantage of the multi-split heat pump is that it can effectively distribute heat around the dwelling while the single-port heat pump will only heat a single zone. In the rowhouse units considered in this study, it is the researcher's opinion that the most cost-effective retrofit would have been a single 2-ton cold-climate mini-split heat pump installed in the main floor living space; with the main floor living and dining room baseboards disabled and the second floor bedroom electric baseboards left on. Installed costs would have been reduced by more than half and the heat pump would have been able to handle most of the load, while also maintaining the benefits of high-efficiency cooling. A multi-split heat pump can maximize energy savings and have superior thermal comfort, but a system combining a mini-split heat pump with existing baseboards would lower installed cost and improve

overall cost-effectiveness while maintaining many of the benefits of a multi-split heat pump retrofit.

3. **Maintenance.** The heat pump user manual recommends biweekly cleaning of filters with a vacuum or with water. This may be a reasonable recommendation for some tenants – especially in units with multiple occupants, pets and smokers; but is likely unnecessarily onerous for other tenants. In a multi-unit context, if filter cleaning represents an additional cost for the building owner it may be reasonable to choose a filter cleaning frequency that is appropriate for the tenants.

4. **Estimating energy savings in feasibility assessments**. An estimate of energy savings depends on the expected efficiency of the heat pump. However, *as-installed* efficiency could be different from *rated* efficiency insofar as-installed operational parameters differ from the assumptions of rating procedures. The most obvious example is the return temperature to the indoor fan coils. Ratings assume a return temperature of 21°C in heating mode but every retrofitted unit in this study had higher return temperature and some were much higher. This would reduce overall energy savings. Where energy and cost savings is the driving motivator for a heat pump retrofit, it is advisable to be conservative in regards to performance estimates within business case assessments. It is also recommended to evaluate the sensitivity of the assessment results with respect to the assumptions about heat pump efficiency.

5. **Business case.** Business case assessments should consider non-energy benefits where applicable. This may include: increases in property values; increases in unit marketability, tenant retention and overall satisfaction; and improved health, safety (i.e. risks of heat exhaustion in summer) and comfort of tenants.

6. **Cost of cooling.** A key concern of the building owner going into this study was whether or not introducing cooling into the units would negate the heating mode energy savings and potentially leave the tenants with higher energy bills overall. The data collected in this study showed that a ductless heat pump consumes much less energy than a window-based air conditioning system. However, even if the tenant did not previously use window-based cooling, the additional cost introduced by heat pump cooling would be very low – even if it is heavily used.

7. **Tenant education and empowerment.** Some tenants in electrically-heated units may simply not be fully aware of how their indoor temperature set-point preferences affect their energy bills, and the potential cost savings of reducing those set-points. Tenant outreach and education addressing this issue would beneficial. Real-time feedback on energy

consumption, via a home energy monitor or other services, may also be beneficial. It would enable tenants to make real-time changes to promote energy conservation.

18.0 CONCLUSION

Electric baseboards are the main heating source for 24% of all MURB and rowhouse units in Ontario and heat pump retrofits represent a significant conservation opportunity. This study evaluated the performance of ductless multi-split heat pump retrofits in a rowhouse located in Brantford, ON, using energy and environmental data collected on-site during the approximately one-year study period.

It was estimated that the heat pumps saved energy (up to >3 MWh/year), operating cost (approximately 870$/year) and carbon (on the scale of 0.5 ton eCO_2/year). Most of the savings came from heating mode operation but there were notable cooling mode savings as well since the heat pumps were shown to be much more efficient then the window-based air-conditioners. The magnitude of the cooling mode savings is important to note. Many electrically-heated MURBs have no cooling system at all or rely on inefficient window-based air-conditioning. In the context of a warming climate, efficient building cooling systems may become a necessity to prevent loss of life or other negative health implications during extreme heat events.

The researchers acknowledge that the energy savings measurements in this study are dependent on the behaviours and preferences of the study tenants themselves as well as other installation-specific details. It follows that the results of this study should be understood as a case study. The calculated energy savings apply to the specific study units only. Other units may have greater or lower savings if they undertake a heat pump retrofit, depending on the occupants and installation-specific details.

Tenants were very pleased with the heat pumps. They appreciated the energy savings, addition of cooling, user-friendliness, the simplicity of the retrofit process and increased thermal comfort over electric baseboards.

