Lessons from a Heat Pump Retrofit at CityHousing Hamilton

A TAF CASE STUDY | 2022

About The Atmospheric Fund

The Atmospheric Fund (TAF) is a regional climate agency that invests in low-carbon solutions for the Greater Toronto and Hamilton Area and helps scale them up for broad implementation. We are experienced leaders and collaborate with stakeholders in the private, public and non-profit sectors who have ideas and opportunities for reducing carbon emissions. Supported by endowment funds, we advance the most promising concepts by investing, providing grants, influencing policies and running programs. We're particularly interested in ideas that offer benefits in addition to carbon reduction such as improving people's health, creating local jobs, boosting urban resiliency, and contributing to a fair society.

For more information visit taf.ca or contact Keith Burrows, Senior Manager, Low Carbon Buildings at **kburrows@taf.ca**.

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THE ATMOSPHERIC FUND 75 Elizabeth Street Toronto, ON M5G 1P4

Content

Introduction

This research is part of TAF's Retrofit Accelerator program, aiming to demonstrate solutions and accelerate energy efficiency retrofits across the multi-family building sector.

This pilot project is part of a multi-year initiative to demonstrate the case for heat pump retrofits within multi-family buildings and to advance electrification of space heating in Ontario. The Atmospheric Fund (TAF), working with CityHousing Hamilton (CHH), planned and implemented a pilot project at a three-storey multi-family residential building with 40 units. We installed a heat recovery, variable refrigerant flow (VRF) air source heat pump (ASHP) system in three suites to test the performance of the technology under real-world conditions and to provide best practice recommendations. Results will guide potential scale up within this building and other multi-family buildings in Ontario. This case study provides results, lessons learned, and recommendations.

Project Goals

- Successfully pilot a heat recovery ASHP system in multi-bedroom suites.
- Achieve up to 60% space heating electricity savings compared to existing electric resistance baseboards.
- Inform best practice design and implementation of heat pump systems for broader scale-up of electrifying space heating in multi-family buildings across Ontario.
- Improve indoor comfort for residents by providing them with year-round control of indoor temperatures.
- Provide efficient summertime cooling to improve comfort and mitigate the effects of extreme heating events.
- Develop resident education program and materials around the use and control of the heat pump system.

What is unique about a heat recovery Air Source Heat Pump system?

An ASHP system simply transfers energy in the form of heat from one place to another. During the winter it operates in heating mode, transferring energy from the outside to heat interior spaces. In the summer, the system operates in cooling mode and transfers heat from the interior to the outside to provide air conditioning. A heat recovery ASHP is a little different. It is designed to simultaneously provide efficient heating and cooling across multiple interior building zones—the system can be operated in heating and cooling modes at the same time. This is ideal for buildings that have different space conditioning needs in different areas due to solar exposure, poor insulation, excessive air leakage, or diverse resident comfort preferences. And in addition to the energy conservation benefits, the flexibility of simultaneous heating and cooling removes the need for multifamily buildings to switch HVAC operation modes each season.

This piloted system also has a variable speed (or inverter style) compressor, allowing it to operate with different refrigerant pressures, flows, and temperatures. These fluctuations allow the compressor to have better flexibility and precision to meet varying heating and cooling loads compared to a single-stage system, for example.

Heat Recovery VRF system (VRF-HR)

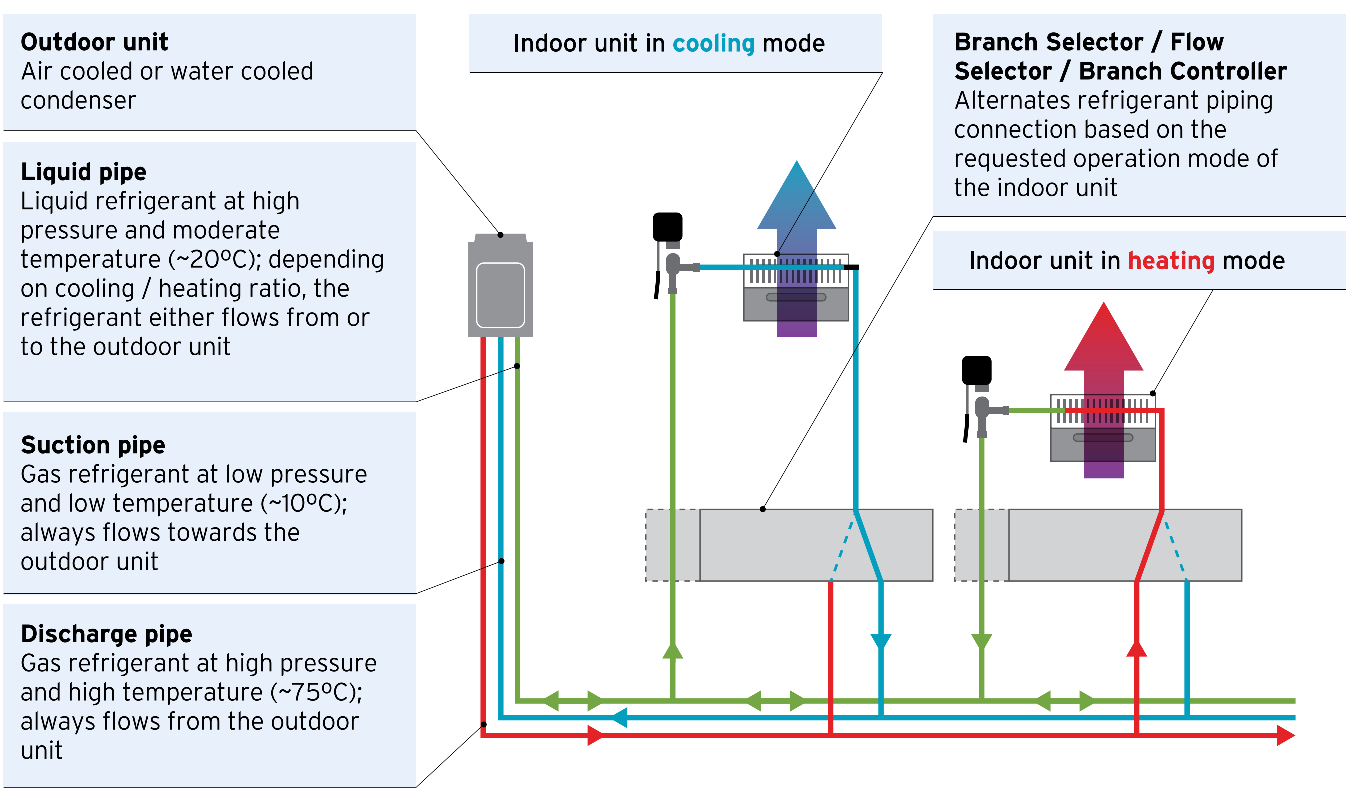

Figure 1. How a Heat Recovery VRF System works[1]

[1] Modified from Daikin, slide 13, https://www.slideshare.net/Ezhils3/vrf-ppt

Project Background

About the Building

25 Lynden Avenue is a multi-residential building owned by CityHousing Hamilton. The site was selected based on criteria including building characteristics, location, utility metering type, and existing heating equipment.

Address	25 Lynden Avenue, Hamilton, ON
Owner	CityHousing Hamilton
Gross Floor Area	30,340 ft^2
Year Constructed	1986
Building Form	3-storey residential building
Parking	Outside surface parking only
Occupancy Type	Seniors
Unit Type:	1 bedroom x 30 suites 2 bedrooms x 10 suites
Heating	**Suites:** Electric resistance baseboard heaters with non-programmable thermostats. **Common Areas:** Two engineered air units (DJ-40-0) with total input capacity of 500 MBH. Some areas served by electric baseboards and unit heaters.
Cooling	**Suites:** Through-the-wall A/C units installed and maintained by tenants, vary in size and efficiency. **Common Areas:** None.
Ventilation	**Suites:** Outdoor air supplied through pressurized hallways and suite entry and patio doors. Bathrooms equipped with ceiling exhaust fans that vent outside. **Common Areas:** Outdoor air supplied by two Engineered Air (DJ-40-0) make-up air units providing common area heating. Each unit has gas fired heating section and supplies 2,000 CFM of fresh air using one-horsepower supply fan.

