Yukon

Air-Source Heat Pump Monitoring Project Technical Report

for 2021-2022

Air-Source Heat Pump Monitoring Project Summary

Canadian homeowners are increasingly adopting air-source heat pumps for heating their homes. The heat pumps use electricity instead of fossil fuels and are highly efficient. The Government of Yukon and partners wanted to assess how air-source heat pumps are installed, operate and perform in the Yukon's cold climate.

Study parameters

In winter of 2020-2021, the Government of Yukon supported the installation of five cold-climate air-source heat pumps with monitoring equipment in five single detached homes in Whitehorse, Yukon. The Government of Yukon's Energy Branch monitored the heat pumps from April 2021 to April 2022.

The Energy Branch collected data on the heat pumps and backup heating systems' heat output, airflow and electricity consumption. The data was analysed to assess and determine the performance of each heat pump. Homeowners provided qualitative feedback that was included in the analysis.

Key Insights

The study's results determined that it is possible to operate a heat pump efficiently in very cold climates. Here are a few highlights on operating cold-climate air-source heat pumps in the Yukon.

Overall performance

The coefficient of performance (COP) is a measurement used to assess the energy efficiency and performance of heat pumps. The seasonal COP results for the five heat pumps in this study are in Table 7 of the technical report and range from 1.02 to 2.41.

In this study, the five heat pumps' COP were typically greater than 1. This means that the heat pumps are more efficient than resistive electric heating systems like baseboards or an electric furnace that have a COP of 1.

At more moderate temperatures, the integrated COP of some heat pump units exceeded 2. This indicates that the heat pumps were more than twice as efficient as other electric heating devices at these temperatures and conditions.

One heat pump achieved a seasonal COP of greater than two for the entire the heating season. This particular system demonstrated the importance of a properly sized, designed, installed and configured system for achieving energy efficiency and excellent performance even in cold climates.

Appropriate duct design is essential for centrally ducted systems

Centrally ducted heat pump systems often have higher airflow requirements compared to the oil or propane furnaces they typically replace. When installing a heat pump as a retrofit, homeowners and contractors must pay attention to duct design to ensure their home's ductwork offers sufficient airflow. Otherwise, inadequately sized ducts can restrict or reduce airflow and inefficiently deliver heat throughout the home.

For some installations in this study, the heat pump performance was lower than manufacturer expectations. This was likely due to ductwork concerns. Heat pumps are responsive systems. When airflow is constrained, the heat pump's sensors automatically adjust the volume of air. Constrained airflow restricts the heat pump's ability to put out higher amounts of heat.

Based on these observations, we recommend that homeowners who want to install a centrally ducted heat pump system get a duct assessment and duct design work completed by a qualified sheet metal worker as part of the installation. A duct assessment could include analyzing the static pressure, reviewing supply and return duct layout, runs or bends and airflow volume.

Homeowners who are switching from oil or propane heating systems to a heat pump may need to increase the size of the ducts in their homes to ensure optimal heat pump performance and energy efficiency. If increasing the ductwork is not an option, homeowners can consider installing ductless mini-splits or smaller centrally ducted heat pumps with lower airflow requirements.

Another consideration, especially for new builds, is to consider installing a centrally ducted heat pump system horizontally, if space is available. This type of orientation may contribute to better airflow management.

Other installation best practices include:

- manufacturer recommended placement of on-board sensors;
- well considered location and orientation of outdoor unit; and
- manufacturer recommended initial settings and commissioning.

Appropriate sizing

Sizing the heating systems appropriately and judiciously is important because heat pumps are able to vary their heat output in a way that conventional heating systems cannot.

A heat pump that is 'under-sized' results in a lower maximum heat output (relative to conventional norms with oil or propane furnaces). This can be less of a concern when there is a backup heating system operating during extreme cold temperatures. Installing an ‘over-sized’ larger unit may be more expensive and have greater airflow requirements to manage.

However, this project’s results suggest that appropriate airflow design modifications and commissioning procedures may matter more than sizing, as a comparatively large heat pump performed best.

Given all these nuances, installers should validate and confirm sizing recommendations with a third-party product such as NRCan’s heat pump sizing tool.

Energy savings

We estimated that the best performing heat pump in the study would deliver a 43 per cent reduction in home energy use, compared to heating with electric baseboards. This is a significant reduction in energy use. The other heat pumps in the study overall were more energy efficient compared to heating from electric baseboards.

Price

The average capital cost for a centrally ducted heat pump system installed in this study was $17,805. The average installation/labour cost for centrally ducted heat pumps in this study was $8,206. This results in total costs of about $26,000. The costs for installing ductless mini-splits may be less.

For reference, a new propane furnace is approximately $8,000 to $12,000 including equipment and installation.

Note that participants in this study received a Government of Yukon rebate of $10,000 for installing a qualifying heat pump and allowing data monitoring and collection.

Participant feedback

Participants reported improved air quality and improved air circulation with their newly installed heat pumps.

One concern was excessive water output during the winter months that corresponded to ice build-up under some of heat pumps. If this issue occurs, the original installer should investigate as soon as possible. Ice build up may damages the outdoor unit and solutions may vary. For one system that had a broken coil from ice buildup, relocating a thermostat and adjusting to correct a tilt of the outdoor unit was necessary.

Next steps

An additional 20 heat pumps of different makes, models and styles have been or are being installed around the Yukon. This includes multiple ductless mini-splits, multi-splits, air-to-water heat pumps and a few more central systems.

The data gathered from these units will continue to be analysed by the Government of Yukon in partnership with Yukon University to support a better understanding of heat pump performance in the Yukon's cold climate.

The Government of Yukon is also working with academic institutions, industry associations and manufacturers to investigate opportunities for additional heat pump training to be provided to local contractors.

Air-Source Heat Pump Monitoring Project

The Government of Yukon's Energy Branch, with Natural Resources Canada, is coordinating a monitoring project on air-source heat pumps and their performance in the Yukon's cold climate.

1.0 Introduction

In winter of 2020-2021, five cold-climate air-source heat pumps were installed in five single detached homes in Whitehorse, Yukon during the first year of the project.

In April 2022, data from the previous 12 months of heating season was downloaded each heat pump and analysed to determine each heat pump's performance in the field. Throughout the duration of the project, feedback from each homeowner was collected and included as part of the analysis.

The goal of this technical report is to provide Coefficient of Performance (COP) results for each of the heat pump installations, compare against manufacturers' specifications, and using further data metrics, make conclusions on their current performance.

2.0 Cold-climate heat pumps

Five cold-climate air-source heat pump systems were installed as part of this project. Northeast Energy Efficiency Partnerships (NEEP) defines a cold climate air-source heat pump as being "best suited to heat efficiently in cold climates (IECC climate zone 4 and higher)"[1] and meets the following performance requirements:

[1] Cold Climate Air-Source Heat Pump Specification (Version 3.0), January 2019, accessed 29/6/2021

- for non-ducted systems: Heating Season Performance Factor (HSPF) >10;
- for ducted systems: Heating Season Performance Factor >9;
- the Co-efficient of Performance (COP) @5°F >1.75 (at maximum capacity operation); and
- the Seasonal Energy Efficiency Ratio (SEER) > 15.

HSPF is measurement of heat pump efficiency over the heating season (total heat output divided by electricity consumed). The HSPF measurements are based on specific climate zones.

The coefficient of performance (COP) is a measurement used to assess the energy efficiency and performance of heat pumps.

SEER is a measurement of heat pump efficiency over the cooling season (total cooling output divided by electricity consumed).

This technical study focused instead on various COP measurements, which are linked to time and temperature, to offer a more nuanced picture of performance. See section 5.2 for more information.

All five systems:

- are Mitsubishi Zuba models, with two rated at 36,000 BTU/hr and three rated at 42,000 BTU/hr;
- are installed with built-in electric auxiliary heating systems;
- are centrally ducted systems; and
- are installed in single detached homes.

Four of the indoor units were installed vertically with single-side return while the fifth indoor unit was installed horizontally.

2.1 Standard heat pump operation

When operating, a heat pump cycles through various system **modes** to meet the demand of the home and keep the indoor and outdoor units operational. This includes **steady state** mode when the heat pump is producing heat, **standby** mode when the home is at the desired temperature or **defrost** when the outdoor unit needs to be defrosted and **off** mode when heat is not required for longer periods of time. The unit may also **start up** and **power down** between each mode.

Ideally, a properly sized heat pump will spend a higher proportion of time in an active steady state mode. In steady state, a cold-climate heat pump will modulate the fan and compressor speed to control the heat produced and maintain occupant comfort over a range of outdoor temperatures. Only at warmer temperatures, when heat is no longer required, may the heat pump sit in standby or off modes. Below a temperature of around -29°C, the backup heat will become the primary heating system.

2.1.1 Oversized / undersized operation

An oversized system will cycle on and off, known as short cycling. A short cycling system will struggle to provide the comfort and energy savings expected of a properly sized heat pump.

Furthermore, an oversized heat pump may encounter issues with engaging defrost mode if short cycling occurs frequently. It may not be efficient for the heat pump to go into defrost mode if the heat pump only runs for a couple of minutes at a time and then shuts off again because it is oversized. Ice buildup on the outdoor unit's coil can potentially lead to damage if left unaddressed.

Conversely, when a heat pump is undersized, the system spends more time at full capacity to achieve the set heating temperature.

In both scenarios, when a heat pump is too big or too small for its operating space, the heat pump uses more electricity to reach a desired indoor temperature.

The heat pump never gets a chance to do what the system does best, maintain a set temperature without having to run at its peak. This is where energy and cost savings are realized.

3.0 Project events and timeline

3.1 Heat pump sizing

Each participant was asked to select their heat pump model from an approved list provided by Natural Resource Canada (NRCan). NRCan also provides a heat pump sizing tool that recommends a size of heat pump based on a number of factors including, home heat load and duct sizes. Table 1 summarizes the heat pump sizing data.

Table 1: Heat pump sizing selection

ASHP	Selected unit	House age	House size (sq ft)	Secondary heat	House heat load (NRCan sizing tool)
1	Mitsubishi PUZ-HA42NKA1 – 42,000 BTU/Hr	1969	1926.7	Wood Stove	34,087 BTU/Hr
2	Mitsubishi PUZ-HA42NKA1 – 42,000 BTU/Hr	1997	2314.2	Wood Stove	42,617 BTU/Hr
3	Mitsubishi PUZ-HA36NKA – 36,000 BTU/Hr	1990	2264.7	Propane Stove	37,874 BTU/Hr
4	Mitsubishi PUZ-HA42NKA1 – 42,000 BTU/Hr	1977	1795.4	Heat Pump Only	39,171 BTU/Hr
5	Mitsubishi PUZ-HA36NKA – 36,000 BTU/Hr	2020	2835.2	Electric Baseboards	27,297 BTU/Hr

3.2 Installation, commissioning and data collection period

Table 2 is a timeline of events to install and commission the monitoring equipment. To commission the system a series of short-term tests were conducted.

Table 2: Key installation dates

ASHP	Heat pump install date	Monitoring commissioning date	Monitoring period
1	November 10 to 16, 2020	January 25 to 29, 2021	April 1, 2021 to March 31, 2022
2	December 1 to 7, 2020	January 29, 2021	April 1, 2021 to March 31, 2022
3	December 8 to 15, 2020	January 8, 2021	April 1, 2021 to March 31, 2022
4	December 14 to 18, 2020	February 22, 2021	April 1, 2021 to March 31, 2022
5*	December 14 to 18, 2020	October 27, 2021	October 27, 2021 to April 31, 2022

*The installation of heat pump #5's monitoring equipment was delayed as the home was a new build. The heat pump was initially installed onto temporary electrical service. The monitoring equipment was installed when the electrical service was transferred over to the main service later in 2021.

3.3 Summary of major events

3.3.1 Pre-installation and reporting period

- *Heat pump sizing* – Prior to each system's installation, an energy audit was completed for each home. The Energy Branch entered data from the audit report into NRCan's sizing tool to determine the appropriate size each unit for the participants' homes. The heating loads and the duct sizes found in the energy assessments were used in conjunction with manufacturer performance data from NEEP as inputs in the NRCan sizing tool to determine the appropriate cold-climate heat pump size for the homes. In some cases, the size of unit selected was higher than the recommended size reported in NRCan's sizing tool at the participant's choice.
- *Freeze-up and humidity* – Due to long winter periods of cold temperature and high humidity, the unit experienced freeze-up with a build-up of frost on the outdoor unit. A wind baffle was installed on each of the heat pumps to negate this issue.
- *Factory defect* – Following occasions where the auxiliary heat was not being engaged when required, a factory defect was identified by the manufacturer and the installer. The unit was incorrectly detecting the outdoor air temperature. This was mitigated by replacing the computer board that was under warranty. This issue may have contributed to the freeze up and caused complications to the defrost cycle.