Up-front costs are a barrier. They were estimated to be greater than $10,000 and potentially approaching $14,000, neglecting incentives. Potential system owners are encouraged to consider the impact of incentives (for example, Save On Energy in Ontario) for their application and context. Despite notable annual savings, it was estimates that the payback time of the multi-split heat pumps for these units is on the same scale as the equipment lifetime of 15 years. This makes the multi-split heat pumps well-suited to applications where both energy savings *and* thermal comfort are top priorities.

Where low up-front costs are key, a single-port mini-split heat pump may be a better solution because it has a much lower up-front cost. The research team believes that the most cost effective solution for this complex would be a mini-split heat pump installed on the main floor with electric baseboards left on elsewhere in the house - essentially a hybrid system where the heat pump does most, but not all, of the work. For larger buildings, VRF systems may help to further reduce costs.

19.0 FUTURE WORK

- This study presented IPMVP-adherent M & V results from two real-world rowhouse units. The researchers acknowledged that the results are subject to the tenant behaviours as well as other installation-specific details. A broader body of third-party M & V study results from a variety of unit- and building-types would help to build consensus on expected energy savings for future retrofits and further identify opportunities to promote optimal system performance.

- This study speculated that because of the drastic disparity in cost between mini- and multi-split systems, a hybrid system consisting of a mini-split in combination with existing baseboards may be able to achieve an improved business case. This should be evaluated in a follow-up study, again utilizing real-world systems and an IPMVP-adherent analysis.

- In a business cases assessment, estimates of energy savings are based on the expected heat pump efficiency. Standardized ratings are helpful but confirmation of the *as-installed* efficiency for real-world installations would be beneficial towards bolstering the validity of these estimates. Towards this end, it would be useful to have a straightforward protocol for measuring the seasonal efficiency of heat pumps installed in the field. This would be similar to the IPMVP protocol for determining energy savings but instead, it would evaluate heat pump efficiency. This protocol would be different than current performance rating procedures because many operating parameters could not be tightly controllable within real-world occupied units. The researchers contend that it ought to be possible to estimate seasonal as-installed heat pump efficiency by using IPMVP Option C alongside measurements of heat pump energy consumption. The efficacy of this approach will be explored in a follow-up research project.

- Evaluations of larger scale variable refrigerant flow (VRF) systems, like the Mitsubishi City-Multi or Daikin VRV Aurora system, in Canadian electrically-heat MURBs would also be beneficial.

20.0 APPENDIX A: IPMVP CONSIDERATIONS

This appendix discusses the key points necessary for an IPMVP-adherent measurement and verification report.

Table 20-1. IPMVP Analysis Considerations

IPMVP adherence limitations	The total normalized energy savings calculation for Unit 3 and Unit 4 in heating mode is adherent with IPMVP Option C (EVO 10000-1:2016) but all other calculations are not.
IPMVP option	*Option C: Whole facility* The rowhouse units in this study are electrically heated and space heating is the largest component of their bill. Significant improvements to the efficiency of their heating system, through a heat pump retrofit, has notably reduced their total electricity bill. This option is therefore well suited to Option C. Option C was also selected because it was possible to confirm the accuracy of the submetering monitoring data by comparing against the existing utility meter.
Measurement boundary	The IPMVP-adherent portion of this study considered all the electrical energy consumed by each rowhouse unit as measured by an electrical submeter.
Independent variables	The independent variable used in the analysis was the average daily outdoor temperature for Unit 3 and weekly aggregated heating degree days for Unit 4. Daily aggregated data based on average outdoor temperature was the preferred option because the resulting figures displayed in units of kWh consumption with respect to daily average outdoor temperature is much clearer to a general audience than kWh per degree-day. However, daily aggregation yielded poor results for Unit 4. Regression coefficients for both Unit 3 and 4 were very good, validating the approach.
Instrumentation	Electrical submeters were installed in all townhouse units participating in the study. Submeters measured the electricity consumption of the whole unit as well as other key circuits. The whole-house submeter was periodically compared against direct readings taken from the corresponding utility meter and found to agree within 2%. An outdoor temperature sensor was installed at the complex. Indoor temperature sensors were installed in the main living space of each unit. Further