Table 1: Case Study Building Information

System Design and Sizing

In June 2018, TAF installed and commissioned a single six-tonne (75,000 BTU/h rated heating capacity) heat recovery ASHP system to provide space heating and cooling for three suites. The system can operate with outdoor ambient temperatures down to -25°C. Three suites were retrofitted with indoor heat pump heads shown in Table 2 and Figure 2. The pilot included a one-bedroom suite for residents with reduced mobility and two standard sized two-bedroom suites. For more information on equipment selection, implementation process, and pilot costs please see Appendix A.

Based on size and configuration of each suite, TAF recommended large open-concept zones be served by one indoor head, with an additional head in sufficiently large bedrooms. In the suites with smaller bedrooms, we recommended placing single heads in corridors facing bedroom and bathroom doors. The living room units were well-situated, mounted to the upper wall corners to deliver sufficient space conditioning to the open concept living room, kitchen, and foyer space. Ultimately, we followed the recommendation from the manufacturer and contractor to serve each zone with its own head, including the small bedrooms in RS2 and RS3.

Suite Number	Size (ft.sq.)	No. of Indoor Units	Location of Indoor Units (Zones)	Rated Heating Capacity (BTU/h) of Indoor Units
Retrofit Suite 1 (RS1)	597	2	Living room	10,500
			Bedroom	10,500
Retrofit Suite 2 (RS2)	666	3	Living room	10,500
			Bedroom 1	8,500
			Bedroom 2	8,500
Retrofit Suite 3 (RS3)	666	3	Living room	10,500
			Bedroom 1	8,500
			Bedroom 2	8,500

Table 2: Pilot Suites System Configuration

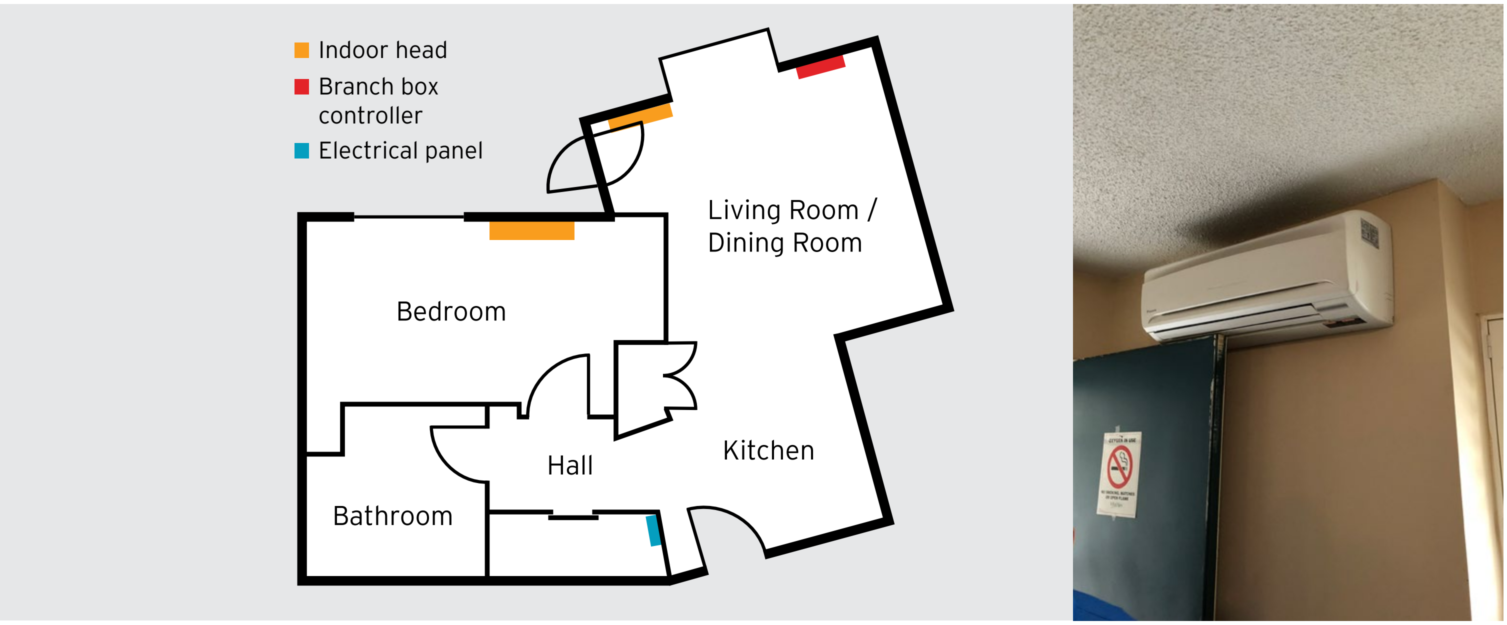

Figure 2: In-suite heat pump configuration of a one-bedroom suite

Figure 3: In-suite heat pump configuration of a two-bedroom suite

Measurement and Verification Approach

Monitoring the Heat Pump System

TAF monitored the performance of the system using the International Performance Measurement and Verification Protocol (IPMVP)[2] Option B (Key Parameter Measurement) which measures the actual energy used in the field by an energy saving system. This option was chosen for a few reasons. Looking at building electricity use for the whole building (as shown in Appendix B) does not provide enough granularity to accurately show the impact of the installed heat pump system. Typically, if an energy saving measure results in less than a 10% impact on a whole building utility meter, system-specific measurement is recommended. Additionally, to develop a deep understanding of how a specific ASHP system is operating and performing (which is not necessary in most installations if performance is satisfactory), the operating parameters of the system need to be monitored to understand which variables help drive efficient operation.

Pre-Retrofit Monitoring

To quantify the space heating energy savings from the heat pump system, TAF monitored the energy consumption of the existing electric baseboards using Monnit's Alta wireless meter series, recording current and voltage at 10-minute intervals over 10 months. Data was transmitted wirelessly from individual sensors across 12 suites to a central gateway, where it uploaded to an online web portal in real time. Additional monitoring details are provided in Appendix C.

Post-Retrofit Monitoring

We monitored the energy consumption of the heat pump system for a period of two years at five-minute intervals. We used Accuenergy's Acuvim IIR Series Power and Energy meter to monitor the energy consumption of the heat pump system. It was set up to record the data from the power supply lines at the outdoor compressor unit. We also deployed a Daikin field diagnostic monitoring system called a Service Checker that was connected to the heat pump system so that we could monitor key operational parameters of indoor and outdoor equipment for nine months (October 2019 to July 2020) at one-minute intervals. The Service Checker allowed monitoring of the compressor and head operating mode and activity, refrigerant return and supply temperatures, and expansion valve status, which allowed us to calculate heating and cooling delivered (BTU/h) and the system operating capacity.

End Use Measured	Parameters Measured
In-suite space heating and cooling	• Current, voltage, and energy • System and zone heating and cooling delivered (BTU/h) • Expansion valve open/closed status • Liquid refrigerant pipe temperatures • Gas refrigerant pipe temperatures

2 For more information on IPMVP, refer to Efficiency Valuation Organization's ***International Performance Measurement and Verification Protocol*** and ***IPMVP Summary***.

The indoor heads of the heat recovery ASHP system are powered by in-suite electrical panels. However, due to monitoring device complications, the monitoring of individual in-suite head electricity usage was not possible. Since the combined electricity usage for all the indoor equipment was small[3], the Acuvim electricity meter and the Daikin service checker were used to measure total system performance.

Monitoring Comparable Suites

Space Heating

We continued to monitor the space heating electricity usage of four non-retrofitted suites using HOBO data loggers deployed directly at each suite's electrical panel from February 2019 to March 2020. We opted for devices that supported manual data download via reoccurring visits to each suite to avoid some of the previous issues we faced with wireless data collection during pre-retrofit monitoring.

Air-Conditioning

We monitored cooling consumption across seven non-retrofitted suites, capturing approximately 18.5% of the total building cooling energy usage profile. Each resident had one A/C unit installed of varying age and condition. HOBO Plug Load Loggers were connected to the air conditioners directly to measure consumption. These loggers recorded current, voltage, and energy consumption at five-minute intervals. The loggers recorded data between August 2018 to February 2019.