- *Damaged coil* – In January 2022, heat pump #4's outdoor unit stopped operating. A damaged coil was identified as the symptom. The cause of the damage was ice build-up in the outside unit due to improper drainage from a leaning outdoor unit.
- *High humidity mode* – After discussions with the installer, it was identified that some units were switched on to a 'high humidity mode' after the replacement of the computer board in March 2021. This potentially caused the units to operate in defrost mode more frequently.
- *Ductwork audits* - From January to April 2022, engineering audits were performed on heat pumps #2 and #4 to identify if airflow issues were the source of some of the challenges.

4.0 Monitoring equipment and methodology

Monitoring equipment was installed on each heat pump and electrical service to record heat pump data, also known as the **raw data points**. The data, recorded in **one-minute intervals** was collected through a data logger and equipment connected through an environmental monitoring board. This data was accessed from an online portal.

Table 3: Monitoring equipment raw data points

Ref.	Raw data points	Equipment	Purpose	Make / model	Precision
(a) (b) (c) (d) (e) (f) (g) (h) (i) (j) (k) (l) (m) (n) (o) (p) (q) (r)	ASHP Indoor Current A ASHP Indoor Voltage A (120V) ASHP Indoor Voltage B (120V) ASHP Indoor Voltage A-B (240V) ASHP Indoor Active Power A (ASHP) ASHP Indoor Active Power B (Backup) ASHP Indoor Reactive Power ASHP Outdoor Reactive Power ASHP Total Active Power ASHP Total Apparent Power ASHP Total Reactive Power ASHP System Power Factor ASHP Indoor Power Factor House Active Power Total House Apparent Power Total House Voltage A House Voltage B House Net and Total Energy	Voltage and current transformers	Measure the electricity consumption of the heat pump	Elkor WattsOn power transducers	ANSI Class 0.2
(s) (t) (u) (v)	Building Indoor Air Density ASHP Return Velocity ASHP Return Volumetric Flow ASHP Return Mass Flow	Airflow sensor for ducts	Measure delivered heat through airflow	Monnit Alta differential air pressure sensor	3% of reading +/- 0.1 Pa
(w) (x)	ASHP Supply Temp – Right, Left and Centre ASHP Return Temp – Right, Left and Centre	3 thermistors	Determine delivered heat energy	Cygnus Tech	
(y)	ASHP Vapour Line Temp	Thermistor	Monitor defrost status	Cygnus Tech	
(z) (aa)	Outdoor Temp Outdoor Humidity	3 combined thermometer 27and relative humidity sensor	Monitor local outside temperature and relative humidity	Monnit Alta Wireless Humidity Sensors and Temperature Sensors	Accurate to +/- 0.3°C +/- 3% accuracy for RH
(ab) (ac) (ad) (ae)	Thermostat Indoor Temp Thermostat Indoor Humidity ASHP Supply Center Humidity ASHP Return Center Humidity	3 combined thermometer and relative humidity sensor	Monitor indoor temperature and relative humidity	Monnit Alta Wireless Humidity Sensors and Temperature Sensors	Accurate to +/- 0.3°C +/- 3% accuracy for RH
(af) (ag)	ASHP Backup Heat Current ASHP Backup Heat Power Factor	Back-up heat source sensor equipment	Determine percentage of heat supplied by the backup system	Variable.	

The data was logged using a Modbus logging software deployed on a Raspberry Pi computer (see Figure 1). Each data logger was directly plugged into an internet modem to avoid Wi-Fi connection issues. An internal clock was added to the data loggers to avoid potential complications due to power outage.

The data collection interval was sampling every second and then averaged values logged every minute. An hourly data submission to a remote server allowed for real-time viewing of the data.

Figure 1: Inside of the indoor cold-climate heat pump unit and the backup auxiliary heat with the power monitoring.

4.1 Power measurements

A majority of the electrical monitoring equipment was installed near the electrical panel. Power monitoring was conducted using Elkor Technologies3 Inc. measuring equipment. The WattsOn-Mark II power transducer was used with MSTC1 and MCTA current transformers for whole house and cold-climate heat pump energy monitoring and the i-Snail-VC series of current transducer was used for current monitoring of fans and electrical backup heat source consumption.

4.2 Airflow measurements

In situ airflow measurements were taken by installing a Dwyer Instrument PAFS-1000 series averaging flow sensor in the return duct. This provided a differential pressure related to the velocity of the air.

The instruments were calibrated and compared against the following instruments:

- TPI DC580 hot-wire anemometer.
- TSI 8345-E-GB hot-wire anemometer.
- TSI 9565 with TSI 960 hot-wire anemometer.
- TSI 9565 with TSI 634634002 pitot tube.

4.3 Environmental monitoring

Temperature and humidity sensing were performed using Honeywell 192502LET-A01 thermistors and HIH-5031 humidity sensors. The return air and supply air temperature and humidity were measured. Indoor and outdoor temperature and humidity were also measured.

4.4 Monitoring equipment verification

A series of short-term tests were completed following each installation to verify that the monitoring equipment was operating and logging data correctly. These included:

- volumetric flow rates comparison with manufacturers' data sheets;
- 24hr data sets of all data points; and
- efficiency calculations.

4.4 Monitoring equipment calculations

In addition to the raw data points listed in the Table 3, a number of pre-set **calculated data points** (see *Table 4*), were built-in to the data logger, to be collected at the same minute-long intervals.

Table 4: Monitoring equipment calculated data points

Ref.	Calculation	Raw data points used	Formula
(ba)	ASHP indoor unit apparent power	ASHP Indoor Voltage A-B (240V) – (a) ASHP Indoor Current A – (b)	$(ba) = (a) * (b)$
(bb)	ASHP indoor unit active power	ASHP Indoor Power Factor – (c)	$(bb) = (ba) * (c)$
(bc)	ASHP outdoor unit active power	ASHP Total Active Power – (d) ASHP Indoor Active Power A (ASHP) – (e)	$(bc) = (d) - (e)$
(bd)	ASHP outdoor unit apparent power	ASHP Outdoor Unit Active Power – (bc) ASHP Total Reactive Power – (f) ASHP Indoor Reactive Power – (g)	$(bd) = (bc) + [(f) - (g)]$* *(f)-(g) = outdoor reactive power
(be)	Outdoor temperature bin	Outdoor Temp – (h)	*See section 4.2 – Temperature Bins*
(bf)	ASHP supply average temperature	ASHP Supply Temp – Right – (i) ASHP Supply Temp – Left – (j) ASHP Supply Temp – Centre – (k)	$(bf) = [(i) + (j) + (k)]/3$
(bg)	ASHP return average temperature	ASHP Return Temp – Right – (l) ASHP Return Temp – Left – (m) ASHP Return Temp – Centre – (n)	$(bg) = [(l) + (m) + (n)]/3$
(bh)	ASHP backup heat power	ASHP Indoor Voltage A-B (240V) – (a) ASHP Backup Heat Current – (o)	$(bh) = [(a) * (o)] / 1000$

4.5 Temperature Bins

To provide deeper analysis into heat pump performance, certain performance metrics in this report have been grouped into 17 temperature bins and the results averaged. This approach can be found in the CSA standard EXP07-19[2].

Table 5: Temperature bins

Temperature bin	Temperature range (°C)
1	Less than -28.9
2	-28.9 to <-26.1
3	-26.1 to <-23.3
4	-23.3 to <-20.6
5	-20.6 to <-17.8
6	-17.8 to <-15.6
7	-15.6 to <-12.5
8	-12.5 to <-10.0
9	-10.0 to <-7.2
10	-7.2 to <-4.4
11	-4.4 to <-1.7
12	-1.7 to <1.1
13	1.1 to <3.9
14	3.9 to < 6.7
15	6.7 to < 9.4
16	9.4 to < 12.2
17	12.2 and greater

[2] CSA EXP07-19 - Load-based and climate-specific testing and rating procedures for heat pumps and air conditioners.

4.6 Data Modelling

The statistical software / programming language R, was selected for this analysis. R is an integrated suite of software facilities for data manipulation, calculation and graphical display. Statisticians from Yukon University's Northern Energy Innovation supported the Government of Yukon in interpreting the data.

The benefits of using R for this analysis were:

- R can handle large data sets, which was beneficial as each heat pump data set included minute-by-minute data for an entire year. Previous analysis used Excel, but a full year's worth of data was surpassing processing power and taking a lengthy time to run the calculations.
- R can provide advanced data visualization for more complex datasets. R can take complicated data and turn it into much easier to understand visual representation.

4.7 System Mode

Detecting system modes required a lot of analysis since the beginning of the monitoring project. The lag between one part of the system powering down, heat remaining in the system, and powering back up again can affect the overall COP. While the unit is powered down, the unit may enter defrost, standby or backup mode. Using different data points to detect each system mode was a challenge, but also a learning experience for the project. The formula used to detect system mode is further analysed in Section 5.2.1.

4.7.1 Active Mode

Figure 2 illustrates the heat pump changing from a standby mode to an active mode of operation where an increase in power to the outdoor unit identifies the heat pump as operational. Active mode is illustrated with the green shaded areas whereas standby mode is illustrated by the yellow shaded area. In active mode, the active power increases and as heat builds in system the vapour line temperature increases.
In active mode, COP values between 1.5 and 2.5 can be seen.
Backup heat for an outdoor temperature of about -21°C
remains off.

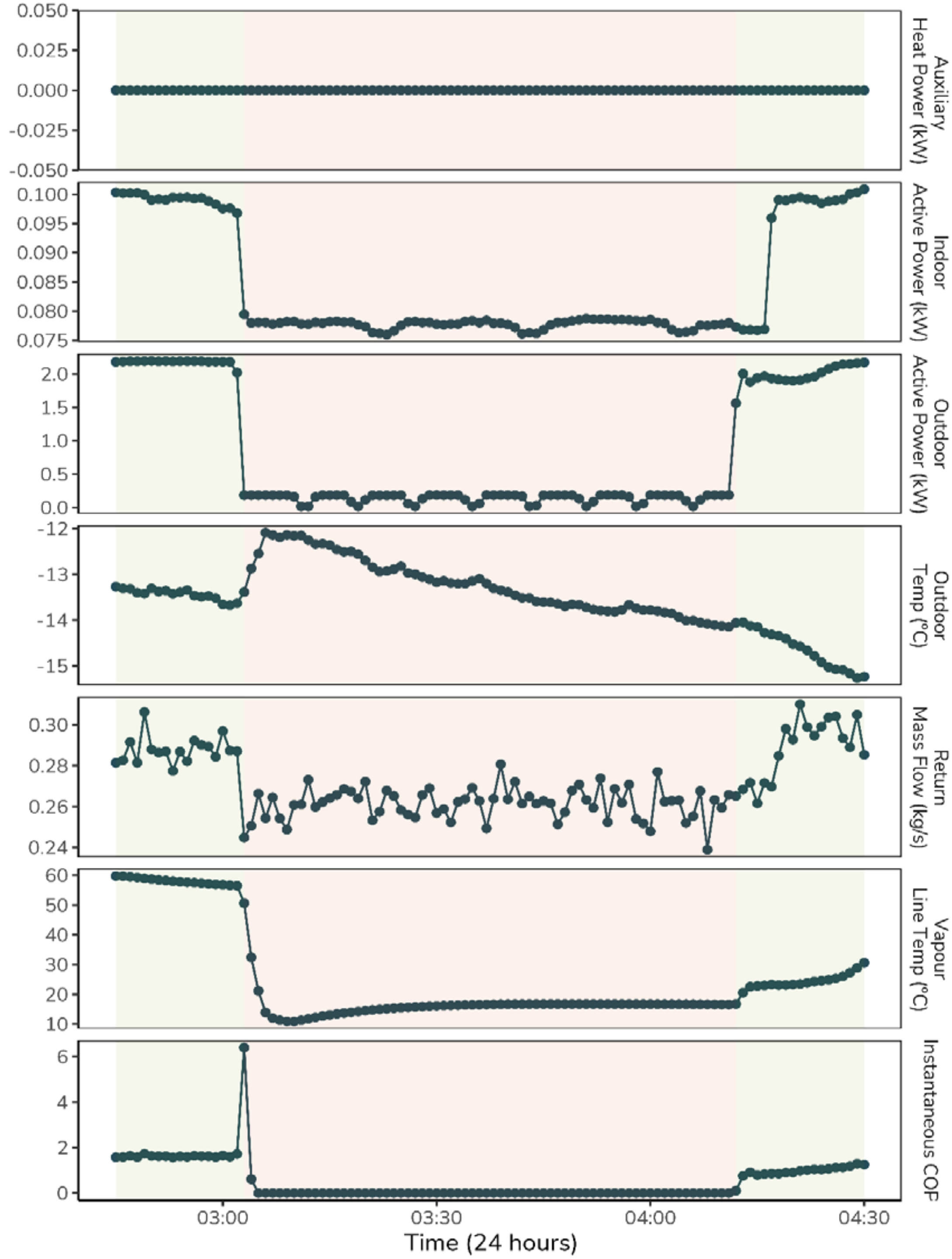

Figure 2: Sample of data illustrating the change from active mode to standby and back to active.

