# Air-Source Heat Pump Monitoring Project Technical Report

2022/2023

# Contents

1 Introduction ... 5
2 Project description ... 6
  2.1 Overview ... 6
  2.2 Project events and timeline ... 6
    2.2.1 Heat pump sizing ... 6
    2.2.2 Installation, commissioning and data collection period ... 7
    2.2.3 Summary of Major Events ... 8
3 Key insights ... 10
  3.1 Overall performance ... 10
  3.2 Duct design as priority consideration ... 11
  3.3 Energy savings ... 12
  3.4 Price ... 12
  3.5 Participant feedback ... 13
  3.6 Load curves and load distribution throughout the day ... 15
4 Energy and cost savings ... 17
  4.1 Method ... 17
  4.2 Results ... 18
    4.2.1 Electricity expenditures ... 19
5 Challenges ... 21
6 Next steps ... 22
7 Conclusion ... 22
8 Sources ... 24

Appendix A Monitoring equipment and methodology ........................................................25

Appendix A.1 Introduction ........................................................................................25

Appendix A.2 Power measurements ..........................................................................26

Appendix A.3 Airflow measurements..........................................................................28

Appendix A.4 Environmental monitoring.....................................................................28

Appendix A.5 Monitoring equipment verification ........................................................28

Appendix A.6 Monitoring equipment calculations ........................................................28

Appendix A.7 Temperature bins ................................................................................30

Appendix A.8 System mode ......................................................................................31

Appendix A.8.1 Active mode ......................................................................................31

Appendix A.8.2 Defrost mode ....................................................................................33

Appendix A.8.3 Backup mode ....................................................................................35

Appendix B Data analysis ..........................................................................................37

Appendix B.1 Temperature and humidity profile ..........................................................37

Appendix B.2 COP, ICOP and SCOP – Comparison to manufacturer specifications 38

Appendix B.2.1 Method.............................................................................................40

Appendix B.2.2 Results .............................................................................................41

Appendix B.3 Heat pump performance .......................................................................46

Appendix B.3.1 Method.............................................................................................46

Appendix B.3.2 Results .............................................................................................47

Appendix B.4 Defrost consumption / ice build-up and damage ....................................51

Appendix B.4.1 Method.............................................................................................51

Appendix B.4.2 Results .............................................................................................52

Appendix C Unit and duct airflow ..... 54
    Appendix C.1 Method ..... 54
    Appendix C.2 Results ..... 55
Appendix D System mode calculations ..... 60

# 1 Introduction

Canadian homeowners are increasingly adopting air source heat pumps for home heating. To accommodate residents in colder regions of Canada, cold climate air source heat pumps, as designated by the Northern Energy Efficiency Partnerships[1], are becoming more and more common.

The Government of Yukon and partners are leading a project to assess air source heat pumps installation, operation and performance in the Yukon's cold climate over the course of three heating seasons.

In winter of 2020/2021, the Government of Yukon supported the installation of five centrally ducted cold-climate air-source heat pumps with monitoring equipment in five single detached homes in Whitehorse, Yukon.[2]

The five heat pumps were monitored from January 2020. Previously, two reports were published.[3, 4] The focus of this third report is on the 2022/2023 heating season, presenting results of the five heat pumps' performance from April 2022 to April 2023.

The Energy Branch collected and analyzed data on the heat pumps and backup heating systems' heat output, airflow and electricity consumption. Homeowners provided qualitative feedback that was included in the analysis.

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[1] Northeast Energy Efficiency Partnerships, "ccASHP Specification & Product List."

[2] Support consisted in a grant of up to 40% of system cost, capped at 10,000 CAD, from Government of Yukon, plus a grant of 8,000 CAD from the Government of Canada.

[3] Yukon Department of Energy, Mines and Resources, "Air-Source Heat Pump Monitoring Project Technical Report for Winter 2021."

[4] Yukon Department of Energy, Mines and Resources, "Air-Source Heat Pump Monitoring Project Technical Report for 2021/2022."

# 2 Project description

## 2.1 Overview

The goal of this technical report is to evaluate heat pump performance through analysis of coefficients of performance, time spent in various system modes, defrost consumption and modelled energy savings.

Results from this report will provide insight on the continued performance of heat pumps three years post-installation.

Five centrally ducted cold-climate air-source heat pump systems were installed as part of this project.

All five systems:

- are Mitsubishi Zuba models, with two rated at 36,000 BTU/h and three rated at 42,000 BTU/h;
- 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 unit was installed horizontally, allowing for dual air return from each side.

## 2.2 Project Events and Timeline

### 2.2.1 Heat pump sizing

The first step after onboarding was that 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.