Monitoring Indoor Environmental Quality

Indoor Environmental Quality (IEQ) was monitored pre and post-retrofit to identify changes in the indoor temperature and relative humidity within the suites. Pre-retrofit IEQ monitoring was conducted using Monnit's Alta wireless temperature and relative humidity sensors installed in 12 suites, capturing data at 10-minute intervals. These communicated and uploaded data via the same gateway and online web portals as the energy monitoring systems.

Post-retrofit IEQ parameters were captured using HOBO wireless temperature and relative humidity sensors in three retrofitted and six non-retrofitted suites, capturing data at 10-minute intervals, from June 2018 to March 2020. We downloaded data from the building using a Bluetooth connection between the sensor and a smart phone device.

IEQ monitoring devices were deployed in the same location in every suite in the living and dining room areas for both pre and post-retrofit monitoring periods, as these were the largest space conditioned areas in every suite.

See Appendix C for more details.

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[3] *Based on manufacturer recommendations, the electric consumption of the indoor heads represents no more than 7% of total electricity usage for the entire heat pump system.*

Performance Analysis

Heat Pump System Meets Heating and Cooling Demand

TAF conducted two years of measurement, verification, and continuous commissioning between 2018 and 2020 and received survey feedback from residents. While outdoor temperatures reached -25°C and -17°C during the first and second winters respectively, the system was able to meet the full space heating demand. All three retrofitted suites maintained indoor temperatures between 21°C and 23°C on average, providing comfortable temperatures during the heating seasons.

The heat pump systems helped maintain cooler indoor temperatures, with average summertime temperatures of retrofitted units 2.5°C lower than the baseline units. This is a critical observation as we see higher summertime temperatures occurring across Canada year over year. However, relative humidity levels were very similar for both the baseline and retrofitted units. We expect this is due to humidity levels being dependent on multiple factors beyond just the heating and cooling systems. See appendix E for more details.

Space Heating Electricity Savings were not Realized

TAF's analysis of the heat recovery ASHP performance found no energy savings when compared to the pre-retrofit baseboard consumption, as shown in Figure 4. The pre-and-post electric space heating consumption is shown, normalized per heating degree day (HDD) and per monitored suite. The data is based on the average consumption of the three monitored suites participating in the pilot which relied on electric baseboards pre-retrofit and the heat pump system post-retrofit. Our initial analysis focused on the coldest periods December to February. Through discussions with CityHousing Hamilton, we agreed to re-run the analysis for the official tenant heating season (September 1–May 15) as regulated by a Hamilton Bylaw. Under both scenarios we found the space heating consumption for the retrofitted suites to be significantly higher compared to electric baseboard suites in the first year post-retrofit, before dropping during the second year. The result was unexpected, so we investigated the root cause of these performance issues and developed plans to address them.

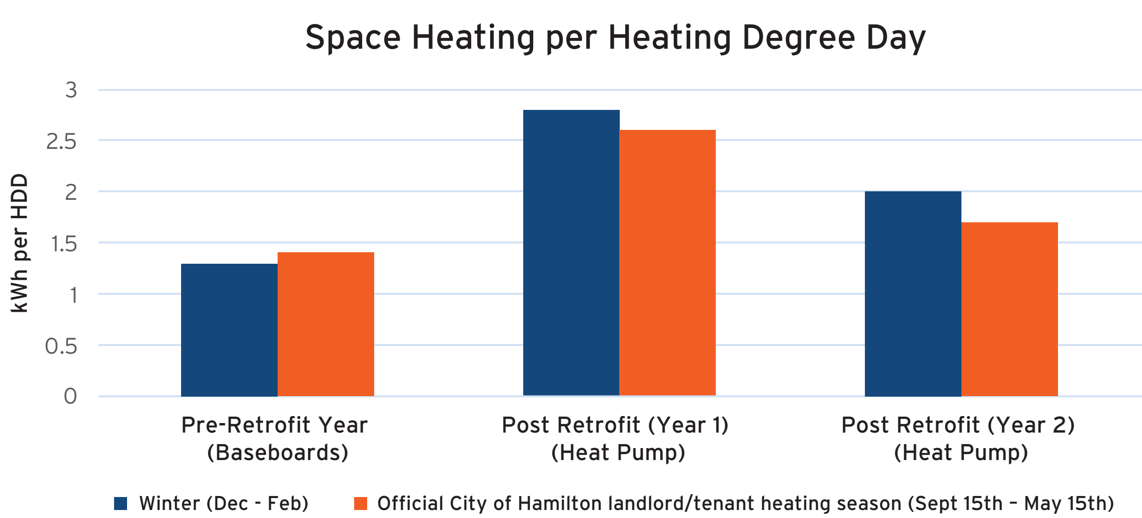


Figure 4: Heating kWh per heating degree per suite for electric baseboards (pre-retrofit) and heat pump (post-retrofit)

Investigating System Performance Issues

System short-cycles during the heating season

The heat recovery ASHP system was on for approximately 44% of the heating season between October 2019 and May 2020. However, we observed frequent short cycles, where the system turned on for less than 10 minutes at a time. Figure 5 shows that even when operating during longer on-cycles, operating capacity maxed at 16.8% of the nominal capacity. This is significant because the capacity control range for this system is between 15% to 100%, and the system is designed to run continuously as much as possible within this range. In fact, the system came on very briefly during milder heating conditions, quickly meeting the indoor heating demand, turning off, and then repeating the process once the delivered heat had dissipated. An analysis of the coldest periods (December 2018 to February 2019) shows similar trends.

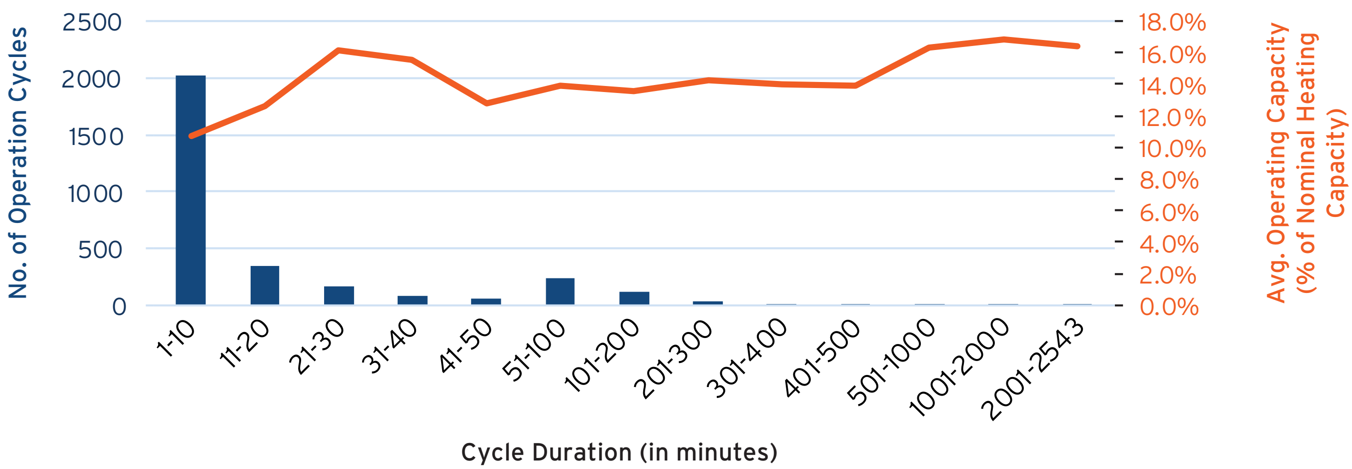


Figure 5: Number of cycles and average system operating capacity between Oct 2019-May 2020

As the system was able to meet the heating demand very quickly, it short cycled and operated near or below the lower end of its capacity control range. Figure 6 shows that the system required more electricity to operate at the lower end of the control range than when capacity utilization was higher. For example, the average operating power of the system was 3.8 kW when operating at <15% of its nominal heating capacity, but the average operating power was only 2.8 kW when operating between 75-90% of nominal heating capacity. Although these power consumption values are below the maximum consumption of 5.9 kW, when operating at the lower end of the control range, the system used significantly more power.