	Instrumentation details are provided in Section 5.0 .
Baseline monitoring period	The baseline monitoring period occurred between January 20th 2018 to March 1st 2018 for Unit 3 and 4. During this time the heat pump was installed but it had been disabled and the rowhouse units were heated using the existing electric baseboards. A submeter on the heat pumps themselves confirmed that they had no electricity consumption during the baseline monitoring period.
Retrofit monitoring period	The retrofit monitoring period encompassed the time when the heat pump was used to meet the load of the rowhouse units. This occurred between November 20th 2017 and January 18th 2018, as well as March 3rd 3018 to August 1st 2018.
Baseline period and reporting period	IPMVP methodology compares a reporting period energy consumption against a baseline period energy consumption. In this study, the baseline and retrofit *monitoring periods* define the time periods where data was collected so as to create a regression model of energy consumption when the rowhouse units used baseboards versus when it was using a heat pump. In contrast, the baseline and reporting periods define the time period over which those models are applied so as to calculate a total baseline or retrofit energy consumption. In this study, the baseline period energy consumption is simply the resultant energy consumption when the baseline monitoring period energy model is applied for a Toronto TMY heating season. Similarly, the reporting period energy consumption is simply the resultant energy consumption when the retrofit monitoring period energy model is applied for a Toronto TMY heating season.
Adjustments	Adjustments are engineering calculations that are used to correct the baseline or retrofit energy models so as to ensure that they form a fair comparison. The research team did two things to identify the need for adjustments: 1) Collected additional monitoring data beyond the independent variable of outdoor temperature. 2) Conducted interviews with the tenants in November, March and June. Based on the interviews and additional data collection, Unit 1 and Unit 2 were not included in the IPMVP analysis. However, no adjustments were made for Unit 3 or Unit 4.
Interactive effects	Other independent variables that may impact energy consumption, but that were not directly measured, included: occupancy levels, hot water consumption, opening of windows or doors, heat gains or losses from adjacent units, solar gain

	and wind speeds. Occupancy, hot water consumption and opening of windows or doors was discussed qualitatively during interviews with the tenant. The research team concluded that these factors did not require any adjustments to the energy data. Solar gain is estimated to be small given that fenestration area is low. Heat gain or losses from adjacent units was considered to be a small factor that, even if present, would likely have affected both the reporting period and the baseline period in comparable ways. Wind was not considered due to the complexity of wind measurements and the difficulty in using any wind data to correct building energy consumption measurements.
Conditions used for normalized energy savings calculation	Both the baseline monitoring period and the retrofit monitoring period regression models were evaluated using typical meteorological (TMY) climate data from the Canadian Weather Year for Energy Calculations (CWEC) database for Toronto. This is why the results are presented as “normalized savings,” specifically, that energy savings have been normalized to a typical year. The data, binned according to a frequency histogram of daily average temperatures during the heating season, is provided in the sample calculation in Appendix B. The specific climate data file used within the CWEC database was: ● CAN_ON_TORONTO-CITY-CENTRE_6158359_CWEC.epw It should be noted that the Toronto CWEC datafile is based on statistical analysis of data collected between 1960 and 1989. Canadian Weather Energy and Engineering Datasets (CWEEDS) are available for more recent years but they are not aggregated into a TMY. The research team opted for the simplicity of using the CWEC TMY dataset within this study. Should any party be interested in applying the linear regression models to a different climate dataset the models have been explicitly provided and the calculation procedure has been clearly laid out.
Energy cost assumptions	Electricity cost savings were estimated for Toronto based on the calculated normalized energy savings and electricity pricing according to the 2017 Ontario Long-term Energy Plan (LTEP). Within the LTEP, average monthly electricity cost is forecasted for an average home consuming 750 kWh per month. A marginal electricity cost was estimated simply by dividing the monthly forecasted bill by 750 kWh. The analysis considered 15 years of operation according to the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) expected lifetime for ASHPs.

21.0 APPENDIX B: SAMPLE CALCULATIONS

21.1 Unit 3

A sample calculation for the Unit 3 normalized energy savings and consumption is shown in Table 21-1. In columns 2 to 4, regression models of the whole-house energy consumption and heat pump energy consumption are evaluated for each value of T_k. Outdoor temperature bins were 1 °C wide and indexed by "k." Column 1 includes all outdoor temperatures that occur within the Toronto TMY heating season.

Column 5 is the difference between Column 2 and Column 3. Column 6 describes the Toronto TMY heating season; it is the number of days where the average daily temperature was within the corresponding temperature bin (i.e. there was 1 day when the average daily temperature fell between -15°C and -16°C). Column 7 is simply Column 2 multiplied by Column 6. Column 8 is Column 3 multiplied by Column 6, and so on. Total baseline period consumption, reporting period consumption, heat pump energy consumption and normalized energy savings, for a Toronto TMY heating season are found by summing Columns 7 to 10.

Table 21-1. Spreadsheet calculation for energy consumption and savings in Unit 3.