4.7.2 Defrost Mode

In defrost mode, the vapour line temperature data point identifies when the heat pump changes to defrost system mode. It takes several minutes to power down. In this instance, COP values can fluctuate. The data can distinguish between standard operation and the heat pump powering down to defrost mode.

In *Figure 3*, defrost mode is shown with the yellow shaded area, confirming a clear transition point.

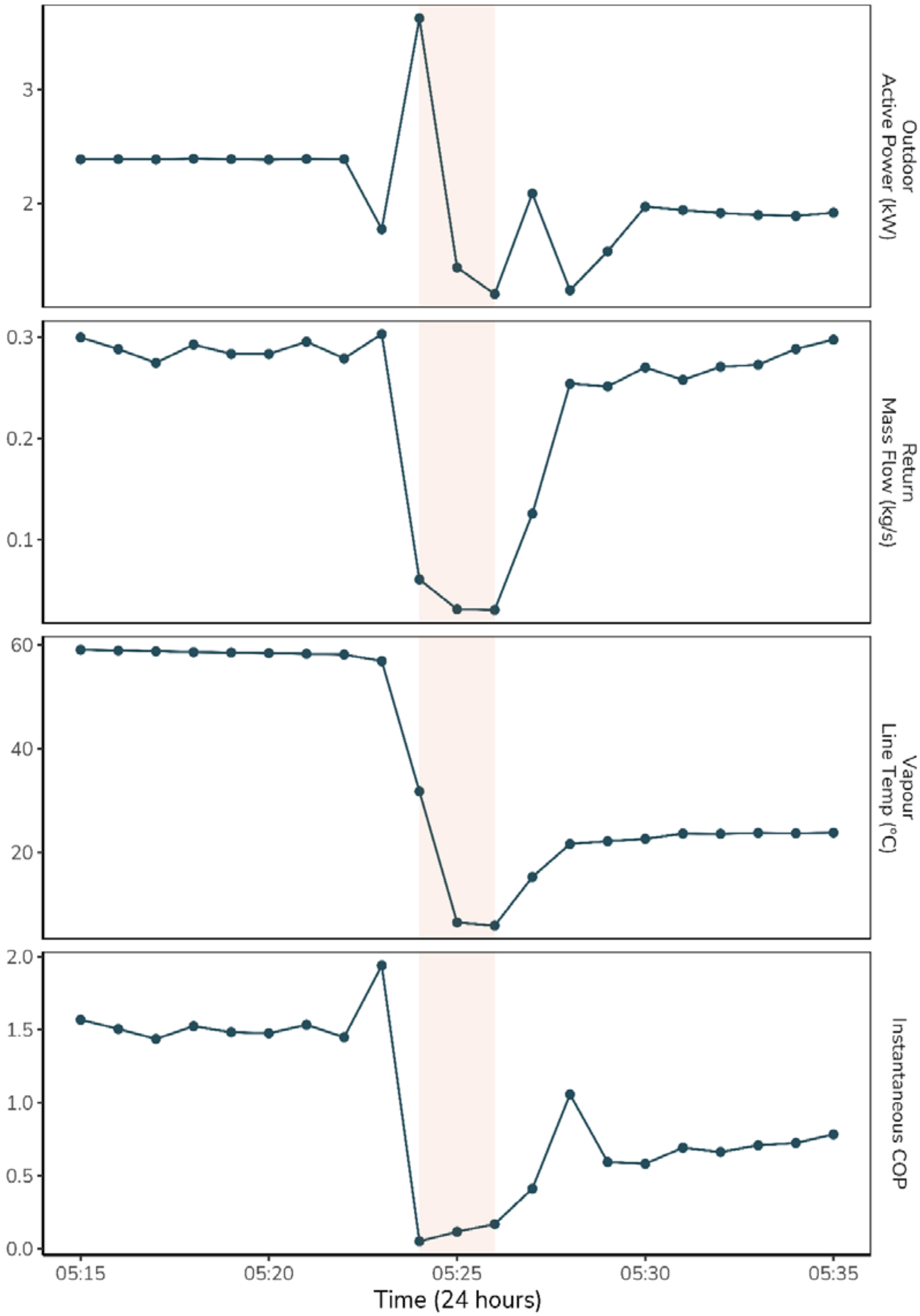

Figure 3: Sample of data illustrating the change of a heat pumps system mode from active to defrost.

4.7.3 Backup Mode

Back up mode is easily identified when the heat pump's auxiliary power data point is greater than 0, as shown in Figure 4 as the yellow shaded area.

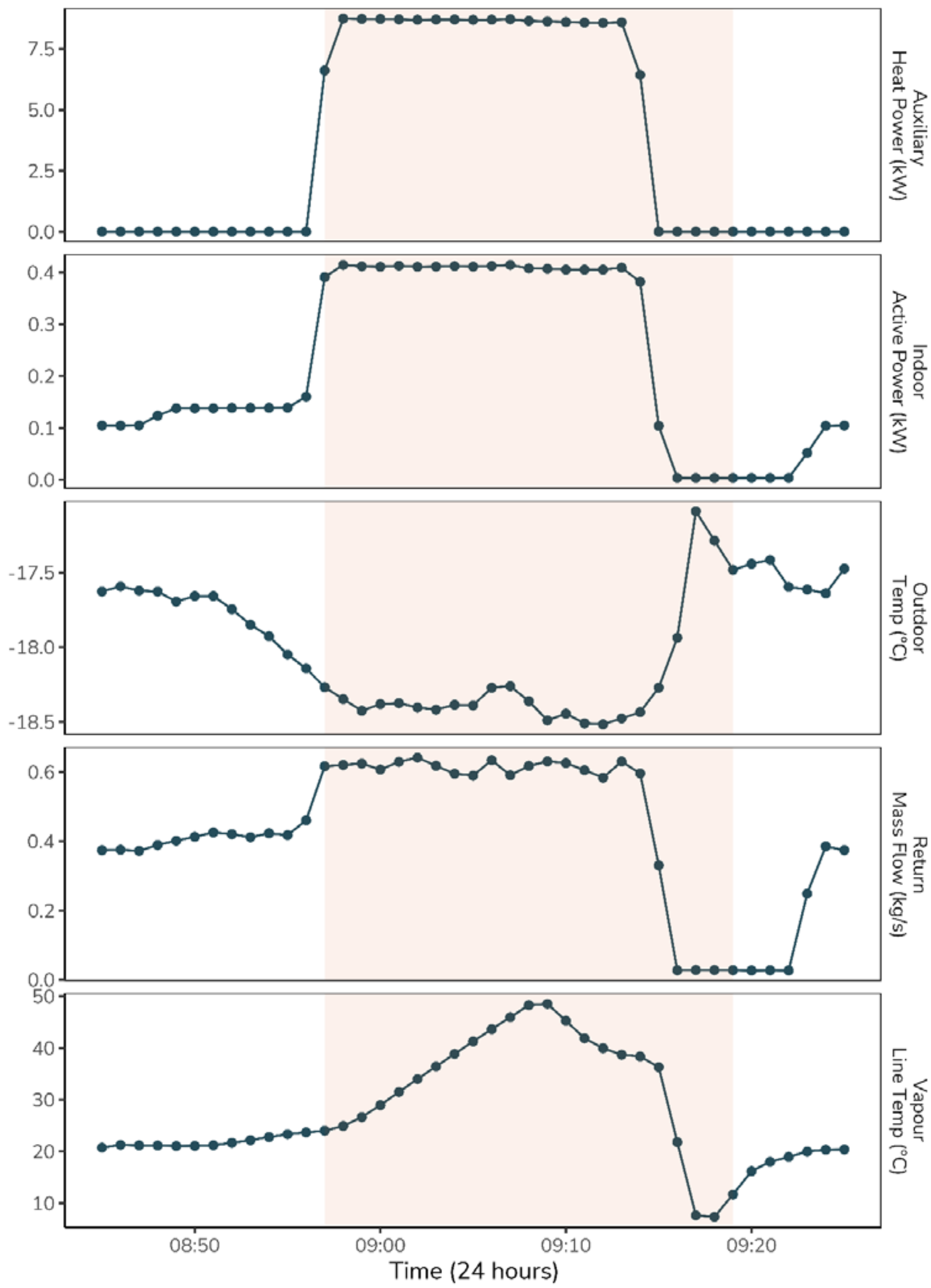

Figure 4: Sample of data illustrating the use of back-up heat, indicated by the rise in auxiliary heat power above zero degrees Celsius.

5.0 Data analysis

5.1 Temperature and humidity profile

A daily average across all five heat pumps is shown in Figure 5 using minute interval data for outdoor temperature and humidity.

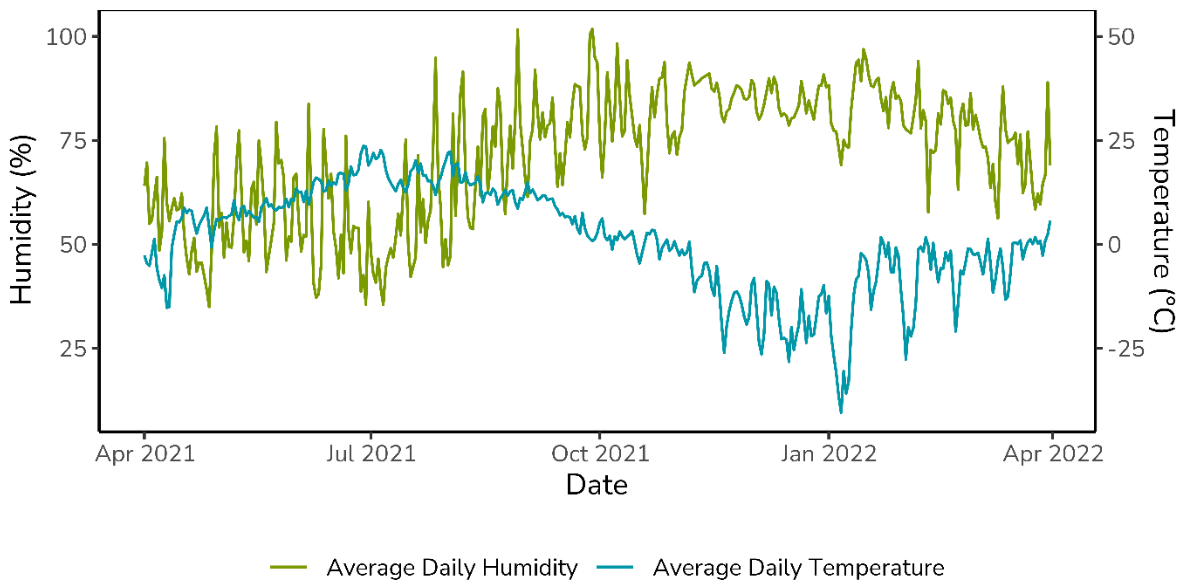

Figure 5: Averaged daily outdoor temperature and humidity profile across four heat pumps.

It is worth noting that the lowest average temperature recorded was roughly -40.5°C, and the lowest recorded temperature was below -45.2°C. Air-source heat pumps are designed to switch to the backup heat source around -29°C. The average daily high was 14.8 °C and the absolute maximum temperature was 38.1°C.

5.2 COP, ICOP and SCOP – Comparison to manufacturer specifications

Coefficient of Performance (COP) is an indicator of the efficiency of a heat pump. It is a measure of the amount of energy that a heat pump delivers compared with what it draws from a power supply.

For example, if a heat pump delivers 10 kilowatt (kW) of heat and draws 2kW from the power supply, the heat pump has a COP of 5. This is calculated as follows: 10/2 = 5. This compares to an electric furnace, boiler or baseboard that have a COP of 1. The higher the COP, the more efficient the system. COP can be calculated as an instantaneous measurement or as an average over a specified time period. The latter is more useful.

When operating, a heat pump cycles through various system **modes** to meet the demand of the home and keep the indoor and outdoor units operational. This includes **steady state** when the heat pump is producing heat, **standby** mode when the home is at the desired temperature and does not require heating or **defrost** when the outdoor unit needs to be defrosted and **off** mode heat is not required for longer periods of time. The unit may also **start up** and **power down** between each mode. Different COP calculations incorporate different combinations of these modes and provide further insight how a heat pump is operating.

COP is typically what the manufacturer quotes for the efficiency of a heat pump system. It is determined by calculating the instantaneous COP during steady state operation at different temperatures.

These instantaneous COPs are then averaged over a period of time, normally a year, to give a typical COP for a given outdoor air temperature. If we analyse a sample COP graph (at -12°C) over an hour, we might see the steady state period of a heat pump (See Figure 6).