Heat pumps #2 and #3 are slightly undersized in comparison to their house heat load, by 2% and 5%. Conversely, heat pumps #1, #4 and #5 are oversized.

| # | House | | | | Heat pump | | |
|---|---|---|---|---|---|---|---|
| | Year | Area [sq ft] | Secondary heat | Heat load [BTU/h] | Model | Capacity [BTU/h] | HP size [%] |
| 1 | 1969 | 1,927 | Wood stove | 34,087 | PUZ-HA42NKA1 | 42,000 | +19 |
| 2 | 1997 | 2,314 | Wood stove | 42,617 | PUZ-HA42NKA1 | 42,000 | -1 |
| 3 | 1990 | 2,265 | Propane stove | 37,874 | PUZ-HA36NKA | 36,000 | -5 |
| 4 | 1977 | 1,795 | None | 39,171 | PUZ-HA42NKA1 | 42,000 | +7 |
| 5 | 2020 | 2,835 | Electric baseboards and wood stove | 27,297 | PUZ-HA36NKA | 36,000 | +24 |

*Table 1: Overview of the five heat pumps installed for the pilot. All heat pumps are centrally ducted Mitsubishi Zuba units. The last column indicates by how much the heat pump capacity is bigger or smaller in comparison to the heating design load.*

### 2.2.2 Installation, commissioning and data collection period

Table 2 is a timeline of the events leading up to and throughout the installation and commissioning of the monitoring equipment in 2020/2021. To commission the system a series of short-term tests were conducted.

| # | Installation date | Monitoring commission | Monitoring | |
|---|---|---|---|---|
| | | | from | to |
| 1 | Nov 10 to 16, 2020 | Jan 25 to 29, 2021 | Apr 1, 2022 | Mar 31, 2023 |
| 2 | Dec 1 to 7, 2020 | Jan 29, 2021 | Apr 1, 2022 | Mar 31, 2023 |
| 3 | Dec 8 to 15, 2020 | Jan 8, 2021 | Apr 1, 2022 | Mar 31, 2023 |
| 4 | Dec 14 to 18, 2020 | Feb 22, 2021 | Apr 1, 2022 | Mar 31, 2023 |
| 5 | Dec 14 to 18, 2020 | Oct 27, 2021 | Oct 27, 2022 | Apr 31, 2023 |

*Table 2: Overview of important dates. November 2022 data for all heat pumps was not collected due to sensor issues. Additionally, between November 2022 and January 2023, sensors on heat pump #3 were not recording data. This may affect performance results for heat pump 3.*

### 2.2.3 Summary of major events

**Heat pump sizing** – Prior to each system's installation in 2020, an energy assessment was completed for each home. The Energy Branch entered data from the assessment 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 in early 2021, the units 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 remedy 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 in 2021. 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 had been 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.

**Data logging issues** – In November 2022, malfunctions with the API resulted in issues with data download and transfer for all heat pumps. This was fixed by early December 2022.

**Sensor unplugged** – In early December 2022, sensors on heat pump #3 were accidentally unplugged and data was not being recorded. This was identified and rectified in early January 2023.

**Formula updates** – In July 2023, the formula for determining system mode was updated to account for power draw during defrost. Defrost mode had previously not been reliably detected. This change ensures that data is properly classified as standby if the power draw does not exceed 0.2 kW.

# 3 Key insights

## 3.1 Overall performance

Over the 2022/2023 heating season, the seasonal coefficient of performance (COP – see Box 1) for the five heat pumps in this study ranged from 1.10 to 2.51 (see Table 3).

| # | **20/21**<br>Apr 1 2020 –<br>Mar 31, 2021 | **21/22**<br>April 1, 2021 –<br>March 31, 2022 | **22/23**<br>April 1 2022 –<br>March 31, 2023 | Average |
|---|---|---|---|---|
| 1 | 1.16 | 1.02 | 1.20 | 1.13 |
| 2 | 1.36 | 1.34 | 1.54 | 1.41 |
| 3 | 1.34 | 1.43 | 1.10* | 1.29 |
| 4 | 1.47 | 1.16 | 1.45 | 1.36 |
| 5 | Not yet installed | 2.41 | 2.51 | 2.46 |

*Table 3: Seasonal Coefficient of Performance (SCOP). Note that Heat Pump #3's network connection was accidentally unplugged between December 2022 to January 2023, which may contribute to the low SCOP.*

Results varied between heat pumps and for different temperatures.

| # | Balance point temperature in °C |
|---|---|
| 1 | -22 |
| 2 | -14 |
| 3 | -11 |
| 4 | -19 |
| 5 | -28 |

*Table 4:Balance point temperatures for the different heat pumps. The balance point temperature is the temperature above which the heat pump outperforms resistive heat. Below the balance point temperature, it is more efficient to use resistive heat or other backup heat sources.*

A common concern with heat pumps is correct sizing to the heat load. It is interesting to note that, in this sample and in this heating season, two heat pumps that were oversized (heat pumps #1 and #5) performed best. (See Table 13 in Appendix B.3.2.)

**Box 1: Coefficient of performance of electrical baseboard heaters and heat pumps**

The coefficient of performance (COP) measures the performance of heat pumps, but it can also be calculated for electric baseboard heaters. To calculate COP, electrical energy consumed is divided by heat energy delivered.

An electric baseboard heater has a COP of one: one unit of electricity is transformed into one unit of heat. This is why resistive heating is described as 100% efficient. Unlike electric baseboards, heat pumps do not transform electricity into heat. Rather, a heat pump transports ("pumps") heat from the outside to the inside. A heat pump's COP can be higher than one because "pumping" heat takes less energy than "making" heat.

When a heat pump has a COP higher than one, more energy is delivered to the interior as heat than is consumed as electricity, making it more efficient than a resistive system. At a COP of less than one, a resistive baseboard heater would be more efficient.

## 3.2 Duct design as priority consideration

For the second consecutive season, one heat pump (#5) achieved a seasonal COP of greater than two. Among the heat pumps in the study, this heat pump is the only system installed in a newly built house, with ductwork sized to the heat pump's requirements.

| | | Ductwork | |
|---|---|---|---|
| | | Correctly sized | Undersized |
| Heat Pump | Oversized | About 2.5 | About 1.3 |
| | Undersized | No data in this study | About 1.3 |

*Table 5: Seasonal COP for the most recent heating season*

The remaining four heat pumps were retrofitted to existing ductwork designed for fossil fuel heating systems. For these heat pumps, performance was lower than manufacturer expectations. This was likely due to ductwork concerns: over or under sizing did not seem to impact performance much. (See Table 4.)