1	2	3	4	5	6	7	8	9	10
T_k	$B_{Unit\ 3}(T_k)$	$R_{Unit\ 3}(T_k)$	$H_{Unit\ 3}(T_k)$	$S_{Unit\ 3}(T_k)$	n_k	$B_{Unit3,tot}$	$R_{Unit3,tot}$	$H_{Unit\ 3,tot}$	$S_{Unit\ 3,tot}$
°C	*kWh/day*	*kWh/day*	*kWh/day*	*kWh/day*	*days*	*kWh*	*kWh*	*kWh*	*kWh*
-19.5	88.3	68.8	38.2	19.5	0	0.0	0.0	0.0	0.0
-18.5	86.2	66.5	37.1	19.8	0	0.0	0.0	0.0	0.0
-17.5	84.2	64.2	36.1	19.9	0	0.0	0.0	0.0	0.0
-16.5	82.1	62.0	35.0	20.1	0	0.0	0.0	0.0	0.0
-15.5	80.0	59.9	34.0	20.2	1	80.0	59.9	34.0	20.2
-14.5	78.0	57.8	32.9	20.2	0	0.0	0.0	0.0	0.0
-13.5	75.9	55.7	31.8	20.2	0	0.0	0.0	0.0	0.0
-12.5	73.9	53.6	30.8	20.2	1	73.9	53.6	30.8	20.2
-11.5	71.8	51.6	29.7	20.1	0	0.0	0.0	0.0	0.0
-10.5	69.7	49.7	28.6	20.0	1	69.7	49.7	28.6	20.0
-9.5	67.7	47.8	27.6	19.9	3	203.0	143.3	82.7	59.7
-8.5	65.6	45.9	26.5	19.7	1	65.6	45.9	26.5	19.7
-7.5	63.5	44.1	25.4	19.5	2	127.1	88.1	50.8	38.9
-6.5	61.5	42.3	24.4	19.2	8	491.7	338.2	194.8	153.5

-5.5	59.4	40.5	23.3	18.9	7	415.8	283.7	163.0	132.0
-4.5	57.3	38.8	22.2	18.5	4	229.3	155.3	88.9	74.0
-3.5	55.3	37.2	21.1	18.1	9	497.4	334.5	190.3	162.9
-2.5	53.2	35.5	20.1	17.7	14	744.8	497.6	281.1	247.2
-1.5	51.1	34.0	19.0	17.2	13	664.8	441.5	247.1	223.3
-0.5	49.1	32.4	17.9	16.6	9	441.7	291.8	161.4	149.8
0.5	47.0	30.9	16.9	16.1	14	658.1	433.0	236.1	225.1
1.5	44.9	29.5	15.8	15.5	19	853.9	560.0	300.1	294.0
2.5	42.9	28.1	14.7	14.8	11	471.7	308.6	161.9	163.0
3.5	40.8	26.7	13.6	14.1	7	285.7	186.8	95.5	98.9
4.5	38.7	25.4	12.6	13.4	12	465.0	304.3	150.9	160.7
5.5	36.7	24.1	11.5	12.6	13	476.9	312.9	149.5	164.0
6.5	34.6	22.8	10.4	11.8	10	346.2	228.2	104.3	118.0
7.5	32.6	21.6	9.4	10.9	11	358.1	237.7	102.9	120.3
8.5	30.5	20.4	8.3	10.0	12	365.9	245.4	99.4	120.5
9.5	28.4	19.3	7.2	9.1	10	284.2	193.3	72.1	90.9
10.5	26.4	18.2	6.1	8.1	13	342.6	237.2	79.7	105.4
11.5	24.3	17.2	5.1	7.1	9	218.6	154.9	45.5	63.8
12.5	22.2	16.2	4.0	6.0	14	311.2	226.9	55.8	84.2
13.5	20.2	15.3	2.9	4.9	11	221.8	167.8	32.0	54.0
14.5	18.1	14.3	1.8	3.8	6	108.6	86.0	11.0	22.5
15.5	16.0	13.5	0.8	2.6	8	128.3	107.7	6.0	20.5
Totals					**253**	**10,002**	**6,775**	**3,282**	**3,228**

21.2 Unit 4

The calculation for Unit 4 is shown in Table 21-2. Heating degree-days were determined on hourly basis from the Toronto TMY weather data. They were then summed into weekly values. Week number is shown in Column 1 and the corresponding number of heating degree days is shown in Column 2. Columns 3 and 4 use the regression models derived from the experimental data for Unit 4 to determine a model baseline and post-retrofit energy consumption for the unit. Column 5 calculates savings. The total consumption and savings values are the sum from all weeks in the year.