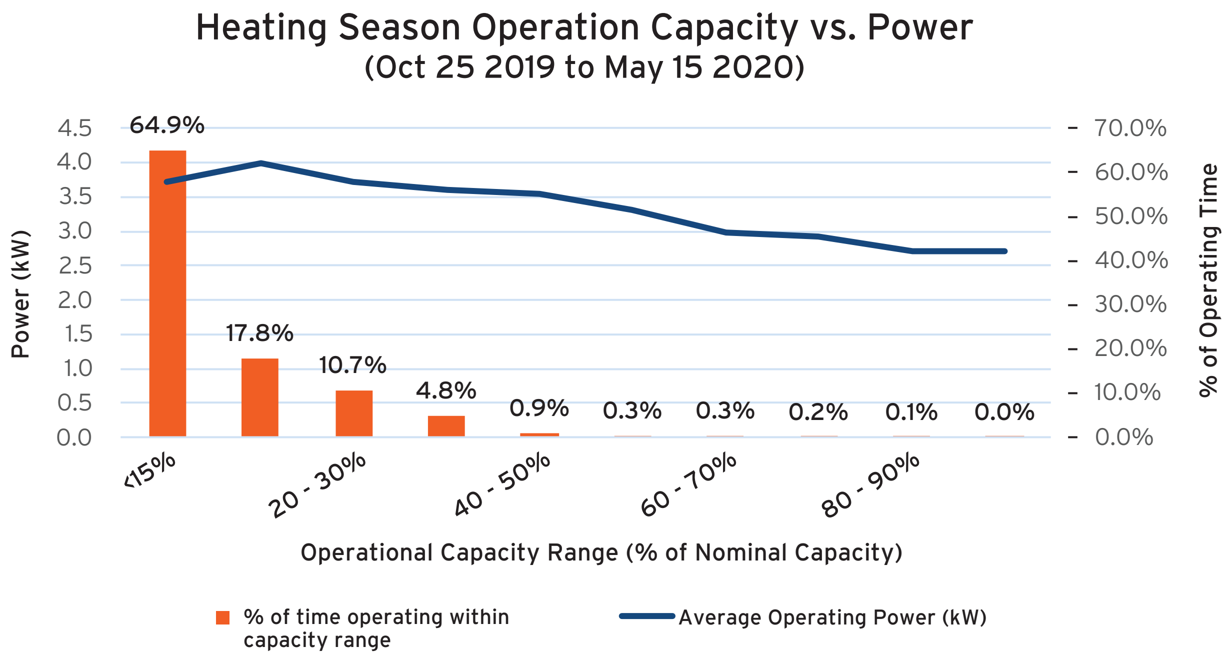


Figure 6: Operational Capacity vs. Power (Dec 2019 to Feb 2020)

This analysis shows that the system was oversized for the heating demand of the three suites. Right sizing heat pump systems is critically important, and balancing is paramount so that systems are sized and calibrated to meet heating demand for the lowest outdoor winter temperatures while ensuring the system is not cycling frequently during milder temperatures. This often can be accomplished in traditional multifamily building heating systems by having certain components staged to only come on during periods of extreme cold. And this case study has shown us that in some situations, heat pump systems may require a similar approach with regards to balancing.

System also short-cycles when cooling

We conducted a similar capacity analysis to verify how much of the system was utilized when delivering air conditioning. The air conditioning turned on for approximately 46% of the time during the cooling period monitored from May 2020 through July 2020. Once again, the data showed that the system was operating at less than 15% of its capacity over 99% of the time it was on. These summertime results also support the conclusion that the heat pump system is oversized, although it is not unexpected or unusual that a heat pump system sized to meet 100% of heating demand in a cold climate will be oversized for cooling.

The Importance Of Matching Size To Demand

It is clear the heat recovery ASHP systems can meet the conditioning demands of multi-family buildings, while keeping occupants comfortable year-round and providing them with the flexibility to independently control various areas of their homes. However, given the misalignment between the designed capacity and the demand, TAF and our manufacturer partners revisited the design and explored how the system could achieve optimal operating capacity and realize the expected savings.

We are confident that the existing system could serve an additional three to four zones to help balance system operation and improve performance. Eight indoor units are currently installed, but the outdoor unit can accommodate an additional four. Increasing the demand through servicing more zones is expected to balance the system, so it runs for longer cycles and operates within the desired capacity control range. Ultimately this will result in the system running at a more efficient power consumption level.

TAF conducted a zoning analysis, comparing how much and how often the indoor units are being activated during the heating and cooling seasons. Each indoor head was using only a quarter of its heating capacity, on average, and approximately 3.1% of the *total* system capacity. By expanding the current system to service an additional four suites, the system operating capacity will be sufficiently raised to avoid cycling and inefficient power consumption. One head would be installed per suite in the living room/dining room areas (covering most of the living area of each suite), and bedroom baseboards would be left connected for supplemental heating. This would allow us to maximize system utilization with the four additional indoor heads, as heads in the main living areas can supply most of the heating and cooling needs for a suite.

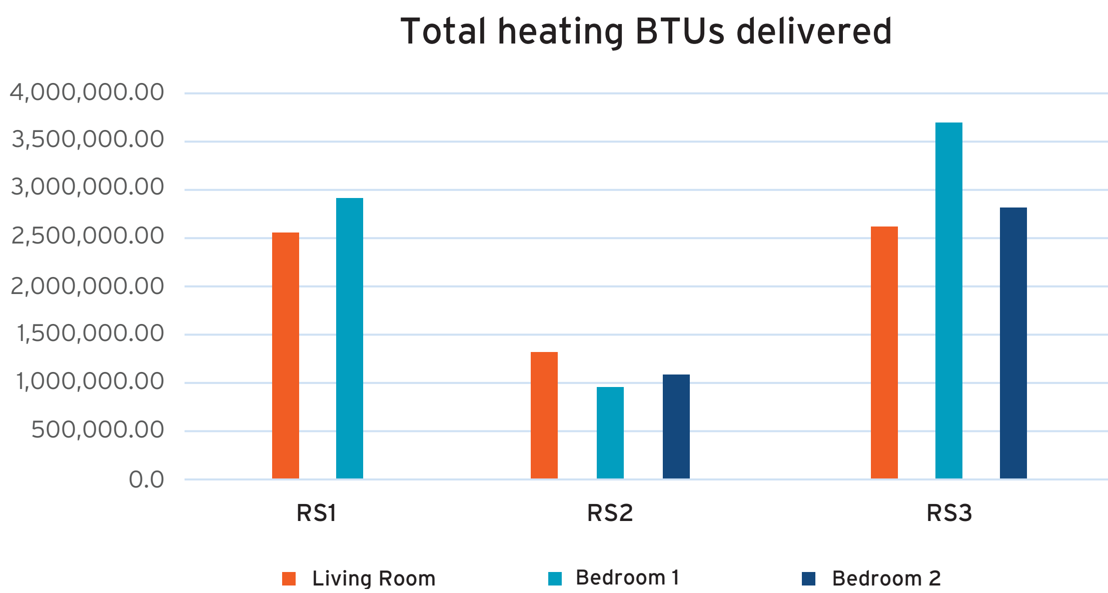
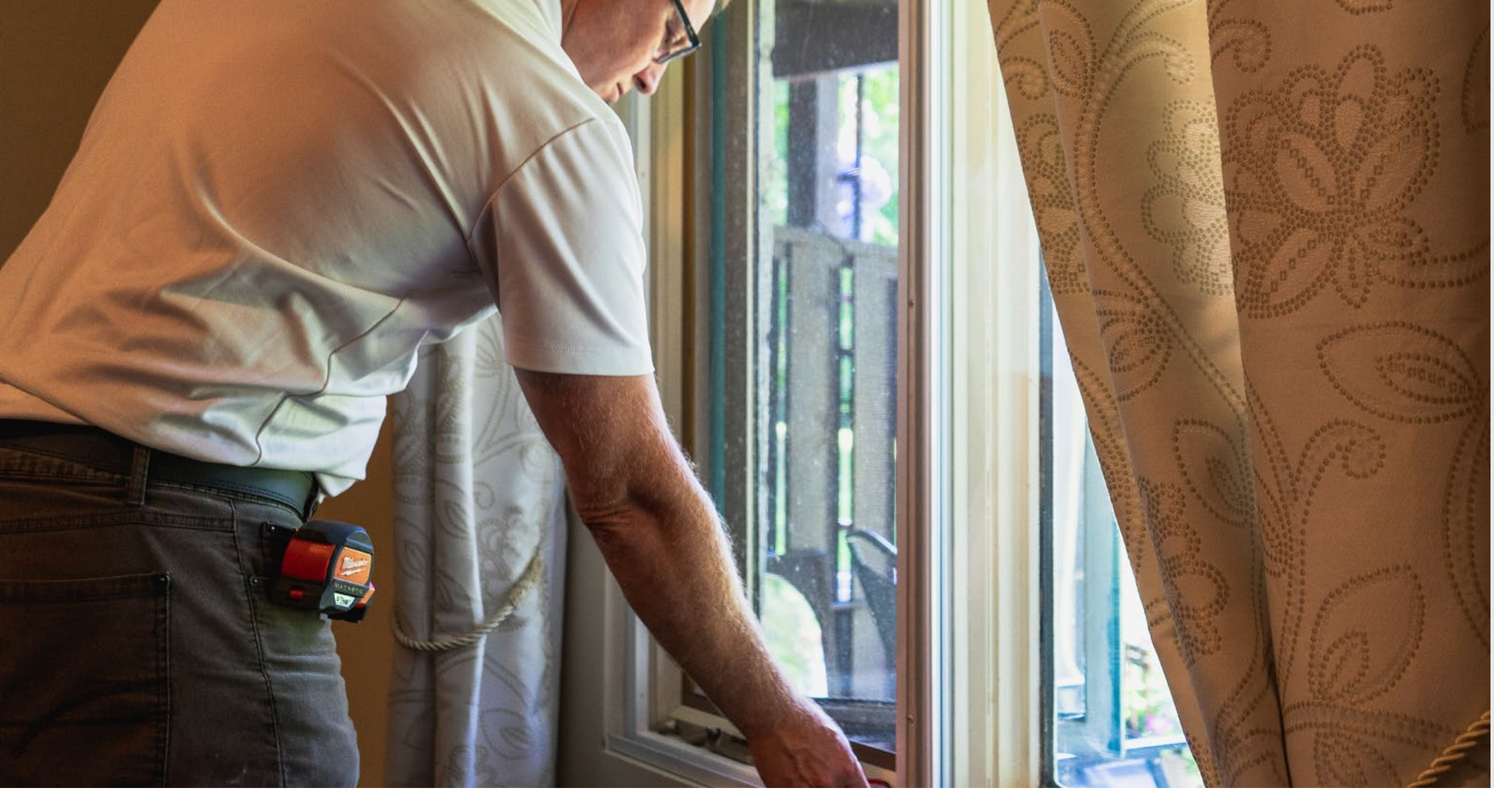