Important observations are:

- The air leaving a heat pump is typically colder than the air leaving a furnace. Therefore, higher airflow is required for heat pumps to move the same amount of heat.
- The heat pumps in this study 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 deliver heat.

This is why homeowners who are switching from oil or propane heating systems to a heat pump likely need to increase the size of the ducts in their homes. If increasing the ductwork is not an option, homeowners should consider installing ductless mini-splits or smaller centrally ducted heat pumps with lower airflow requirements.

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.

## 3.3 Energy savings

Modelling suggests energy savings in each of the five homes, ranging from 7% to 45%.

## 3.4 Price

The average system cost for ducted systems installed in 2023 was $27,629, the average system cost for mini-split systems was $11,437.

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

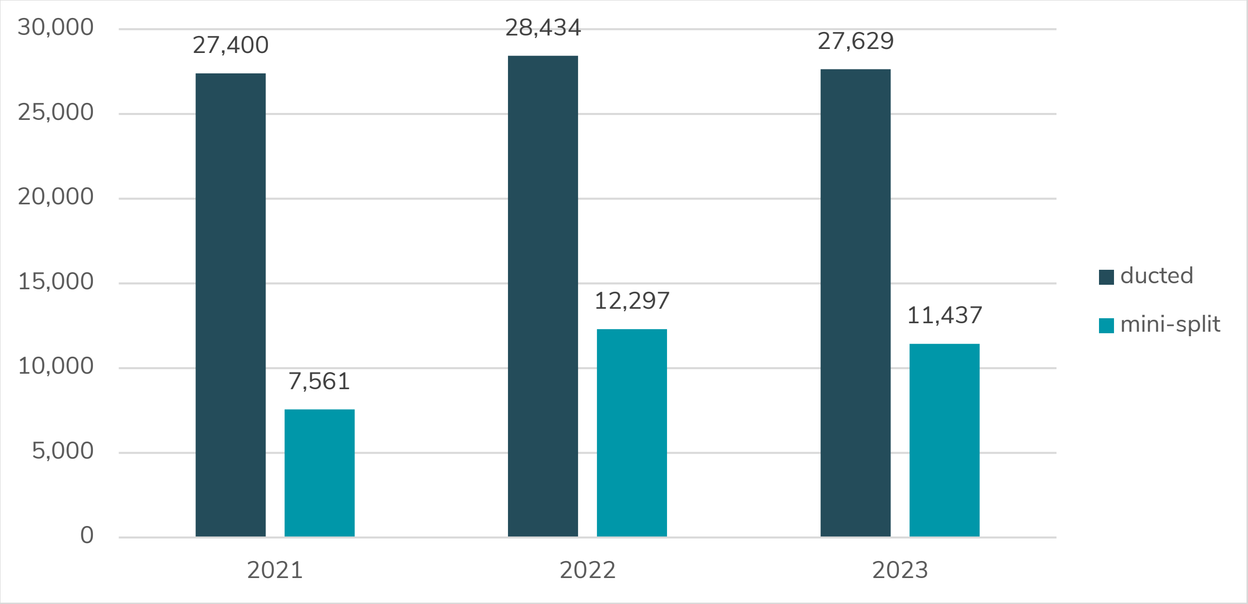


*Figure 1: Average total system cost for the last three years. Note that this figure draws on a much larger sample (63 heat pumps installed from 2021-2023) than the technical analysis.*

## 3.5 Participant feedback

The monitored heat pumps were reported to maintain set temperatures and overall comfort in the homes. Participants also noticed improvements in air quality and circulation since installing their heat pumps.

In some cases, cost savings were noticed in comparison with their prior heating system; however, this varied from home to home and was difficult to confirm as some converted from wood or fossil fuel heating to heat pumps.

Some participants mentioned a low, consistent hum from the indoor unit fan. Centrally ducted heat pumps, much like HRV systems, should thus be installed away from bedrooms when possible. Outside units should ideally be structurally separated from the house so as not to transmit sounds and should ideally be placed on walls away from bedrooms.

A concern during previous winters was excessive water output during the winter months that led to ice build-up under the heat pumps. Previously, one system experienced a broken coil from ice buildup, and this issue was rectified by relocating an indoor thermostat and adjusting the outdoor unit's tilt to improve drainage. During the winter of 2022/23, there were less complaints about ice buildup. It is not clear if this is due to lower ice buildup, different weather conditions, or simply because participants were getting used to this. The addition of wind baffles and/or a small roof over the units may have helped mitigate the issue.

*Figure 2: Outdoor unit of one participant showing wind baffles (to reduce ice buildup) and a sled used to periodically remove ice during the winter.*

## 3.6 Load curves and load distribution throughout the day

The sample size is very small, but we can extract load curves at different temperatures for four of the five systems. Note that these are all centrally ducted systems, so this is not representative of heat pumps in general.