Table 21-2. Spreadsheet calculation for energy savings and consumption in Unit 4.

1	2	3	4	5
i	HDD_i	$R_{Unit\ 4}(HDD_i)$	$B_{Unit\ 4}(HDD_i)$	$B_{Unit\ 4}(HDD_i) - R_{Unit\ 4}(HDD_i)$
	°C - day	kWh	kWh	kWh
1	108.0	413.3	565.8	152.5
2	91.4	383.0	512.1	129.2
3	94.1	387.8	520.6	132.8
4	90.4	381.0	508.6	127.6
5	85.9	372.8	494.0	121.3
6	95.9	391.2	526.7	135.5
7	110.7	418.1	574.4	156.2
8	79.1	360.4	472.2	111.8
9	79.0	360.2	471.9	111.6
10	111.0	418.7	575.4	156.7
11	66.9	338.1	432.7	94.6
12	63.4	331.7	421.3	89.6
13	41.7	292.1	351.2	59.1
14	48.6	304.7	373.6	68.9
15	40.1	289.2	346.0	56.9
16	26.1	263.6	300.8	37.2
17	13.8	241.1	261.0	19.8
18	19.0	250.6	277.8	27.2
19	5.5	225.9	233.9	8.1
20	10.5	235.1	250.3	15.2
21	0.4	216.6	217.6	1.0
22	0.0	0.0	0.0	0.0
23	0.0	215.9	216.4	0.4
24	0.0	0.0	0.0	0.0
25	0.0	0.0	0.0	0.0
26	0.0	0.0	0.0	0.0
27	0.0	0.0	0.0	0.0
28	0.0	0.0	0.0	0.0
29	0.0	0.0	0.0	0.0
30	0.0	0.0	0.0	0.0
31	0.0	0.0	0.0	0.0
32	0.0	0.0	0.0	0.0
33	0.0	0.0	0.0	0.0
34	0.0	0.0	0.0	0.0
35	0.0	0.0	0.0	0.0

36	0.0	0.0	0.0	0.0
37	1.0	217.7	219.5	1.8
38	1.3	218.3	220.5	2.2
39	0.0	0.0	0.0	0.0
40	4.2	223.5	229.8	6.3
41	5.3	225.5	233.3	7.8
42	12.8	239.2	257.5	18.4
43	9.8	233.9	248.1	14.2
44	20.1	252.6	281.2	28.7
45	19.7	251.8	279.9	28.1
46	45.0	298.1	361.8	63.7
47	81.8	365.4	481.0	115.6
48	45.5	299.1	363.6	64.5
49	62.8	330.7	419.6	88.9
50	83.2	367.9	485.4	117.5
51	109.4	415.7	570.1	154.4
52	96.9	393.0	529.9	136.9
Totals		**11,424**	**14,085**	**2,661**

22.0 APPENDIX C: REGRESSION STATISTICS AND SAMPLE UNCERTAINTY CALCULATIONS

22.1 Unit 3

A summary of the regression analysis parameters for Unit 3 is shown in Table 22-1.

Table 22-1. Unit 3 regression analysis summary.

Parameters	Value	Recommendation
Baseline monitoring period number of days	41	N/A
Retrofit monitoring period number of days	133	N/A
Baseline monitoring period coefficient of determination (R^2)	0.89	> 0.75
Retrofit monitoring period coefficient of determination (R^2)	0.85	> 0.75
Heat pump monitoring period coefficient of determination (R^2)	0.91	N/A
Baseline monitoring period standard error of the estimate	3.95 kWh/day	N/A
Retrofit monitoring period standard error of the estimate	4.86 kWh/day	N/A
Heat pump standard error of the estimate	2.62 kWh/day	N/A

In combination with a t-table, the standard error of the estimate for the linear regression models was used to define the model uncertainty. The standard error of the estimate was calculated using Equation 9[17] Where:

- $\widehat{Y_i}$ is the predicted value;
- Y_i is the actual value;
- n is the number of data points; and,

[17] See: International Performance Measurement and Verification Protocol: Statistics and Uncertainty. June 2014. Pg. 9. Equation 11.

- p is the number of independent variables.

$$SE_{\gamma} = \sqrt{\frac{\sum(\hat{Y}_i - Y_i)^2}{n - p - 1}} \qquad \text{Equation 9}$$

As an example, the baseline energy model standard error is 3.95 kWh/day. The model was generated using 41 data points and 1 independent variable; for reasons beyond the scope of report, this translates to 39 degrees of freedom (DF). According to a t-table, the t-value corresponding to 39 DF and 95% confidence is 2.02.