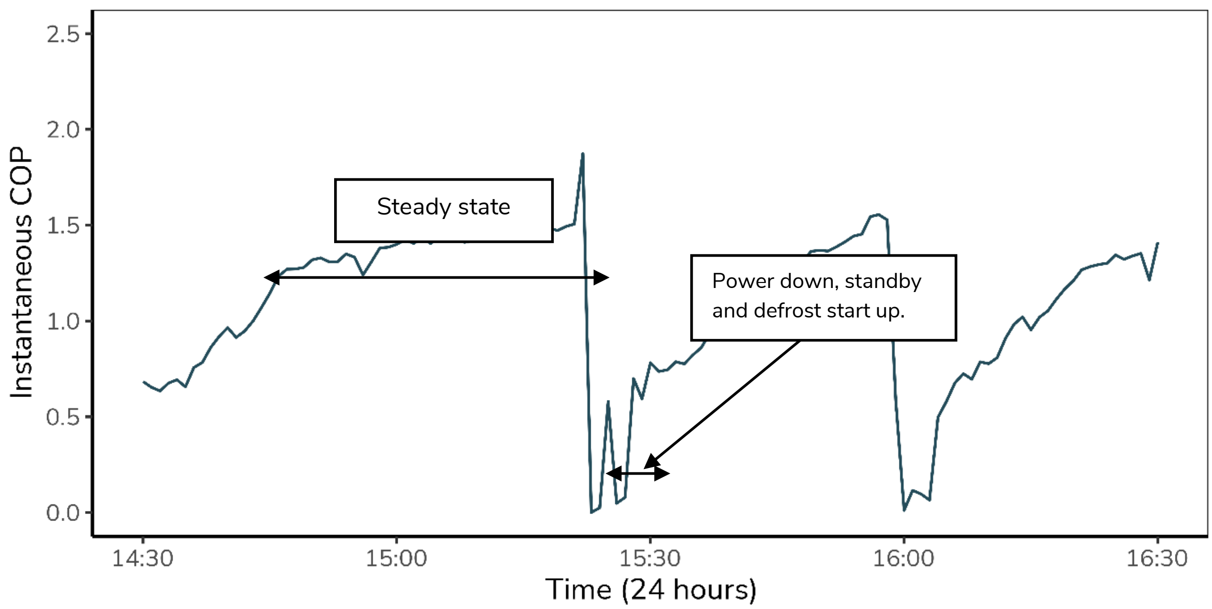

Figure 6: COP of a heat pump over time at -12ºC.

Integrated COP (ICOP) is a measure of the efficiency of heat pumps that includes all system modes and, similar to COP, is reported at a specific outdoor air temperature. This provides an additional layer of analysis, and can provide much needed insight into how a heat pump is operating at different temperatures. For example, while COP could remain high, a low ICOP might suggest a heat pump is in standby mode often, still drawing power and therefore less efficient.

Seasonal COP (SCOP) a single value that measures the efficiency of heat pump. SCOP includes all system modes at all temperatures and is averaged over a period of a year that includes an entire heating season. Like ICOP, it gives a realistic idea about how energy efficient a heat pump system is in practice and overall.

5.2.1 Method

To calculate COP, ICOP and SCOP the following formula was used:

Table 6: COP calculation methodology

Calculation		Data points used	Formula
COP	$Q_{HP_{Active-on}}$	(s) - Building Indoor Air Density (v) - ASHP Return Mass Flow (bf) - ASHP Supply Average Temp (bg) - ASHP Return Average Temp Other data: Air density – 1.006	FOR EACH TEMPERATURE BIN: $Q_{HP_{Active-on}} = \sum (s) * 1.006 * (v) * [(bf) - (bg)]$
	$P_{HP_{interior_{Active-on}}}$	(bb) - ASHP Indoor Unit Active Power	FOR EACH TEMPERATURE BIN: $P_{HP_{interior_{Active-on}}} = (bb)$
	$P_{HP_{outdoor_{Active-on}}}$	(bc) - ASHP Outdoor Unit Active Power	FOR EACH TEMPERATURE BIN: $P_{HP_{outdoor_{Active-on}}} = (bc)$
	COP	$Q_{HP_{Active-on}}$ $P_{HP_{interior_{Active-on}}}$ $P_{HP_{outdoor_{Active-on}}}$	FOR EACH TEMPERATURE BIN: $COP = \frac{Q_{HP_{Active-on}}}{P_{HP_{interior_{Active-on}}} + P_{HP_{outdoor_{Active-on}}}}$
	DESCRIPTION	To calculate COP QHP is summed for all data points where the heat pump is in active mode and broken down into temperature bins. Both power calculation for the indoor and outdoor unit are calculated by the monitoring equipment. Dividing the total heat output of the heat pump by the power attributable to the indoor and outdoor units will give the COP.	
ICOP	$Q_{HP_{Total}}$	$Q_{HP_{Active-on}}$ $Q_{HP_{Standby}}$ $Q_{HP_{BackUpHeat-On}}$ $Q_{HP_{Defrost}}$	$Q_{HP} = \sum (s) * 1.006 * (v) * [(bf) - (bg)]$ FOR EACH TEMPERATURE BIN: $Q_{HP_{Total}} = Q_{HP_{Active-On}} + Q_{HP_{Standby}} + Q_{HP_{BackUpHeat-On}} + Q_{HP_{Defrost}}$
	$Q_{Aux_{Total}}$	$P_{Aux_{Total}}$	FOR EACH TEMPERATURE BIN: $Q_{Aux_{Total}} = P_{Aux_{Total}}$ (ASSUMES 100% EFFICIENCY)
	$P_{HP_{interior_{Total}}}$	(bb) - ASHP Indoor Unit Active Power $P_{HP_{interior_{Active-on}}}$ $P_{HP_{interior_{Standby}}}$ $P_{HP_{interior_{BackUpHeat-On}}}$ $P_{HP_{interior_{Defrost}}}$	FOR EACH TEMPERATURE BIN: $P_{HP_{interior_{Total}}} = P_{HP_{interior_{Active-On}}} + P_{HP_{interior_{Standby}}} + P_{HP_{interior_{BackUpHeat-On}}} + P_{HP_{interior_{Defrost}}}$

Calculation		Data points used	Formula
ICOP	$P_{HP_{outdoor_{Total}}}$	(bc) - ASHP Outdoor Unit Active Power $P_{HP_{outdoor_{Active-on}}}$ $P_{HP_{outdoor_{Standby}}}$ $P_{HP_{outdoor_{BackUpHeat-On}}}$ $P_{HP_{outdoor_{Defrost}}}$	For each temperature Bin: $P_{HP_{outdoor_{Total}}} = P_{HP_{outdoor_{Active-On}}} + P_{HP_{outdoor_{Standby}}} + P_{HP_{outdoor_{BackUpHeat-On}}} + P_{HP_{outdoor_{Defrost}}}$
	$P_{Aux_{Total}}$	(bh) - ASHP Backup Heat Power	For each temperature Bin: $P_{Aux_{Total}} = \sum(bh)$
	ICOP	$Q_{HP_{Total}}$ $Q_{Aux_{Total}}$ $P_{HP_{interior_{Total}}}$ $P_{HP_{outdoor_{Total}}}$ $P_{Aux_{Total}}$	For each temperature Bin: $ICOP = \frac{Q_{HP_{Total}} + Q_{Aux_{Total}}}{P_{HP_{interior_{Total}}} + P_{HP_{outdoor_{Total}}} + P_{Aux_{Total}}}$
	Description	To calculate ICOP Q_{HP} is summed for all data points where the heat pump is in all modes; active, standby, defrost and back up heat on. Similarly to COP, ICOP is broken down into temperature bins. Power calculations for the indoor and outdoor unit, and the back up heat are calculated by the monitoring equipment. Dividing the total heat output of the heat pump and the auxiliary heat by the power attributable to the indoor and outdoor units, and the auxiliary heat will give the ICOP.	

Calculation		Data points used	Formula
SCOP	System mode	(u) - ASHP Return Volumetric Flow (y) - ASHP Vapour Line Temp (z) – ASHP Return Volumetric Flow (w) – ASHP Backup Power	FOR EACH MINUTE OF DATA: IF $P_{HP_{outdoor\,Active-on}} < 0.2 : P_{HP_{flag}} = 1$, ELSE 0 IF $Q_{HP_{Total}} < 0.2$: $Q_{HP_{flag}} = 1$, ELSE 0 $(y)_{slope} = \frac{\Delta(y)}{\Delta t * 60 * 60 * 24}$ IF $(y)_{slope} < -1000$: $(y)_{flag} = 1$, ELSE 0 IF $(y)_{slope} > 1000$: $(y)_{flag} = 1$, ELSE 0 APPLY A ROLLING WINDOW ACROSS $(y)_{flag}$ OF LENGTH 7, IF THERE IS AT LEAST A SINGLE VALUE OF 1 SET ALL VALUES IN WINDOW TO 1. $(z)_{slope} = \frac{\Delta(z)}{\Delta t * 60 * 60 * 24}$ IF $(z)_{slope} < -100$: $(z)_{1_{flag}} = 1$, ELSE 0 IF $(z)_{slope} > 100$: $(z)_{1_{flag}} = 1$, ELSE 0 IF $(z) < 0.2$: $(z)_{2_{flag}} = 1$, ELSE 0 IF $(y)_{flag} + (z)_{1_{flag}} + (z)_{2_{flag}} = 3$: $defrostState = 1$, ELSE 0 APPLY A ROLLING WINDOW ACROSS (w) OF LENGTH 6, IF THERE IS AT LEAST A SINGLE VALUE GREATER THAN 0 SET $backupState = 1$. IF $P_{HP_{flag}}$ OR $Q_{HP_{flag}}$ IS 1 SET $standbyState = 1$, ELSE 0. ITERATE MINUTE BY MINUTE. IF $backupState = 1, systemMode =$ BACKUP IF $defrostState = 1, systemMode =$ DEFROST IF $standbyState = 1, systemMode =$ STANDBY ELSE $systemMode =$ ACTIVE
	Temperature bin ratio	Timestamp data System mode	FOR EACH TEMPERATURE BIN: $Ratio = \frac{Active\ mode_{mins} + Standby_{mins} + Defrost_{mins} + BackUpHeat_{mins}}{Total\ number\ of\ data\ minutes}$

Calculation		Data points used	Formula
SCOP	SCOP	ICOP Temperature Bin Ratio	$SCOP = \sum ICOP * Temperature\ Bin\ Ratio$
	DESCRIPTION	SCOP is a single value that indicates the efficiency of a heat pump system over an entire heating season. SCOP is calculated by taking the ICOP for each temperature bin and multiplying it by the temperature bin ratio. A sum of all ratio ICOP values will give the SCOP. As with ICOP, SCOP includes data when the heat pump is in all modes; active, standby, defrost and back up heat on.	

For this analysis, the formula for setting the system mode was adjusted from the one found in Technical Interim Report #1 to better reflect the data and heat pump behaviour. In particular, in the previous report, it was found that data indicating defrost and standby modes were being incorrectly assigned, especially in warmer temperatures.

There were two significant changes made to the formula:

- The window for determining backup mode was widened by several time steps to include any residual heat after the backup system had turned off.
- The methodology for determining defrost mode was changed to include flags for:
  - a) when the airflow was very low;
  - b) the slope of the airflow with respect to time indicated a large drop or increase; or
  - c) when the vapour line temperature slope with respect to time indicated a large drop or increase.

5.2.2 Results

Typically, it was observed that the heat pumps' COP was greater than 1, indicating a net energy benefit over resistive electric heat. For some units, and more moderate temperatures, the COP exceeded 2, indicating the heat pumps were more than twice as efficient as resistive heating devices at these temperatures and conditions.

Figure 7 compares the COP data from three 42,000 British Thermal Units per hour (BTU/hr) heat pumps, and how they compare to the expected manufacturer specified rated capacity (heat pump #3 and #5 are compared in Figure 8 as they are smaller units).

A gap between the observed performance and the manufacturer COP data shows that, for some installations, the heat pump performance is lower than expected based on manufacturer specifications by approximately 33 per cent.