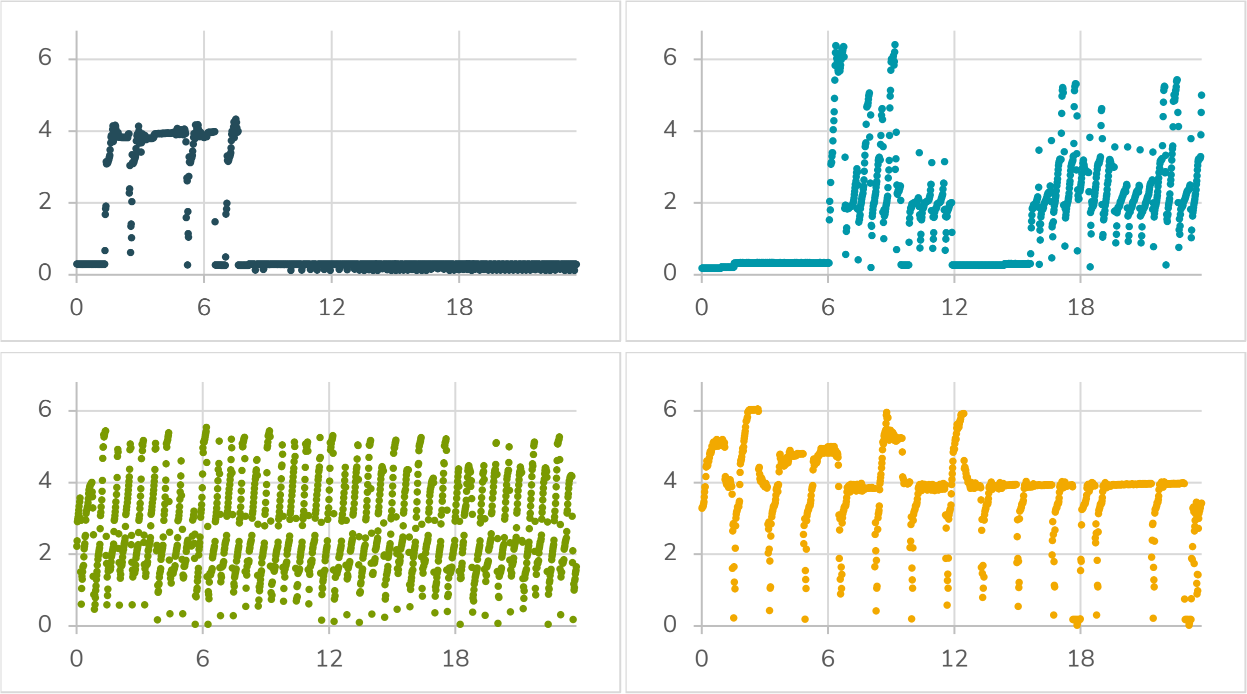
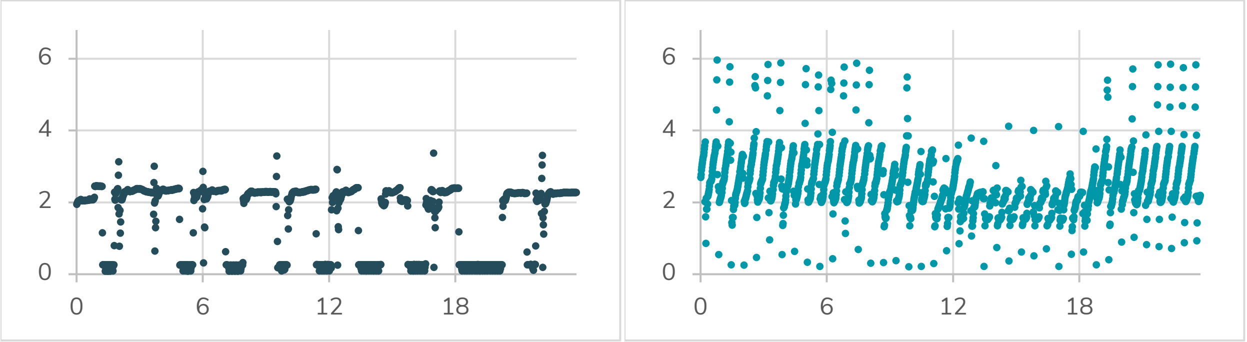


*Figure 3: Load curves from four heat pumps on a day with an average temperature of -27 degrees. kW power shown on y axis, time of day on x axis.*



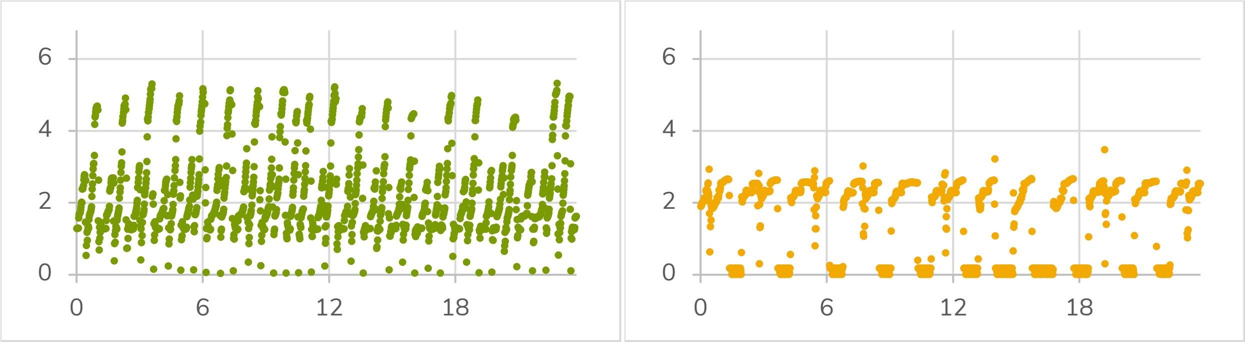


*Figure 4: Load curves from four heat pumps on a day with an average temperature of -10 degrees. kW power shown on y axis, time of day on x axis.*