Figure 7: ASHP heating BTUs delivered per indoor zone (Dec 2019 to Feb 2020)

The exact number and location of suites to include for expansion should be determined by carefully analyzing existing suite-level heating system use and consumption and using this information to select suites that will increase heating demand enough to ensure the heat recovery ASHP consistently operates within the capacity control range.



Lessons Learned and Recommendations

TAF and third-party experts have concluded that the heat pump system was significantly oversized relative to the heating load demand, leading to inefficient operation and use of electricity. This resulted in a system that responded to the thermal load in a very abrupt manner. This operation is not typical of the gradual ramping up of inverter-driven compressors from minimum power draw to meeting the full demand.

Lessons learned from this case study are intended to inform best practice approaches in designing and implementing similar systems. Our recommendations include:

1. **Engineers and Installers**

   Optimize system sizing and balancing to avoid heat pump cycling and savings shortfalls. A key lesson learned was that rule-of-thumb sizing (the ASHP was sized to meet the capacity of the existing baseboards) for heat pumps can lead to extreme oversizing and poor performance. A much smaller (and less expensive) system could have met the heating and cooling demand of these suites, and during peak wintertime conditions, the existing baseboards could have been used as supplemental /backup capacity. However, it should be noted that baseboard backup may not always be the best approach and should be evaluated on a case-by-case basis. Appropriate care should be taken by a qualified professional to analyze the space conditioning needs per zone to select the right sized equipment, layout, integration controls and sequencing to achieve optimal system balancing and performance.

2. **Building Owners**

   Monitor pre-retrofit to help with system sizing. A pre-retrofit measurement and verification plan which includes monitoring consumption at select suites as well as investigating resident behaviour can add important context to the design process and will provide a check on engineering heat loss calculations. This type of pre-retrofit analysis will not only align system capacity to the actual demand but can also help reduce capital costs in avoiding the installation of a larger system.

3. **Manufacturers**

   Offer a wider range of indoor head sizes to help drive adoption of heat pumps in multifamily retrofits. In Canada, the demand for heat pumps is still low compared to Asian and European countries. Consequently, manufacturers and distributors lack incentive to offer a broad selection of indoor equipment sizes, even if they are available overseas. This limits how often heat pumps are considered for multifamily retrofits, as contractors cannot match the available equipment to the zone demand in some cases. More importantly, providing more and adequte options reduces the risk of perceptions of poor performance that could slow down the pace of heat pump adoption.

4. **Building Owners**

   Perform startup and optimization commissioning to ensure performance. Commissioning HVAC systems is a process that follows installation to test operational functionality with a focus on the system's ability to efficiently meet demand. Startup commissioning happens shortly after the system is turned on. Optimization commissioning is the process of evaluating operational performance of the system over an extended period of time and taking action to achieve optimal system performance if necessary. Both start-up and optimization commissioning should be performed by trained and experienced professionals. In this project, start-up commissioning was performed by a VRF expert, but start-up commissioning alone is not likely to identify capacity issues, which are more likely found during optimization commissioning.

5. **Industry Trainers and Funders:** Advance industry capacity to include designing and implementing heat recovery heat pump systems. Scaling deep retrofits in Canada will require trained and experienced contractors and technicians that can service the emerging high efficiency technologies needed for meeting our targets in the building sector. Heat recovery VRF heat pumps are a new and emerging technology in Canada with few industry practitioners having knowledge and expertise in designing, installing, and maintaining these systems. For this particular project a lack of local industry experience created difficulty in obtaining contractor bids, which slowed down the process of system and contractor selection. Without sufficient and qualified industry capacity, we will be unable to electrify buildings at the scale needed to meet our emission reduction goals.

Appendix A: Equipment Selection, Implementation, and Costs

Equipment Selection Process

Selection of the right heat pump style, make, and model will always be context specific. The final selection and sizing of the heat recovery ASHP system was done using the following process:

Equipment Manufacturer	Equipment Model
Preliminary Selection (2017)	• TAF estimated that up to six suites could be retrofitted at the site under the research budget. This was based on the data from three engineering audits performed by third-party engineers and their cost consultants. • TAF reviewed the performance and functionality literature for numerous multi-split systems (Carrier, Daikin, Fujitsu, LG, Mitsubishi, and Panasonic) and narrowed the selection to models made by Daikin and Mitsubishi.
Detailed Selection: (2017-2018)	• Daikin and Mitsubishi helped TAF select the best suited models and connect with contractors that could provide quotes on the pilot project. • Daikin and Mitsubishi cold climate models were reviewed in detail. • Ultimately Daikin was selected as the best financial and technical fit for this project. • The three Daikin systems that were reviewed in detail were: – VRF ASHP system (RXYQ72TTJU) lowest cost option capable of operating at -20˚C. – VRF ASHP system with heat recovery (REYQ72TTJU) mid-range cost option capable of operating at -25°C. – Aurora VRF ASHP system with heat recovery (RELQ72TATJU) – most expensive option capable of operating at -30°C. • TAF ultimately selected the mid-range Daikin option because of its expected superior performance within budget compared to a non-heat recovery heat pump.

The selected system details are as follows:

Description	6-Ton Heat Recovery VRF Unit
Rated Heating Capacity (Btu/hr):	75,000
Nominal Heating Capacity (Btu/hr):	81,000
Rated Heating Operation Range	-25 Celsius to 16 Celsius
Required Power Supply:	208-230 Volts / 60 Hz / 3-phase
Capacity Control Range (%):	15 - 100

Implementation Process

Design process: 2017/2018	• Daikin's commercial VRF team and the installation contractor presented a design proposal to TAF and CHH, including system design and sizing. • Both TAF and CHH reviewed and provided feedback. • CHH provided final signoff to proceed with the retrofit pilot.
Installation: 2018	• The installation contractor managed all aspects of equipment and material procurement and installation, apart from line set covering, which was managed by TAF directly with a local third-party contractor already approved by CHH. • TAF and CHH inspected all work during the project. Installations were completed in June 2018.
Start-up Commissioning: June 2018	• Daikin and a third-party Daikin affiliate VRF systems expert, Direct Expansion Solutions, executed the start-up commissioning process. The system was operational by end of June 2018.