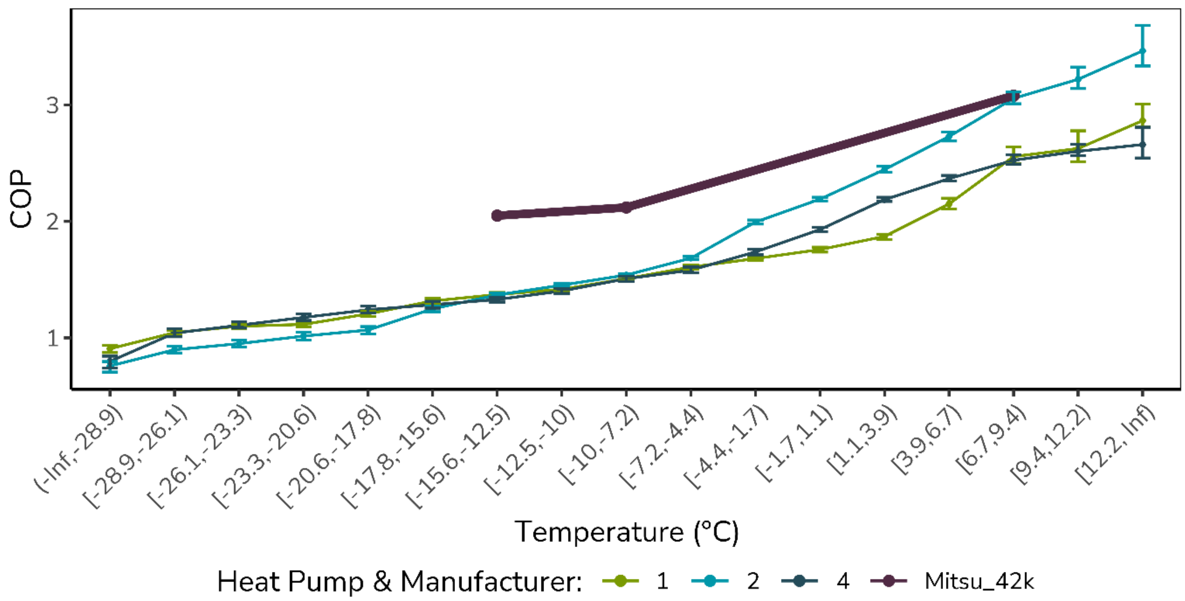

Figure 7: Comparison to manufacturer specifications (42,000BTU/hr) with heat pumps #1, #2 and #4.

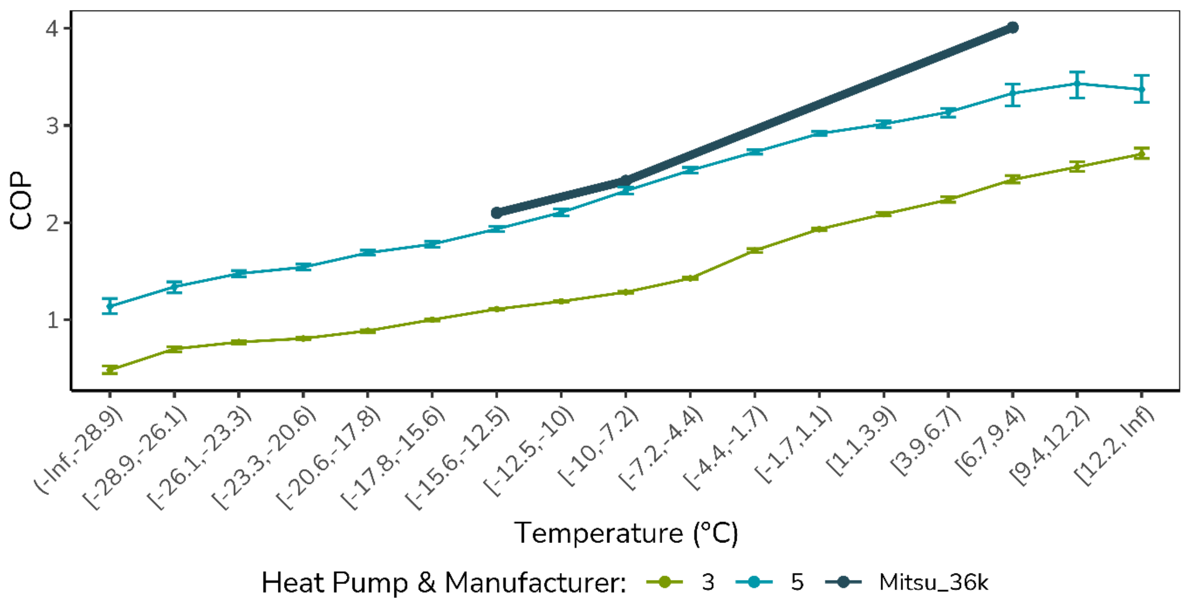

Figure 8: Comparison to manufacturer specifications (36,000BTU/hr) with heat pumps #3 and #5.

Figure 8 conveys a similar trend to the results in Figure 7, with a gap between heat pump #3's COP data and the manufacturer data for the 36,000 BTU/hr unit. Heat pump #5 was installed horizontally and by a different installer. It performs noticeably closer to the manufacturer specifications. In some cases, COPs below 1 were observed particularly at low temperatures. This was unexpected. A possible explanation is that as temperatures drop, the units spend greater amounts of time in defrost mode resulting in greater energy consumption to keep the units operational. Additional data and observations will be required however to fully understand this cause of these observations.

Figure 9 compares ICOP across all four installations showing a similar trend in the -15°C to -5°C range, but at the coldest and warmest temperatures, the graphs vary. Interestingly, at the coldest temperatures the ICOP for heat pump #1 and #3 is below 1.00.

Factors contributing to this result could include lower than desirable airflow, and the use of secondary heat with defrost cycles. At temperatures greater than six degrees, there is a decline in ICOP for all heat pumps. This could be explained by short cycling of the units during times of low heat demand from the home.

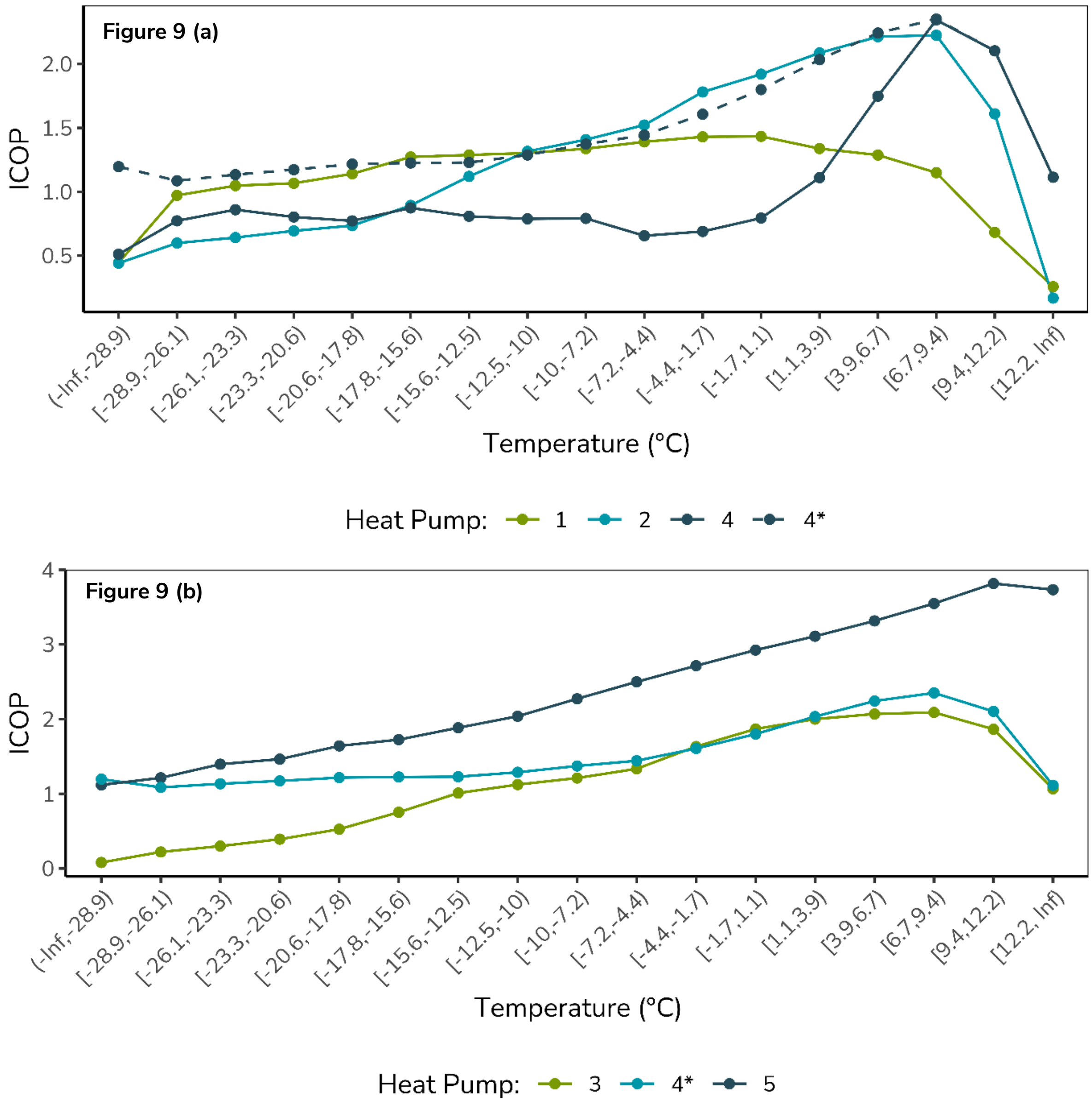

Figure 9 (a) and (b): Comparison of ICOP data from a) 42,000 BTU/hr heat pump units and b) 36,000 BTU/hr systems. Heat pump #4 had a broken coil during operation and data from before (dashed line) and after (solid line) is presented for completeness.

Figure 9 shows that heat pump #1 has generally a lower ICOP at most temperature bins suggesting a less efficient system than the other installations. A review of the SCOP results in Table 7 confirms this. The underlying causes of low SCOP values are discussed in subsequent sections.

Table 7: Heat Pump SCOP

Heat pump	Interim report results February 1, 2021 – April 30, 2021)	SCOP summer (April 1, 2021 to August 31, 2021)	SCOP winter (September 1, 2021 to March 31, 2022)	SCOP (April 1 2021 to March 31, 2022)
1	1.16	0.65	1.26	1.02
2	1.36	1.20	1.44	1.34
3	1.34	1.46	1.40	1.43
4	1.47	1.57	0.91 (1.51)*	1.16 (1.54)*
5	Not operational	Not operational	2.41	2.41
*On January 12, 2022, the compressor coil on heat pump #4's outdoor unit broke, resulting in the unit remaining in back up heat mode for the rest of the reporting period. Results in brackets show the heat pump performance prior to this date.				

5.3 Unit and duct airflow

5.3.1 Method

A review of commissioning test data was completed with a focus on the following data points in Table 8.

Table 8: Commissioning test data methodology

Review	Data points reviewed	Formula
Commissioning Test Data	ASHP Return Volumetric Flow – (u) Manufacturer Flow Rate Specifications	For each 24hr Test period identify: Maximum volumetric flow rates
	Description	The test data supplied during installation will give an indication how much flow is being detected in the system. If the flow rate is less than the manufacturer specifications, this could cause the system to be less efficient.

5.3.2 Results

While it was not determined which fan speed each unit was operating at the time of the commissioning test, four test results fall below the manufacturers flow rate for the lowest fan speed. Only heat pump #5 reached the manufacturer suggested levels (Table 9). Each flow rate measurement was verified using multiple pieces of equipment (see *Section 4.2*). Airflow was likely reduced in part due to inadequate duct sizing.

This hypothesis was supported by third party engineering audits of several units and their ductwork in early 2022. The engineering audits also indicated poor airflow through ducts that were generally too small to support the volume of airflow recommended by the manufacturer.

Table 9: Commissioning test results

Heat Pump	Duct size	Selected unit size	Unit location	Installation orientation	Return sides	Manufacturer flow rates: high, medium, low fan speeds	Test data (maximum flow rate detected in 24 hour period)
1	11” by 24”	42,000 BTU/Hr	Basement	Vertical	Single, gap underneath	1450 cfm, 1200 cfm, and 1000 cfm	640cfm
2	10” by 20”	42,000 BTU/Hr	Basement	Vertical	Single, gap underneath	1450 cfm, 1200 cfm, and 1000 cfm	878cfm
3	18.25” by 20.25”	36,000 BTU/Hr	Basement (in utility room)	Vertical	Single, gap underneath	1450 cfm, 1200 cfm, and 1000 cfm	672cfm
4	17” by 8” 16” by 8” 14” by 8”	42,000 BTU/Hr	Basement	Vertical	Single, small 2” gap underneath	1450 cfm, 1200 cfm, and 1000 cfm	730cfm
5	18” by 8”	36,000 BTU/hr	Crawlspace	Horizontal	Single, open underneath	1450 cfm, 1200 cfm, and 1000 cfm	1098cfm

It is important to note that heat pumps warm air to a lower temperature than fossil fuel furnaces and compensate for this by delivering a greater volume of air. Especially in heating system retrofits, homeowners may notice that the output air feels cooler, even while similar amounts of thermal energy are being distributed through the home due to higher airflow rates. These higher airflow rates require larger ductwork than has typically been installed with older fossil fuel furnaces.

Without sufficient attention to duct design, airflow may be restricted, reduced or delivery is inefficient. Based on this experience, it is recommended that homeowners considering a ducted heat pump get a duct assessment and duct design work completed as part of the installation by a qualified sheet metal worker.

Increased noise is also a by-product of insufficient attention to duct sizing. Some participants noted increased noise levels resulting from smaller ducts than ideally required.

The primary installer participating in this project noted that a typical retrofit installation includes a single-side air return with a vertical unit, although the manufacturers guideline suggest double-sided return air would be acceptable. Each vertical installation included a small air gap underneath the unit allowing for increased return air. Heat pump #5 was installed horizontally in a crawl space. This offered more space for duct management, likely contributing to its better performance.