The model uncertainty at predicting the energy consumption based on average daily outdoor temperature is the t-value multiplied by the standard error (Equation 10),[18] in this case, 8.0 kWh/day. In other words, with a probability of 95%, the baseline linear regression model will predict the baseline energy consumption of Unit 3 for a given day to within ±8.0 kWh/day. The 95% confidence level of the Unit 3 baseline energy consumption model is illustrated in Figure 22-1.

The total baseline energy consumption for a Toronto TMY heating season is determined by adding the daily baseline energy consumption for the 253 days (n_{tot}) which make up the heating season[19]. The standard error of the sum is given by Equation 11[20]. For the baseline model, it is 62.8 kWh. To determine the uncertainty, like before, this is multiplied by the corresponding t-statistic to yield 127 kWh. Note that the relative uncertainty of the sum is much less than the relative uncertainty of any individual measurement. This is because the uncertainties tend to cancel the data is summed.

$$Uncertainty = \pm\, t \times SE_{\gamma} \qquad \text{Equation 10}$$

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[18] See: International Performance Measurement and Verification Protocol: Statistics and Uncertainty. June 2014. Pg. 9.

[19] In other words, there are 253 days when the average daily outdoor temperature is below 16°C within the climate data file.

[20] See: International Performance Measurement and Verification Protocol: Statistics and Uncertainty. June 2014. Pg. 13.

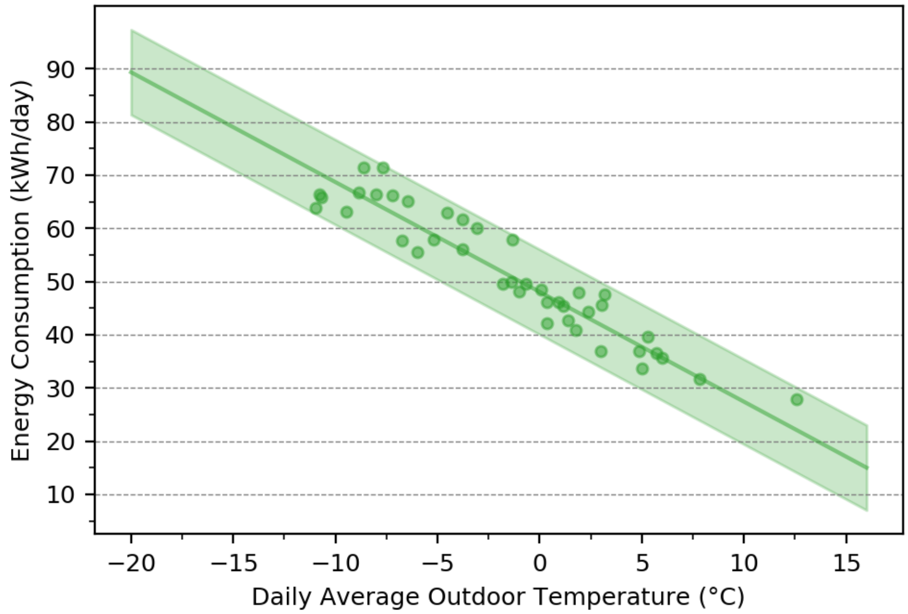

Figure 22-1. With a probability of 95% the actual baseline energy consumption of Unit 3 will fall within the shaded area.

$$SE_{total,\ base} = \sqrt{n_{tot} \cdot SE_{base}^2} \quad \text{Equation 11}$$

To determine the standard error of the energy savings, Equation 12 was used. The t-value was then used to translate this into an uncertainty.

$$SE_{savings} = \sqrt{SE_{base}^2 + SE_{retrofit}^2} \quad \text{Equation 12}$$

22.2 Unit 4

A summary of the regression analysis parameters for Unit 4 is shown in Table 22-2.

Table 22-2. Unit 3 regression analysis summary.

Parameter	Value	Recommendation
Baseline monitoring period number of weeks	5	N/A
Retrofit monitoring period number of weeks	16	N/A

Baseline monitoring period coefficient of determination (R^2)	0.92	> 0.75
Retrofit monitoring period coefficient of determination (R^2)	0.89	> 0.75
Baseline monitoring period standard error of the estimate	29.5 kWh/week	N/A
Retrofit monitoring period standard error of the estimate	30.1 kWh/week	N/A