Pilot Project Cost

The total retrofit pilot costs were $56,753 (excluding taxes). These figures include the supply and installation of all system equipment, materials, and a dedicated electricity meter.

ITEM	COST[4]	SCOPE OF WORK
Heat recovery VRF system installation and commissioning	$49,895	Supply and installation of indoor and outdoor VRF equipment.
Exterior line covering	$4,650	Supply and installation of sheet metal coverings for all exterior insulated line set runs.
Electricity meter for heat recovery system	$2,208	Supply and installation of electricity metering equipment in an outdoor weatherproof box for monitoring heat recovery system performance.
TOTAL	**$56,753**	

Note: TAF and the contractor did not apply for any incentives, which could reduce project costs.

4 *Excluding any applicable taxes.*

Appendix B: Methodology and Detailed Data

Analysis Part 1: Savings were not realized

To establish a benchmark, TAF aggregated the metered consumption of all three suites' baseboards and created a linear regression model where heating daily degree days (HDD) was the independent variable and daily electrical baseboard consumption the dependent variable. TAF projected baseboard consumption for October 2018 through April 2019 using this regression model and compared the results to the outdoor compressor's actual consumption during the same period.

TAF's benchmarking of the heat recovery VRF ASHP to the projected electrical baseboard consumption revealed that during the 2018-2019 heating season, the heat recovery VRF ASHP consumed 54 per cent (22 kWh) more than the electrical baseboard heaters were projected to consume on average per day. Providing a broader perspective, Figure 1 below shows the recorded daily ASHP and expected baseboard electricity consumption. Figure 1 plots consumption against daily Heating Degree Day (HDD, base 18°C) over the 2018-2019 post-retrofit monitoring period.

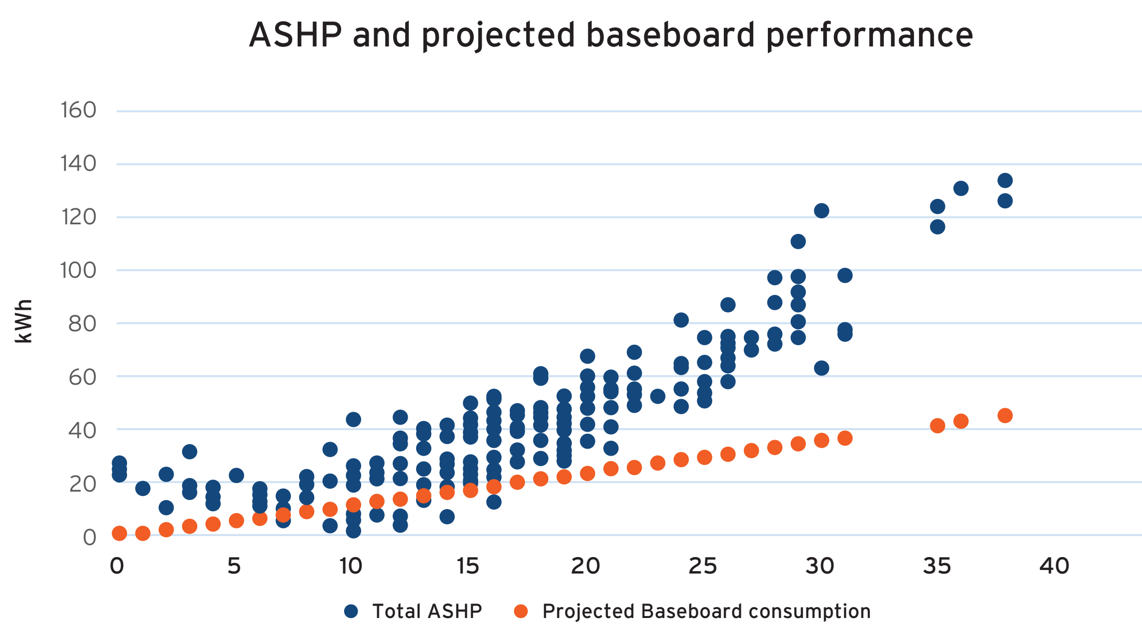


Figure B1: ASHP and projected electric baseboard performance

TAF is aware of heat pump retrofits where resident behaviour led to reduced savings, but for this phase of the analysis we were not able to identify specific behaviour(s) that might account for the lack of energy savings. Based on surveys, site visits, and discussions with residents, the TAF team made the following observations regarding pre-and-post retrofit behaviour:

- The thermostat operating settings for the baseboards and heat pumps were mostly between 22°C and 24°C during the pre-retrofit and post-retrofit periods. The setpoints only changed during extreme cold conditions, according to feedback provided by residents.
- During TAF's site visits, residents have confirmed that they do not often open their windows during the winter and the heat pumps operate on "HEAT" mode during the post-retrofit heating season.
- During an interview with one of the residents, they mentioned that they rarely needed to use their baseboard heaters prior to the heat pump installation; their pre-retrofit consumption reflects this limited use.

Analysis Part 2: Taking a closer look at heating performance

As the savings were lower than anticipated, the first possible explanation is to see if the system had been short cycling. The operation data monitored spanned the period from October 25, 2019 to July 24, 2020. By comparing the results to manufacturer rated specifications, TAF was able to reference the actual operating performance and correlate it with the lack of savings seen from the analysis results presented in Part 1.

Operational Capacity

To arrive at the actual real-time operational capacity of the heat pump, the heat blown across all zones had to be aggregated and referenced to nominal and rated heating capacity. Some of the operating parameters gathered from the service checker data, such as the indoor liquid pipe temperature and gas pipe temperature, were used to calculate the heat blown into the zones. The volumetric flow rates as well as thermal and mass properties of air were extracted from manufacturer data and standards sheets, respectively. The mathematical formula utilized to approximate the heat blown is:

$$\text{Heating BTUs} = \text{CFM} \times \Delta T \times 0.075 \frac{\text{lbs}}{\text{CFM}} \times 0.24 \frac{\text{BTUs}}{\text{Lbs } \Delta T} \times 60 \frac{\text{minutes}}{\text{hour}}$$

The above equation is applied to calculate the Heating BTUs delivered for each of the indoor units. The "Heating BTUs" mathematical model is an established heat transfer equation, and the accuracy of the results should be a close reflection of the performance. When the expansion valve is shown to be off across all indoor heads data, the operational capacity is zero. If not, the total heat blown is aggregated, then divided by the nominal outdoor unit capacity to arrive at an operating capacity at a certain timestamp. The nominal heating capacity for the installed system was 81,000 Btu/h, the rated heating capacity was 75,000 Btu/h, and the capacity control range was 15%-100%.

	Measured Capacity vs. Nominal Capacity		Measured Capacity vs. Rated Capacity	
Capacity Range	**# of time stamps when system ON**	**% of time stamps when system ON**	**# of time stamps when system ON**	**% of time stamps when system ON**
>0% and <15%	**41,715**	**64.12%**	**37,990**	**58.39%**
≥15% and ≤20%	12,169	18.70%	14,214	21.85%
>20% and ≤30%	6,658	10.23%	6,816	10.48%
>30% and ≤40%	3,304	5.08%	4,304	6.62%
>40% and ≤50%	617	0.95%	1,015	1.56%
>50% and ≤60%	175	0.27%	232	0.36%
>60% and ≤70%	210	0.32%	170	0.26%
>70% and ≤80%	153	0.24%	180	0.28%
>80% and ≤90%	60	0.09%	115	0.18%
>90% and ≤100%	0	0.00%	25	0.04%
TOTAL	**65,061**	**100%**	**65,061**	**100%**

Table B1: Heating Season capacity utilization, December 2019 to February 2020

Given that the heat pump was rarely using more than 20 per cent of its capacity, the system was determined to be oversized. This led to inefficient use of electricity due to a consistently higher electricity draw when operating below the optimal capacity range.