5.4 Heat pump performance use of heating capacity

The percentage of time the heat pump spent in each system mode (active, standby, backup/defrost) was calculated. A heat pump that spends a large percentage of the time in standby mode may be short cycling and is an indication that the heat pump is oversized. In standby mode, the unit is still consuming electricity but not producing heat, thus reducing the efficiency. A review of heat produced versus the heating capacity of the unit also provides insight into performance and potential unit sizing issues.

5.4.1 Method

To calculate the percentage each heat pump spent in each system mode, the following formula was used (see Table 10).

Table 10: System mode methodology

Calculation		Data points used	Formula
System Mode %	% Heat Pump in Active Mode	COP Temperature Bin	FOR EACH MINUTE OF DATA: IF $COP > 0.1, sytem\ mode = Active - On$ FOR EACH TEMPERATURE BIN: $\%\ Active\ mode = \frac{Data\ points\ in\ Active\ mode}{Total\ Data\ Points\ for\ all\ modes} * 100$
	% Heat Pump in Back Up Heat Mode	$P_{Aux_{Total}}$	FOR EACH MINUTE OF DATA: IF $P_{Aux_{Total}} > 0, system\ mode = BackUpHeat - On$ FOR EACH TEMPERATURE BIN: $\%\ Back\ Up\ Heat\ mode = \frac{Data\ points\ in\ Back\ Up\ Heat\ mode}{Total\ Data\ Points\ for\ all\ modes} * 100$
	% Heat Pump in Defrost Mode	(u) - ASHP Return Volumetric Flow (y) - ASHP Vapour Line Temp	FOR EACH MINUTE OF DATA: IF $(u) < 0.05\ AND\ (y) < 10, system\ mode = Defrost$ FOR EACH TEMPERATURE BIN: $\%\ Defrost\ mode = \frac{Data\ points\ in\ Defrost\ mode}{Total\ Data\ Points\ for\ all\ modes} * 100$
	% Heat Pump in Standby Mode		FOR EACH MINUTE OF DATA: ALL OTHER DATA POINTS, $sytem\ mode = Standby$ FOR EACH TEMPERATURE BIN: $\%\ Standby\ mode = \frac{Data\ points\ in\ Standby\ mode}{Total\ Data\ Points\ for\ all\ modes} * 100$
	DESCRIPTION	As formulated in section 5.1 for the SCOP calculation, defrost is identifying when the fan speed of the heat pump was below 0.05m^3/s and the heat pump vapour line temperature was below 10°C. By summing the total power of the heat pump, and summing the power when the heat pump is in defrost mode, the consumption and percentage of total heat pump consumption can be found.	

To calculate heat pump capacity, the following data points were used and compared with the maximum capacity of the heat pump from the manufacturer specifications (see Table 11).

Table 11: Heat capacity data methodology

Graph	Data points used	Formula
Heating Capacity vs Temperature	$Q_{HP_{Total}}$ $Q_{Aux_{Total}}$ Outdoor Temp - (z)	FOR EACH MINUTE OF DATA GRAPH: Scatterplot
	Manufacturer Specifications Sheet (42,000BTU/hr unit)	PLOT ON SCATTERPLOT: At -25°C Rated Heat Cap is 11.25kW At -15°C Rated Heat Cap is 14.07kW At -8°C Rated Heat Cap is 14.07kW At 8°C Rated Heat Cap is 15.82kW
	Manufacturer Specifications Sheet (36,000BTU/hr unit)	PLOT ON SCATTERPLOT: At -25°C Rated Heat Cap is 10.55kW At -15°C Rated Heat Cap is 11.14kW At -8°C Rated Heat Cap is 11.14kW At 8°C Rated Heat Cap is 11.72kW
	DESCRIPTION	Graphing the heat output of the heat pump against temperature, and comparing against the manufacturer specifications will identify how the heat pump is operating at different temperatures, and highlight the range of capacity the unit uses to meet the demand of the building.

5.4.2 Results

Figures 10, 11 and 12 show the percentage of total time each heat pump spent in active, standby and backup modes respectively at each temperature range.

In Figure 10, heat pump #5, which had the highest SCOP, is operating between 50 to 75 per cent of the time at most temperature bins including 0°C. This demonstrates the modulating ability of the heat pump to vary heat output. It is consistent with advice from manufacturers to ensure that the heat pump is running consistently for best efficiency. It would appear that even with heat pump #5's rated capacity exceeding the home's heating demand (described in Table 12), the unit allows the heat pump to operate efficiently at a wide range of temperatures.

Heat pump #1 and #4 follow a similar trajectory to each other and operate in active mode more often at the coldest temperatures and less than the other heat pumps at the more moderate temperatures.

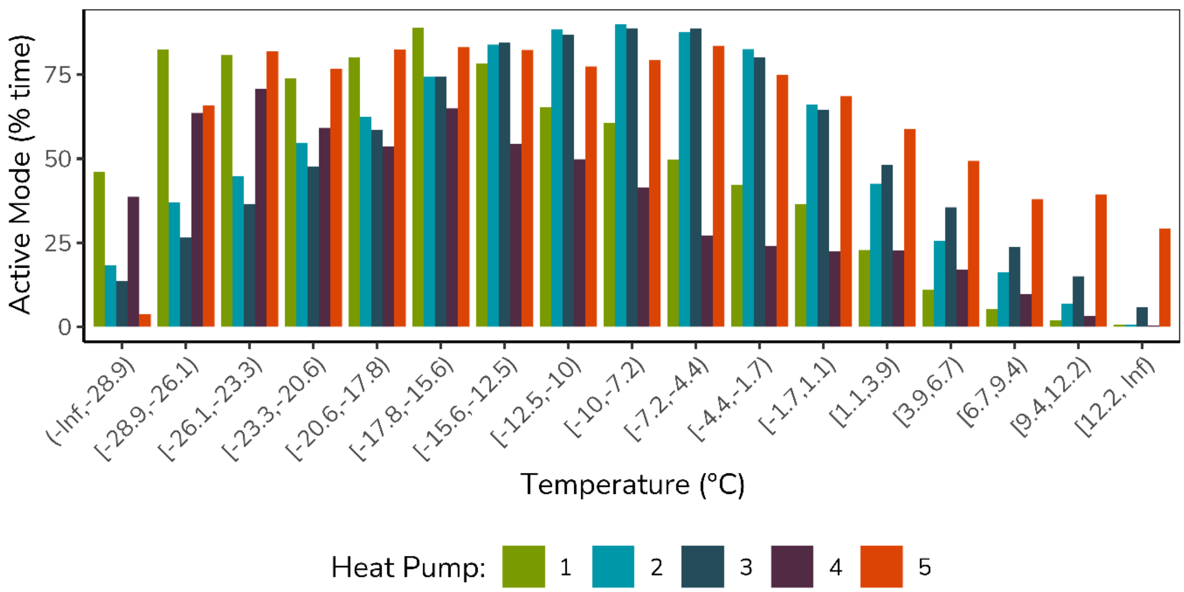

Figure 10: Percentage of time each heat pump spends in active mode.

Figure 11 shows the significant time that heat pump #1 spends in standby mode at temperatures around zero. While this might have indicated oversizing, the fact that heat pump #1 and heat pump #5 both show a similarly large heat capacity-to-heating-demand ratio suggests that other factors may be contributing to the reduced operation time of heat pump #1.

The data for heat pump #4 is included for reference. This heat pump had a damaged coil midway through the heating season. This means the backup heat was operational at warmer temperatures (see Figure 12) when no other backup heating was captured on the other units. Heat pump #2 and #3 used the backup heat more at lower temperatures. The majority of the year had temperatures above -15°C and as such in terms of absolute amount of time spent in backup mode, the units were all quite similar, with the exception of heat pump #4 that experienced technical issues.

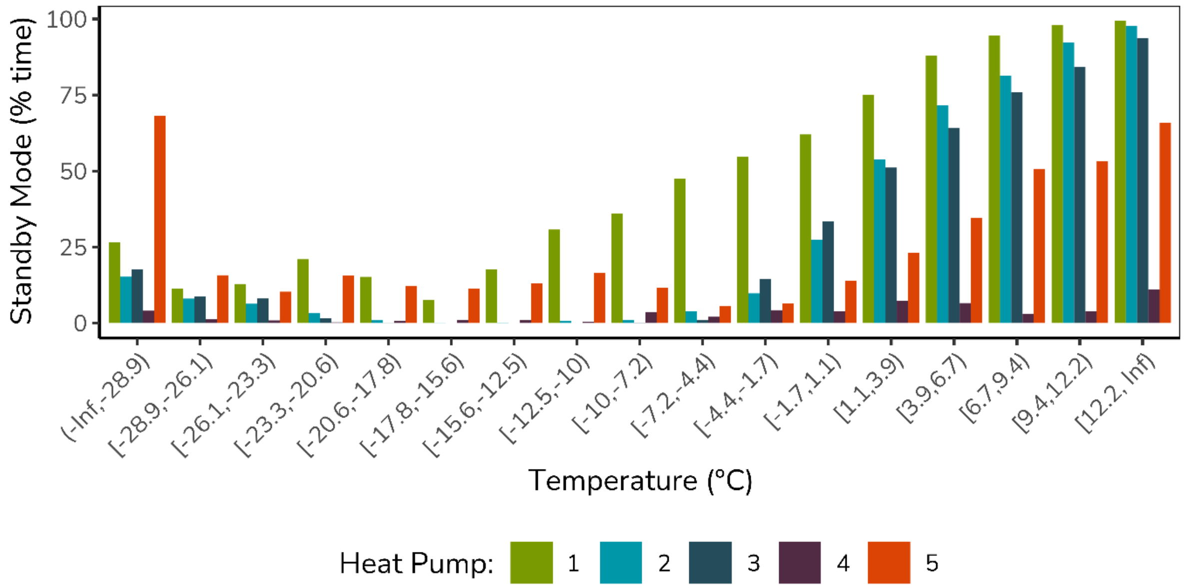

Figure 11: Percentage of time each heat pump spent in standby mode.

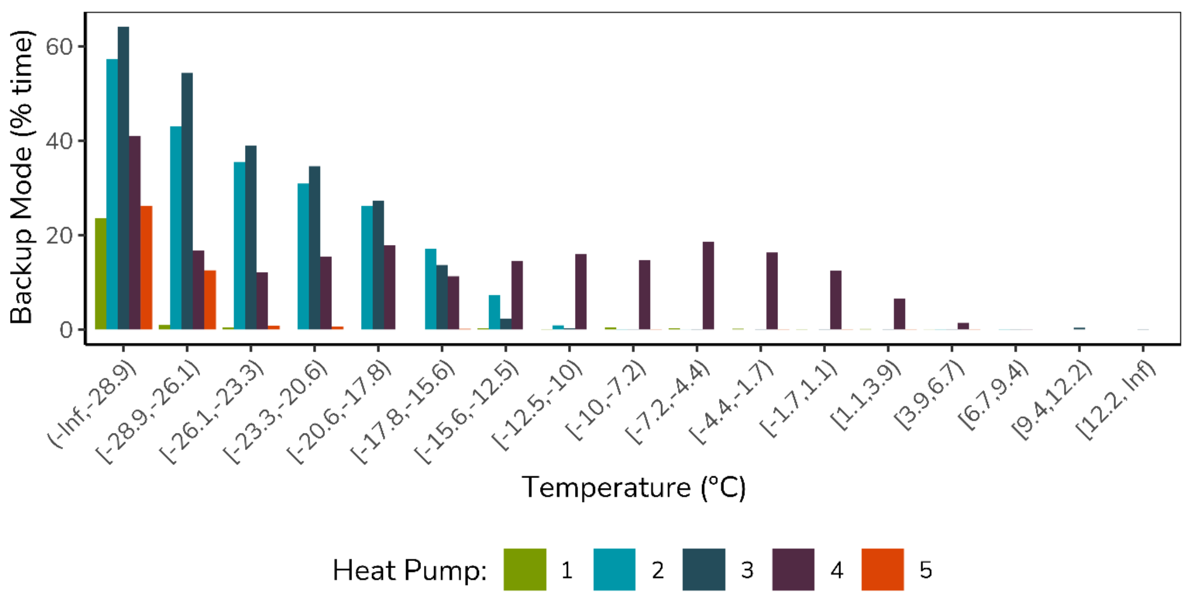

Figure 12: Percentage of time with the backup heat operational.
Lower values indicate that the heat pump is operational.

Table 12 lists the house heat load, selected heat pump size and percentage overall that each heat pump spent in each system mode. The largest gap between house heat load and selected unit size can be seen for heat pump #5. This has not impacted performance though as the unit has the highest SCOP (2.41, see Table 7). Table 12 does show room for efficiency improvements for units #1 and #4. Heat pump #4 spends more time in defrost mode than the other heat pumps.