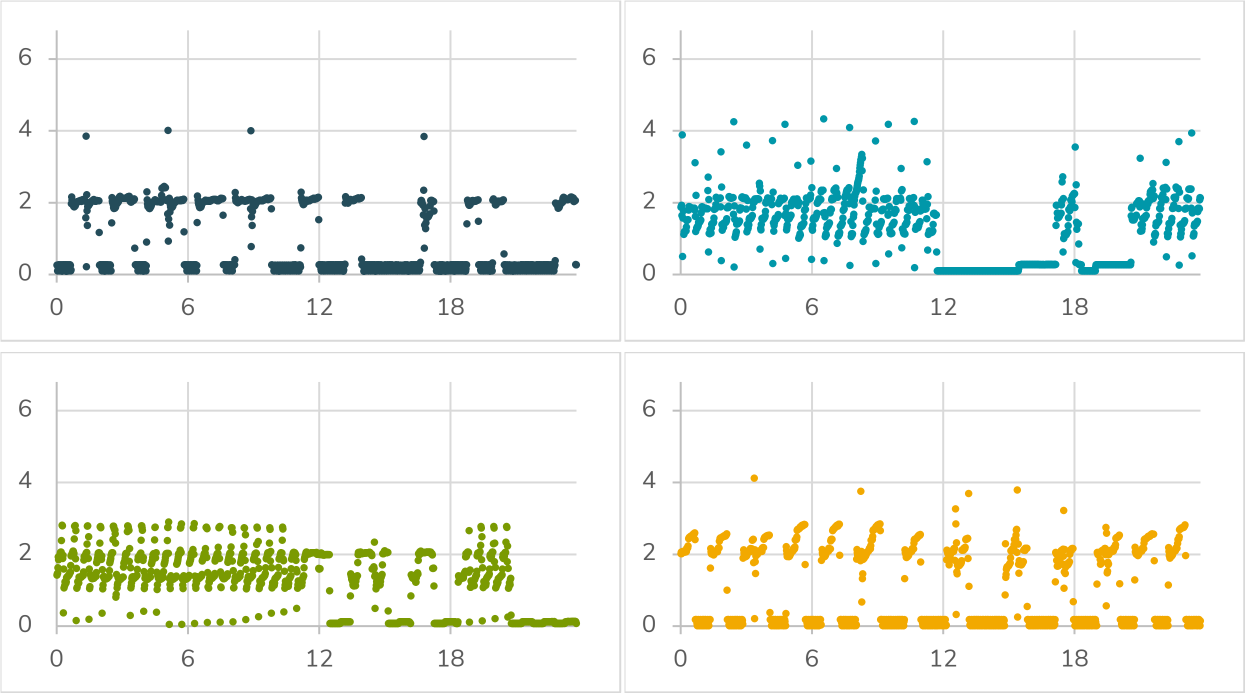


*Figure 5: Load curves from four heat pumps on a day with an average temperature of -3 degrees. kW power shown on y axis, time of day on x axis.*

It is interesting to note that the heat pumps in our sample are all the same model (albeit of different capacities). Still, the load curves are different from system to system, indicating that variables beyond heat pump make and model are important, such as the fit of the heat pump to the design heat load, existence and use of secondary heat sources such as woodstoves or baseboard heaters, user behaviour and differences in meteorological conditions from one location to another.

We can also investigate if the load peaks of the various heat pumps occur at the same time of day. In our dataset, they do not, see table below.

| | **1** | **2** | **3** | **4** | **nominal max [kW]** | **actual max [kW]** | **%** |
|---|---|---|---|---|---|---|---|
| -27 degree day | 4.34 | 6.41 | 5.54 | 6.05 | 22.34 | 17.95 | 80% |
| -10 degree day | 3.38 | 5.97 | 5.33 | 4.00 | 18.68 | 13.57 | 73% |
| -3 degree day | 4.02 | 4.35 | 3.00 | 4.13 | 15.49 | 10.89 | 70% |

*Table 6: Individual maximum loads for each heat pump and total load. Nominal maximum load is the load that would have been measured had all the individual maximum loads occurred at the same time. Actual maximum load is the maximum load that occurred during each day. This shows that the individual maximum loads do not occur at the same time. The final column indicates the actual maximum load as percentage of the nominal maximum load.*

# 4 Energy and cost savings

## 4.1 Method

Reviewing homeowner energy bills to evaluate cost and 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 and variety in pre-heat pump heating systems in participant homes. Without energy bills, cost savings are challenging to analyze, and energy savings must be relied upon as a proxy.

VoltaSnap, 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. Base case (pre-install) scenarios are based on energy audits that were completed prior to installing the heat pump, and include details on insulation, air leakage and space heating relevant to the home's energy efficiency. The post-installation simulation then replaces the original heating system and SCOP values are used to determine the individual energy savings for space heating in each home.

## 4.2 Results

Modelled energy savings are shown in Table 6. Results from the 2022-2023 heating season indicate that the best performing heat pump is not expected to yield the highest energy savings. The observed difference is likely attributed to the base case scenario; heat pump #5 was installed in a newly built home and factors such as insulation and air sealing were factored into the current analysis. On average, newer, well-built homes will consume less energy than older homes. Additionally, the original heating systems in all 5 homes differed from each other, introducing variation in overall energy savings not attributable to SCOP values.