Operating Capacity Range	Average Voltage	Average Compressor Current (Amps)	Average Operating Power (kW)	% of time system operates within capacity range
>0% and <15%	**208**	**18.1**	**3.77**	**64.89%**
≥15% and ≤20%	208	19.2	4.00	17.82%
>20% and ≤30%	208	17.9	3.72	10.71%
>30% and ≤40%	208	17.4	3.62	4.84%
>40% and ≤50%	208	17.1	3.56	0.87%
>50% and ≤60%	208	15.8	3.28	0.26%
>60% and ≤70%	208	14.1	2.94	0.31%
>70% and ≤80%	208	14.1	2.92	0.22%
>80% and ≤90%	208	13.1	2.72	0.08%

Table B2: Heating Season operating power, December 2019 to February 2020

Analysis Adjusted to Hamilton Bylaw Heating Season (Sep 15 to May 15)

Through discussions with CityHousing Hamilton we agreed that it made sense to re-run the analysis for the official landlord/tenant heating season (Sept. 15 – May 15) as regulated by the Hamilton Bylaw. The hypothesis was that system should be more efficient in the shoulder seasons at higher outdoor ambient temperatures, and looking only at the coldest months, December to February, potentially ignores the largest chunk of savings. However, as we have previously reviewed, the system performed worse in the shoulder season due to increased cycling and running below its capacity control range.

Appendix C: Monitoring Equipment

Pre-Retrofit Monitoring Equipment

Data was wirelessly transmitted from each sensor to the Alta cellular gateway and then to an online monitoring portal where it could be remotely downloaded or viewed in near real-time. The pre-retrofit monitoring period spanned the 2017-2018 heating season.

Type	Manufacturer and Model	Location	Range	Operational Accuracy
Current meter	ALTA wireless AC current meter	In-suite service/ control panel	Current 2-150A	±2%
Voltage meter	ALTA wireless voltage meters	In-suite service/ control panel	Voltage 0-500V	±3%
Cellular gateway	ALTA 3G Cellular Gateway	Common areas in the building	N/A	N/A

Plug-in load meters were used to measure the A/C consumption at five suites, from August 2018 – February 2019. These suites were not retrofitted and were monitored to approximate the air conditioning consumption.

Type	Manufacturer and Model	Location	Range	Operational Accuracy
Plug load meter	HOBO UX120 Plug Load Logger	Power socket feeding A/C window units	Current 0-14A	±0.5%

Post-Retrofit Monitoring Equipment

A power meter was installed at the outdoor ASHP unit to monitor the current and voltage consumption of the circuit lines from August 2019 to July 2020.

Type	Manufacturer and Model	Location	Range	Operational Accuracy
Power and energy meter	Accuenergy Acuvim Power Meter plus Meter Box AcuPanel 9104X-IIR-333-P1	Installed on circuit lines dedicated to ASHP's Outdoor unit on the exterior of the building	Voltage 10V-1000kV Power 9999MW-9999MW	±0.2%
Alternating Current transformer	Accuenergy AcuCT – H040-40:333	Installed inside power meters	Current 5mA-50000A	±0.5%
Wireless transceiver	AXM-WIFI Communication Module	Outdoor unit	N/A	N/A

The Accuvim IIR has the CTs and fused terminal blocks for voltage connections pre-wired and pre-configured. The AcuMesh allows wireless connection between RS-485 supported devices and the Accuvim Power meter raw data. This is done by connecting a computer device on-site with the meter's real-time data through the online portal. The historical data can be accessed and downloaded as CSV files.

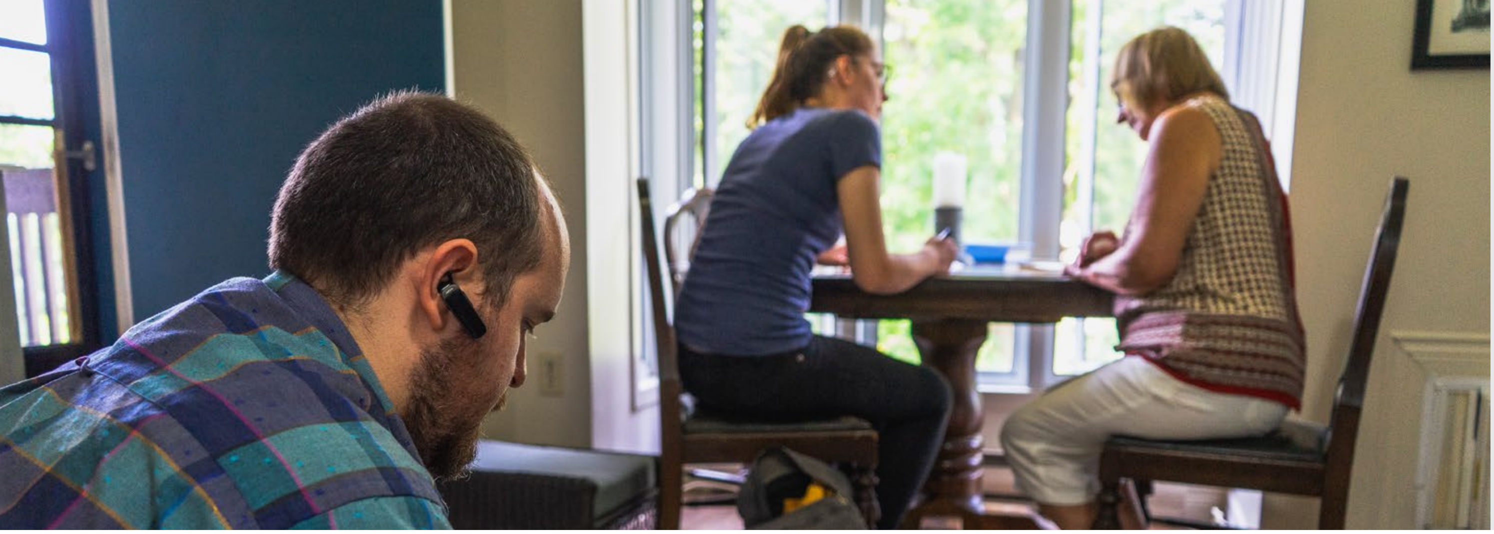
Daikin Service Checker

The Daikin service checker used for this pilot project is a field diagnostic device that is connected to the heat pump system and monitors key operational data through temperature sensors, pressure sensors, and several kinds of solenoid valves. The service checker was used to assess detailed operational performance of the system—something that could not be done by monitoring electricity consumption and indoor conditions alone. This device simultaneously monitors all components of the system, including the outdoor unit and the multiple indoor heads. The Daikin service checker connection is made to the transmission terminal board located on the printed circuit board of the outdoor unit. The operation data is then pushed to a computer through a RS-232 to USB adapter cable. Using a Bell mobility WIFI hub and TeamViewer remote access account, operation data can be accessed remotely and downloaded.

IEQ Monitoring Equipment

TAF installed indoor temperature and relative humidity sensors that monitored the interior conditions. 12 suites were monitored pre-retrofit between October 2017 and September 2018, and 6 non-retrofitted suits and three retrofitted suites were monitored, between June 2018 to March 2020.

Type	Manufacturer and Model	Location	Range	Operational Accuracy
Temperature sensor	HOBO-mx1101-datalogger	Living Rooms/ Bedrooms	-20°C to 70°C	±0.21°C from 0°C to 50°C
Relative Humidity sensor	HOBO-mx1101-datalogger	Living Rooms/ Bedrooms	0-99%	±2.0% from 20% RH to 80% RH to a maximum of ±4.5% (including hysteresis) at 25˚C; ±6% below 20% RH and above 80% RH



Appendix D: Resident Survey

TAF surveyed residents already participating in the energy monitoring study to better understand their habits, perceptions and concerns relating to indoor environmental quality. Specific questions regarding indoor temperature, humidity, ventilation, and presence of odours were asked. Participation in the survey was voluntary. Six non-retrofitted and three retrofitted units were surveyed.

Key trends are summarized below.

Resident Profiles

- All respondents have lived in their suites for more than two years.
- All respondents were seniors and reported being at home for much of the day.
- Some respondents take measures to reduce odours/drafts in their homes, while others do not. Respondents that report taking measures focus on their windows and doors.