Table 12: Heat pump system mode results

Heat Pump	House heat load (NRCan sizing tool)	Selected unit size	Unit size minus heat load	Active mode (%)	Standby mode (%)	Back-up heat mode (%)	Defrost mode (%)
1	34,087 BTU/Hr	42,000 BTU/Hr	7,913 BTU/hr	30.1	67.6	1.7	0.5
2	42,617 BTU/Hr	42,000 BTU/Hr	-617 BTU/hr	45.0	44.8	5.5	4.7
3	37,874 BTU/Hr	36,000 BTU/Hr	-1,875 BTU/hr	44.9	46.5	4.3	4.3
4	39,171 BTU/Hr	42,000 BTU/Hr	2,829 BTU/hr	22.5	5.3	64.0	8.2
5	27,297 BTU/Hr	36,000 BTU/Hr	8703 BTU/hr	70.9	16.1	11.9	1.0

Figures 14 to 18 illustrate the heat output of the heat pump against temperature, compared against the manufacturer maximum capacity specifications. An appropriately sized heat pump will have a range of heating capacity readings at the same temperature. Visually, this will look as a thick green cloud covering the area below the manufacturer's blue line. A heat pump that is not utilizing its full range, or heating capacity, will not vary heat output, and will have a thin green cloud.

Figure 13 is a sample heating capacity graph with four specific areas are highlighted. Explanations follow Figure 13.

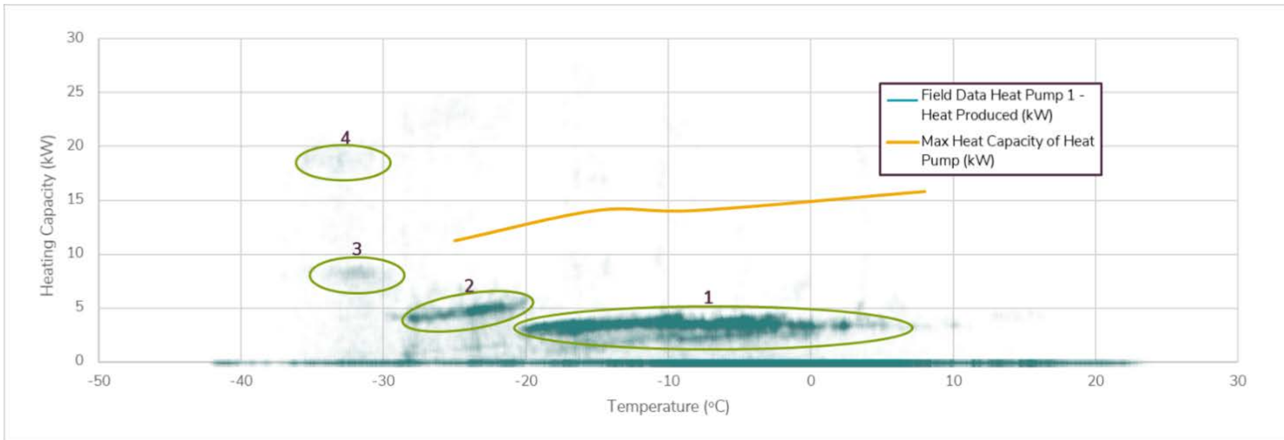

Figure 13: Sample heating capacity for all data points across all temperature ranges with sections highlighted for explanatory purposes. Maximum capacity of heat pump unit included.

Explanations:

- Area 1 – the majority of data points exist in this area, and suggests the unit is using low capacity and cycling on and off to meet the demands of the house above -20°C.
    - As discussed in Section 2.1, a standard operating heat pump modulates its capacity to meet the demands of a home and cycling on and off is not desirable.

- Area 2 – Below -20°C, it appears that the heat pump unit draws more power to meet the demand of the home.

- Area 3 and 4 - Below -29°C, the backup heat becomes the primary heating source which typically consists of two thermal resistance elements. Area 3 represents the start up and shutdown of the first and Area 4 represents the two elements together.

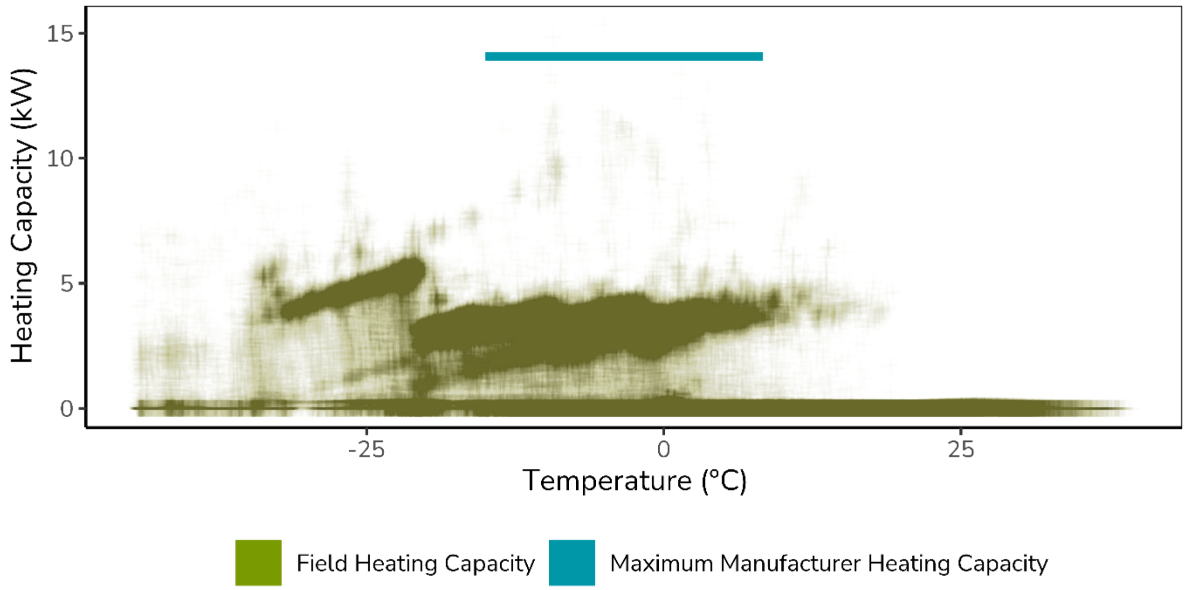

Figure 14: Heating capacity for all data points across all temperature ranges for heat pump #1. Maximum capacity of heat pump unit included.

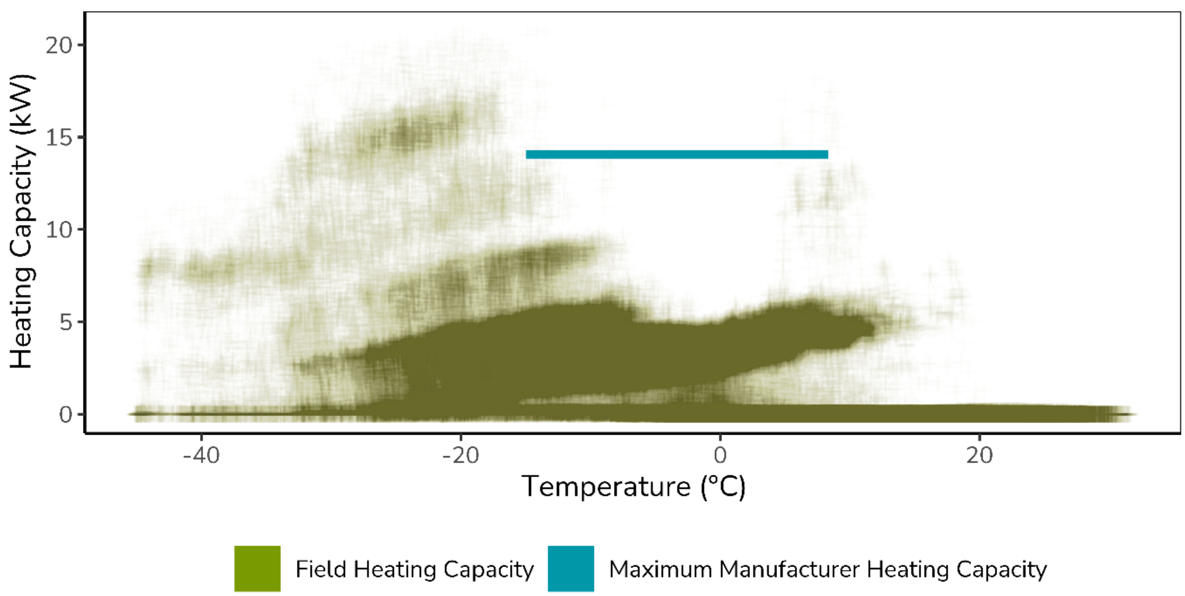

Figure 15: Heating capacity for all data points across all temperature ranges for heat pump #2. Maximum capacity of heat pump unit included.

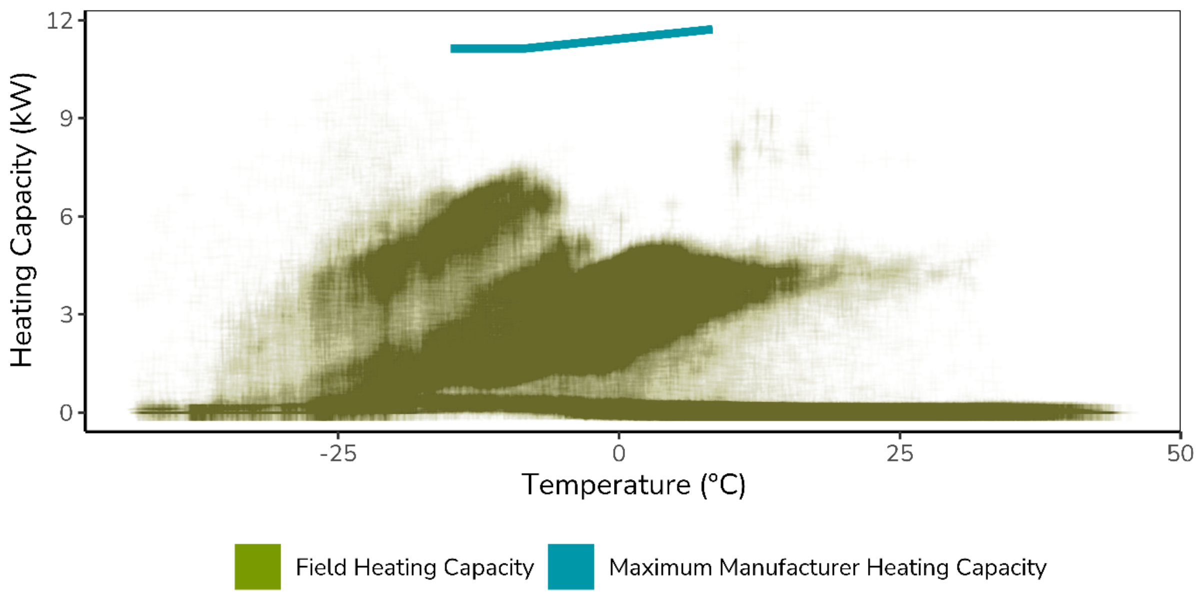

Figure 16: Heating capacity for all data points across all temperature ranges for heat pump #3. Maximum capacity of heat pump unit included.

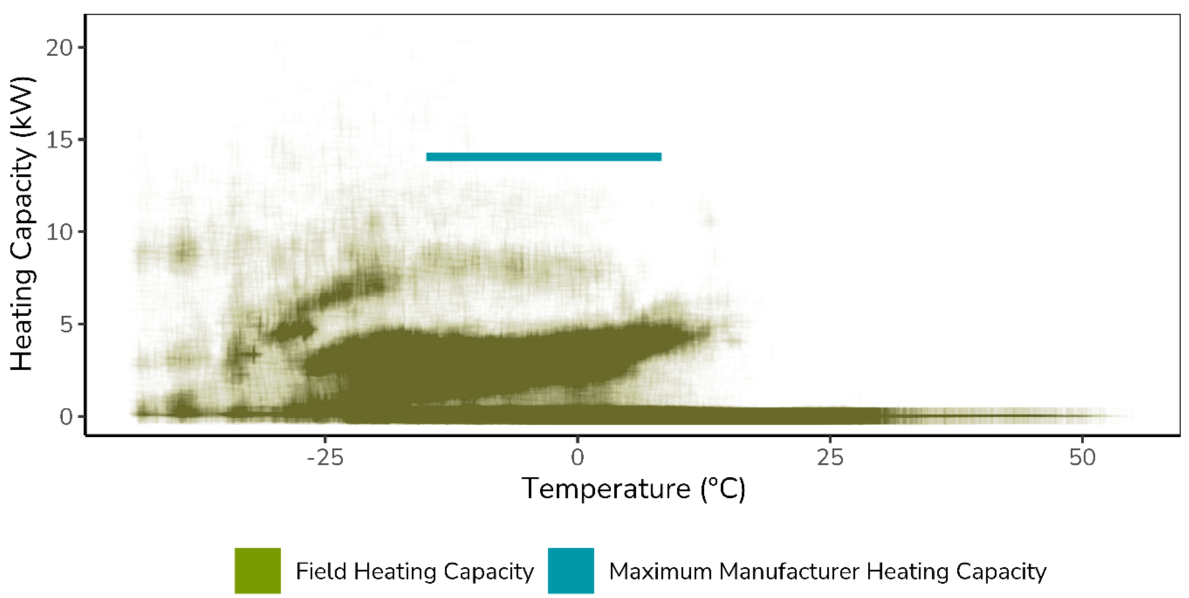

Figure 17: Heating capacity for all data points across all temperature ranges for heat pump #4. Maximum capacity of heat pump unit included.