In order to ensure benefits from energy savings, 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;
- location and orientation of outdoor unit: facing away from bedrooms, structurally separate from outside walls and building foundation; and
- manufacturer recommended initial settings and commissioning.

Energy consumption modelling for the house with heat pump #2, a home previously relying on wood heat, suggests a 45% decrease in energy consumption. All modelled scenarios yielded energy savings, although heat pump #3 demonstrated a much lower value.

An overall increase in energy savings is seen during the 2022-2023 heating season when compared to the previous year.

This suggests that energy savings improve as owners become more familiar with heat pump settings and mitigation strategies for ice build-up.

| # | Base Case Heating System | SCOP | Space heat | | Energy savings – heat | |
|---|---|---|---|---|---|---|
| | | | Base case | Upgrade | | |
| | | | [GJ/a] | [GJ/a] | [GJ/a] | % |
| 1 | Oil furnace and wood stove | 1.20 | 65.31 | 41.51 | 23.8 | 36 |
| 2 | Wood stove | 1.54 | 82.70 | 45.76 | 36.94 | 45 |
| 3 | Propane furnace | 1.10 | 61.02 | 56.61 | 4.41 | 7 |
| 4 | Electric furnace and ASHP (not cold climate) | 1.45 | 56.56 | 37.56 | 19 | 34 |
| 5 | Electric baseboards | 2.51 | 33.16 | 21.54 | 11.62 | 35 |

*Table 7: Energy savings analysis*

Note that the 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. Conversely, other households switching from fuel to heat pumps found they were spending less on average; while their electricity costs increased, they were spending less on oil or propane, resulting in an overall decrease in heating costs.

### 4.2.1 Electricity expenditures

The electricity cost to operate each of the systems is estimated below.

| **Heat Pump** | Total consumption | Cost, annual | Cost, monthly average |
|---|---|---|---|
| | [kWh] | [$] | [$] |
| **1** | 3915 | 857 | 71 |
| **2** | 7427 | 1679 | 140 |
| **3** | 6074 | 1362 | 114 |
| **4** | 5610 | 1254 | 104 |
| **5** | 2983 | 639 | 53 |

*Table 8: Total consumption and estimate of total electricity cost. Note that this is an estimate based on Jan 2024 electricity tariffs for Whitehorse, see here: [https://www.atcoelectricyukon.com/en-ca/customer-billing-rates/bill-calculator.html](https://www.atcoelectricyukon.com/en-ca/customer-billing-rates/bill-calculator.html)*

The cost cited is indicative only. The estimation has been made by entering the heat pump's electricity consumption into a utility bill calculator, using tariffs valid on January 2024. Please note that this assumes that the heat pump is the only electrical load. If there are other loads, a real-world household may end up in a different tariff block.

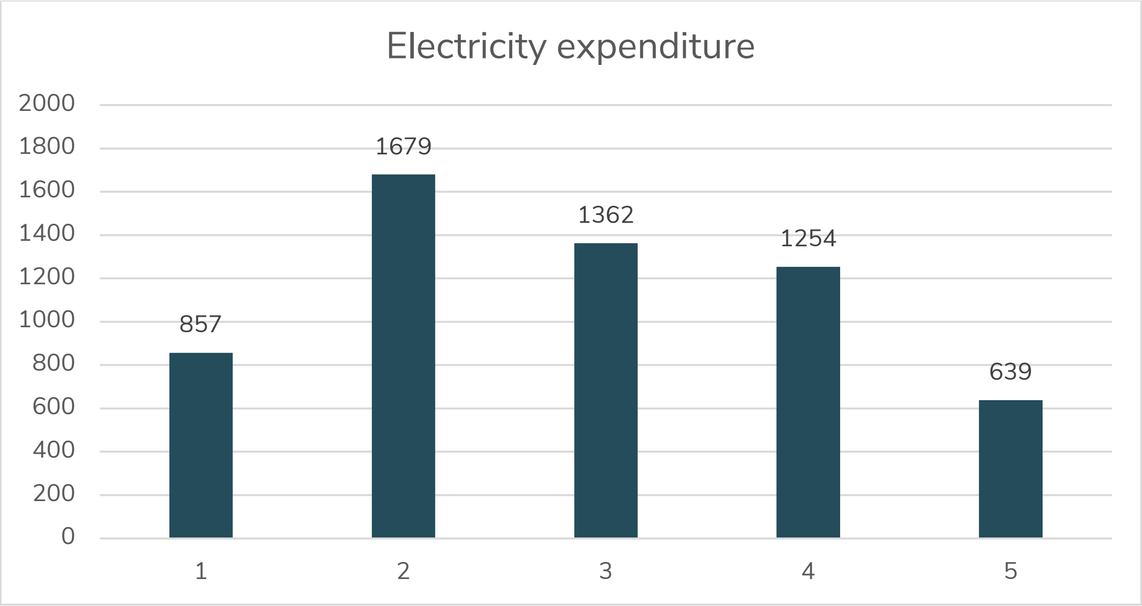


*Figure 6: Annual electricity cost to operate each of the heat pumps. Note that this is an estimate based on Jan. 2024 electricity tariffs for Whitehorse, see here: https://www.atcoelectricyukon.com/en-ca/customer-billing-rates/bill-calculator.html*

Average annual electricity expenditure to operate the heat pumps is $1,158, or around $100 per month.