Thermal Comfort and Odours

- Two non-retrofitted suites reported that dry air year-round and tobacco smoke/other smoke from neighbours bothered them every day. One non-retrofitted suites reported own and neighbourhood cooking smells bothered them once or twice a week, particularly in the summer. One retrofitted suite reported that they were bothered by dry air every day and their own cooking smells once or twice a week, year-round.
- Out of 10 respondents, two suites reported drafts in their living room (pre-retrofit). No suites reported drafts post-retrofit.
- Pre retrofit, majority of respondents reported opening their windows every day and using window blinds, year-round. Two suites reported doing this once or twice a week.
- Pre-retrofit, 80% of respondents reported thermal comfort was 'just-right' across all rooms, year-round. 16% of respondents reported kitchens and living rooms were too warm in the summer and 4% reported bathrooms and hallways were too cold year-round.

Use of Supplemental Equipment

- Pre-retrofit: three suites reported using portable fans every day, year-round and two suites reported using these once or twice a week. Two suites reported using air fresheners every day, year-round and two suites reported using these once or twice a week. Two suites reported using window A/C every day during the summer and one unit reported using these once or twice a week in the summer.

Heat Pump System

- 63% of respondents reported the heat pump system is ‘significantly better’, 25% reported ‘somewhat better’, and 13% were not sure.
- When asked how easy it was to operate the heat pump system, respondents had varying responses. Some reported it was ‘difficult’, while others reported ‘somewhat easy’ and ‘very easy’. One unit specifically reported that it was somewhat difficult to switch between heating and cooling. Majority of respondents reported there was no change in how easy the system was to use over time.

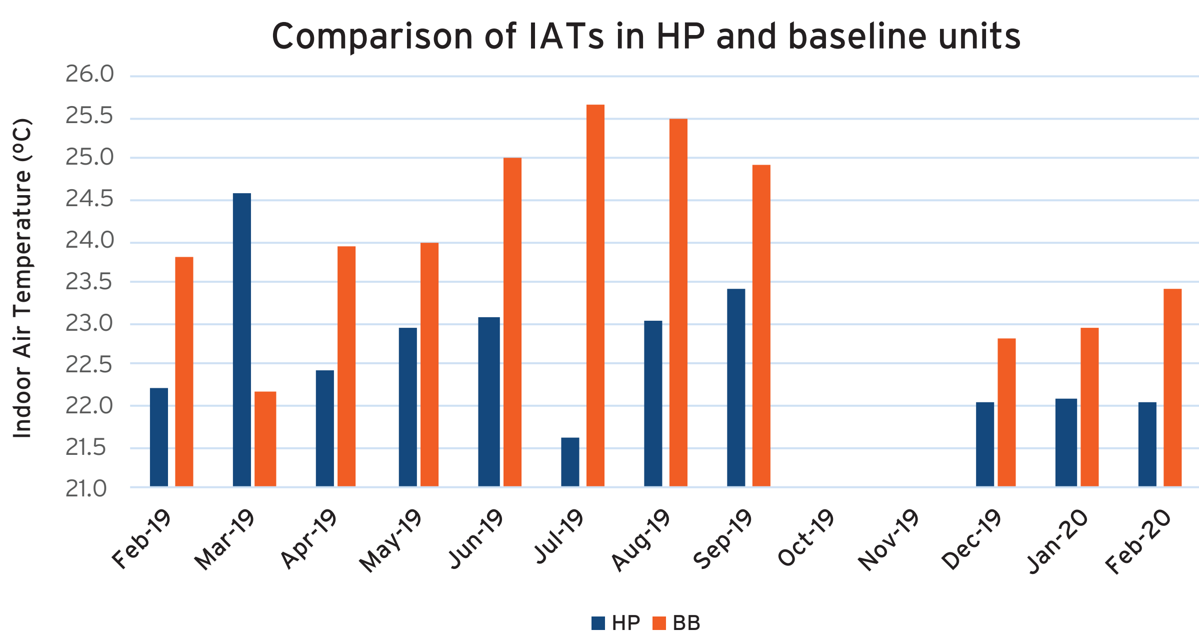
Additional Free-Form Comments

- One respondent reported they don’t want to be forced into switching to new system, and like the fact that can control their own temperature. They are worried combined system might limit temperature.
- One respondent reported they need weather stripping on doors and windows because they do not use any heat in winter. The stovetop vent does not work, and the window air conditioner is very loud.
- One respondent reported living room floors are cold because of opening in the wall for the air conditioning unit.
- One respondent reported that they must turn on two fans and open the balcony door when cooking otherwise the smoke alarms will go off. Heating is uneven (gets too hot then too cold when you turn it off).
- One respondent reported liking the system but had trouble controlling the cooling.
- One respondent reported temperature is progressively colder in the bedrooms during summer cooling mode. Noise coming from one unit between 9-11PM.
- One respondent reported being happy with the quick fix of water dripping on the balcony during cooling mode.

Appendix E: Indoor Air Temperature and Relative Humidity

Throughout the year, temperatures in baseline units (where residents used electric baseboard heaters and air conditioners) remained higher in comparison with retrofitted units by an average of 1.3ºC. Average temperatures in retrofitted and baseline units were 22.7ºC and 24.01ºC, respectively. Monthly averages of both types of suites are shown below.

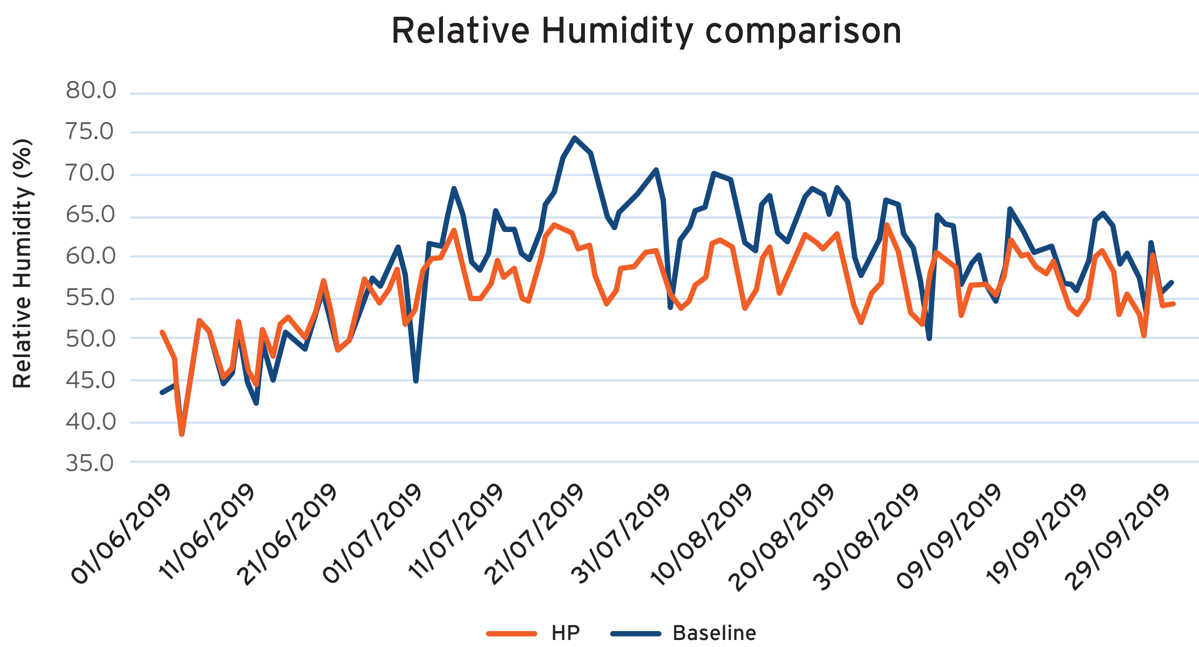
Indoor Air Temperature Findings



During the summer, the interior temperature of the retrofitted units was 2.5ºC, on average, lower than the baseline units. The graph below also shows that during summer peaks, where the outdoor air temperature (OAT) remained over 25ºC, tenants with heat pumps were able to maintain lower indoor temperature.

Relative Humidity Findings

Humidity levels are very similar for both the baseline and retrofitted units. This is largely because humidity is dependent on factors other than just the heating and cooling systems. The number of occupants and their daily habits can have a big impact as well as the air tightness of the building envelope and efficacy of the bathroom and kitchen range hood ventilation systems.



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