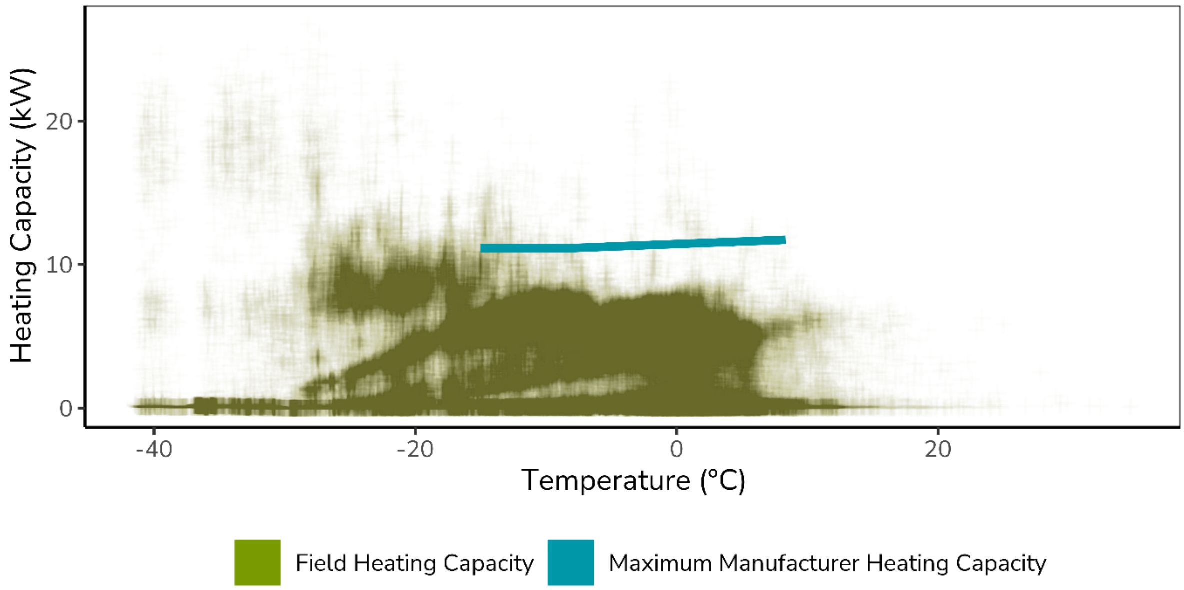

Figure 18: Heating capacity for all data points across all temperature ranges for heat pump #5. Maximum capacity of heat pump unit included.

In the case of heat pumps #1, #2 and #4, the units appear to not be maximizing the full range of the variable speed heat pump. Heat pump #3 and #5 appear to offer greater modulation of the heat produced at the majority of temperature ranges. This suggests that other factors related to the installation (return air, duct size, control configuration, etc.) may have more of an effect than sizing, as unit #5 is potentially oversized but performs well. As the number of units studied is limited, more information from more units is required to draw conclusions on the impact of sizing.

Recognizing the impacts from oversizing early on (in Interim Report #1), the Government of Yukon supported additional training on NRCan's heat pump sizing tool, running training sessions for interested installers. All other heat pumps participating in the program must follow the sizing recommendations.

5.5 Defrost consumption / ice build-up and damage

It was noted by participants that outdoor units produced high levels of defrost water. This required additional maintenance to control ice build up and water run off during the winter months. A review of defrost consumption was completed to determine if there were any unusual results that would require investigating.

5.5.1 Method

Table 13 details the methodology to calculate defrost consumption and percentage of total heat pump consumption.

Table 13: Defrost consumption methodology

<table>
<tr><th colspan="2">Calculation</th><th>Data points used</th><th>Formula</th></tr>
<tr><td rowspan="4">Defrost</td><td>Total heat pump consumption</td><td>$P_{HP_{interior_{Total}}}$
$P_{HP_{outdoor_{total}}}$</td><td>$p_{HP_{Total}} = \frac{(P_{HP_{interior_{total}}} + P_{HP_{outdoor_{total}}})}{60}$(kWh)</td></tr>
<tr><td>Total defrost consumption</td><td>$P_{HP_{outdoor_{defrost}}}$</td><td>$P_{HP_{outdoor_{defrost}}} = \sum \frac{P_{HP_{outdoor_{defrost}}}^{*}}{60}$(kWh)</td></tr>
<tr><td>DEFROST %</td><td>$p_{HP_{Total}}$
$P_{HP_{outdoor_{defrost}}}$</td><td>$Defrost\,\% = \frac{P_{HP_{outdoor_{defrost}}}}{P_{HP_{outdoor_{defrost}}}} * 100$</td></tr>
<tr><td>DESCRIPTION</td><td colspan="2">As formulated in section 5.1 for the SCOP calculation, defrost is identifying when the fan speed of the heat pump was below 0.05m^3/s and the heat pump vapour line temperature was below 10ºC.

By summing the total power of the heat pump, and summing the power when the heat pump is in defrost mode, the consumption and percentage of total heat pump consumption can be found.</td></tr>
</table>

5.5.2 Results

Using the formula in Table 13, the results are shown in Table 14.

Table 14: Defrost consumption results

Heat pump	Heat pump Consumption (kWh)	Defrost Consumption (kWh)	Defrost (%)
1	7,502	225	**3.0%**
2	10,852	798	**7.3%**
3	10,317	482	**4.6%**
4	5,088	449	**8.8%**
5	8363	209	**2.5%**

The data showed that heat pump #2 had defrost cycles approximately every 30 minutes. An incorrect setting was identified as the cause and corrected. Normal heat pump operation is when the heat pump goes into defrost only when required.

Defrost percentage is high for heat pump #4. The consumption is in keeping with the other units, but because the heat pump was operating for less time (i.e. fewer total minutes operational), the relative proportion of time spent in defrost is higher.

The results indicate the complexity of the units, as multiple factors likely have contributed to these issues.

1) A discussion with the installer indicated that unit #2 might have been erroneously set to a 'high humidity' mode, as a compensation for a previous thermistor issue. This may have contributed to a greater amount of defrost cycling and was corrected.
2) Heat pump #4 had a broken coil in January 2022. The outdoor unit was on a tilt, causing improper drainage leading to ice build-up on the coil. The additional ice build up may have contributed to higher defrost.

5.6 Energy Savings

5.6.1 Method

Reviewing homeowner energy bills to evaluate energy savings was not completed because of time constraints and the incomplete picture such records would provide due to the prevalence of supplemental wood heat in participant homes.

Instead, an energy modelling software was used to replicate before and after scenarios, using the individual heat pump data (SCOP) to inform the modelling of the heat pump.

5.6.2 Results

The energy savings in Table 15 roughly correlate to the SCOP results observed in Table 7. Given this data set, the importance of proper system design appears critical to achieving expected energy savings.

Key installation factors include:

- sufficient attention to duct design and airflow volumes;
- appropriate unit sizing;
- manufacturer recommended placement of on-board sensors;
- well considered location and orientation of outdoor unit; and
- manufacturer recommended initial settings and commissioning.

The best performing heat pump (heat pump #5) offers a modelled 43.2 per cent energy savings over the base case scenario.

Table 15: Energy savings analysis

Client	Base case primary heating system	Base case secondary heating system	COP	Space heat base case (GJ/yr)	Space heat upgrade case (GJ/yr)	Energy savings - heat (GJ/yr)	Energy savings - heat (%)
1	Furnace - oil	Woodstove	1.02	67.34	65.99	0.10	2.0%
3	Furnace - propane	None	1.43	63.49	56.15	3.60	11.6%
2	Wood	None	1.34	85.77	80.83	7.80	5.8%
4	Furnace - electric	ASHP (non-cc)	1.16	81.17	73.05	8.80	10.0%
5	ccASHP	Baseboards	2.41	44.51	25.26	19.25	43.2%

Note that that cost savings are not always correlated directly with energy savings, as it depends on the previous fuel source. Households that had access to inexpensive wood sources noticed an increase in payments, as electricity per unit, is more expensive.

6.0 Challenges

The project encountered a number of challenges during the first year and a half:

- Very few installers are active in Yukon.

- The trend in heating is to size larger than design heating load.

- Auxiliary heat transition issues. Mitsubishi has solved this and improved their programming in the unit. Homeowners should confirm (if getting a Mitsubishi Zuba) that this change has occurred.

- Retrofit limitations may affect ducted heat pump's performance:
    - The size of mechanical rooms or crawlspace may mean a vertical installation is the only option, but a horizontal installation should be considered; and
    - Duct design is essential. If too small, or calculations are not completed, there may be restricted airflow, and a drop in efficiency.

- Compatibility with backup heating sources. Initially, the project was focused on heat pumps paired with typically fossil fuel backup: propane or oil.
    - In reality, the airflow requirements vary, so combined ducted systems are challenging to facilitate. Furthermore, homeowners are looking to remove their oil furnaces and there seem to be few products that could integrate with these backups in a ducted capacity.
    - Instead, mini-splits are being installed to pair with a centralized fossil-fuel backup heating system.

7.0 Average Costs

The average materials cost for the ducted heat pumps under study was $17,805. The average installation cost for ducted heat pumps was $8,206.

These costs do not included the Government of Yukon rebate of $10,000 to bring the ducted heat pumps costs more inline with fossil-fuel based systems.

For reference, a new propane furnace is approximately $8,000 to $12,000.

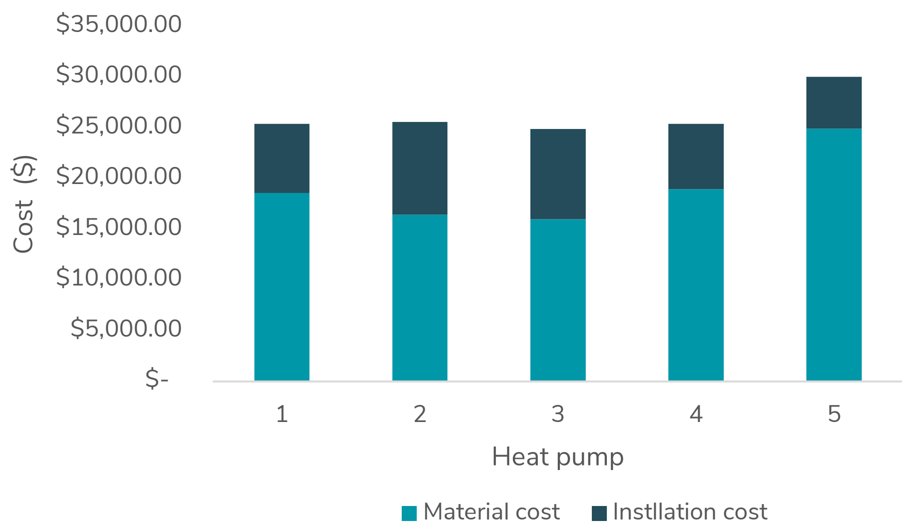

Figure 19: Material and installation costs for the ducted heat pumps.

8.0 Conclusion

This study highlights a few important realities of cold-climate air-source heat pumps. The first is that even in very cold climates, efficient heat pump operation is possible. Even though four out of five heat pumps demonstrated lower than expected performance, the fifth heat pump provided evidence that a properly installed and configured system is able to achieve a seasonal coefficient of performance greater than two over the heating season. This best performing heat pump would expect to benefit from a 43 per cent reduction in energy use, as compared to electric baseboards.

The second major conclusion is that care around ductwork should be prioritized when installing retrofit ducted systems. Homeowners should seek out a duct design from a qualified sheet metal technician and expect to increase the duct size to see best performance from a heat pump. If increasing the ductwork is not an option, those households would be best to consider other heat pump options such as ductless mini-splits.

General installation best practices also involve:

- manufacturer recommended placement of on-board sensors, which can ensure accurate temperature readings and operation of the heat pump;
- well considered location and orientation of outdoor unit, to prevent access issues; and,
- manufacturer recommended initial settings and commissioning, which can assist with efficient operation.

9.0 Next Steps

An additional 20 plus heat pumps of different makes, models and styles have been or are being installed around the Yukon. This includes multiple ductless mini-splits, multi-splits and air to water heat pumps.

The data gathered from these units will continue to be analysed in partnership with Yukon University to support a better understanding of heat pump performance in the Yukon's cold climate.