# 5 Challenges

This pilot project encountered and identified a number of challenges during the first two and a half years:

- Very few installers are active in Yukon. Some participants in phase 2 have expressed concerns about contractor knowledge and experience.
- The common practice in heating seems to be to size larger than design heating load – a practice that might be reasonable for different technologies but hurts heat pump efficiency. Better contractor awareness and training would likely mitigate this.
- 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.
- In retrofits, ducts may be too small to accommodate the required air flow, leading to a drop in efficiency.
- Compatibility with backup heating sources. Initially, the pilot 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.
    - Mini-split heat pumps appear to be a better fit when paired with a centralized fossil-fuel backup heating system, since they do not share any ductwork.

# 6 Next steps

An additional 18 heat pumps of different makes, models and styles have been installed around the Yukon. This includes 13 ductless mini-splits and multi-splits and 2 air to water heat pumps and an additional 3 central forced air heat pumps. These systems are paired with a range of different backup heating sources and include locations within Whitehorse and in surrounding communities.

In addition to four of the current monitored heat pumps, the data gathered from 18 of these units will be analyzed by the Government of Yukon 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 and sizing tools to be provided to local contractor.

# 7 Conclusion

Results from this study demonstrate that with proper installation and attention to configuration details, cold-climate air-source heat pumps have the potential to perform efficiently in the Yukon.

This pilot provides evidence that heat pumps are a viable, energy efficient option in very cold climates, with a seasonal coefficient of performance exceeding 1, indicating higher efficiency than conventional electric heating.

Heat pumps in homes relying on wood heat in addition to the heat pump and backup heating systems were found to spend more time in standby, with very low power draw. This boosted the integrated COP values for the two heat pumps. However, it is important to ensure that wood stoves do not circulate air using the heat pump system fan while the heat pump is running.

Throughout the heating season, heat pumps could be relied upon to work more efficiently than conventional electric heat down to an average of -20°C. Results also indicate that all heat pumps worked to -29°, albeit at COPs lower than 1. (See Figure 13)

Results from the 2022-2023 heating season are consistent with those from the previous season and demonstrate that care around ductwork should be prioritized during installation to achieve the best performance. It is recommended that homeowners seek out a duct design from qualified sheet metal technicians prior to installing a heat pump. Increases in duct size will likely be required to accommodate air flow and ensure heat pump performance. In homes without existing ductwork, or those for which increasing ductwork is not feasible, non-ducted cold-climate air-source heat pumps such as mini-splits may be a better option. Non-ducted and air to water heat pump performance will be studied over the next two heating seasons.

# 8 Sources

CANMET Energy. “Air-Source Heat Pump Sizing and Selection Guide,” n.d.

CSA Group. “CSA EXP07:19. Load-Based and Climate-Specific Testing and Rating Procedures for Heat Pumps and Air Conditioners.” Accessed December 6, 2023. https://www.csagroup.org/store/product/CSA%20EXP07:19/.

Northeast Energy Efficiency Partnerships. “ccASHP Specification & Product List.” Accessed November 21, 2023. https://neep.org/heating-electrification/ccashp-specification-product-list.

Yukon Department of Energy, Mines and Resources. “Air-Source Heat Pump Monitoring Project Technical Report for Winter 2021,” n.d.

Yukon Department of Energy, Mines and Resources, Graham. “Air-Source Heat Pump Monitoring Project Technical Report for 2021/2022,” n.d.

# Appendix A Monitoring equipment and methodology

## Appendix A.1 Introduction

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.

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

## Appendix A.2 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.

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

*Table 9: Monitoring equipment data collected*

## Appendix A.3 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, and
- TSI 9565 with TSI 634634002 pitot tube.

## Appendix A.4 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.

## Appendix A.5 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;
- data sets of all data points; and
- efficiency calculations.

## Appendix A.6 Monitoring equipment calculations

In addition to the raw data points listed in Table 8, a number of pre-set calculated data points (see Table 9) were built-in to the data logger, to be collected at the same minute-long intervals. The statistical software / programming language R was selected for this analysis.

| Ref. | Calculation | Raw data points used | Formula |
|---|---|---|---|
| (ba) | ASHP indoor unit apparent power | ASHP Indoor Voltage A-B (240V) – (a)<br>ASHP Indoor Current A – (b) | $(bbbb) = (bb) * (bb)$ |
| (bb) | ASHP indoor unit active power | ASHP Indoor Power Factor – (c) | $(bbbb) = (bbbb) * (cc)$ |
| (bc) | ASHP outdoor unit active power | ASHP Total Active Power – (d)<br>ASHP Indoor Active Power A (ASHP) – (e) | $(bbcc) = (dd) - (ee)$ |
| (bd) | ASHP outdoor unit apparent power | ASHP Outdoor Unit Active Power – (bc)<br>ASHP Total Reactive Power – (f) ASHP Indoor Reactive Power – (g) | $(bbdd) = (bbcc) + [(ff) - (gg)]$* |
| (be) | Outdoor temperature bin | Outdoor Temp – (h) | *(f)-(g) = outdoor reactive power |
| (bf) | ASHP supply average temperature | ASHP Supply Temp – Right – (i)<br>ASHP Supply Temp – Left – (j) ASHP Supply Temp – Centre – (k) | See Appendix A.2 |
| (bg) | ASHP return average temperature | ASHP Return Temp – Right – (l)<br>ASHP Return Temp – Left – (m) ASHP Return Temp – Centre – (n) | $(bbff) = [(ss) + (jj) + (kk)]/3$ |
| (bh) | ASHP backup heat power | ASHP Indoor Voltage A-B (240V) – (a)<br>ASHP Backup Heat | $(bbgg) = [(ll) + (TT) + (ss)]/3$ |

| Ref. | Calculation | Raw data points used | Formula |
|---|---|---|---|
|  |  | Current – (o) |  |

Table 10: Monitoring equipment calculated data points

## Appendix A.7 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 EXP07-192.[5]

| Temperature bin | Temperature range |
|---|---|
| 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 |

Table 11: Temperature bins

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[5] CSA Group, “CSA EXP07:19. Load-Based and Climate-Specific Testing and Rating Procedures for Heat Pumps and Air Conditioners.”

## Appendix A.8 System Mode

Detecting system modes has 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 complicate the overall COP calculation. 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 discussed in Appendix B.3.1.

### Appendix A.8.1 Active Mode

Figure 8 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 the system the vapour line temperature increases.

In active mode, COP values between 1.5 and 2.5 can be seen in the sample data below.

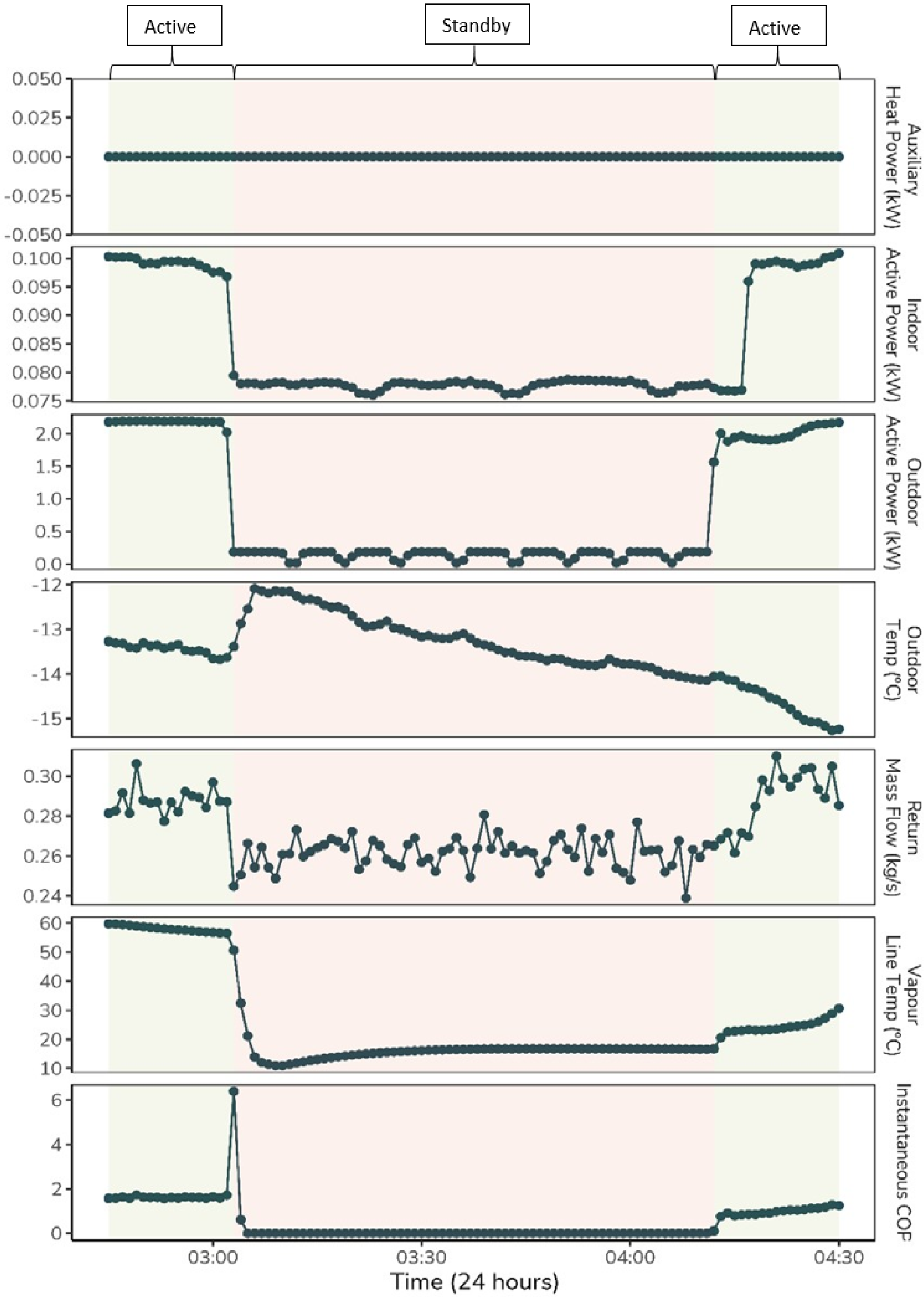

*Figure 8: Sample of data illustrating the change from active mode to standby and back to active.*

## Appendix A.8.2 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. During the transition, COP values can fluctuate. The data can distinguish between standard operation and the heat pump powering down to defrost mode.

In Figure 9 defrost mode is shown with the yellow shaded area, confirming a clear transition point.

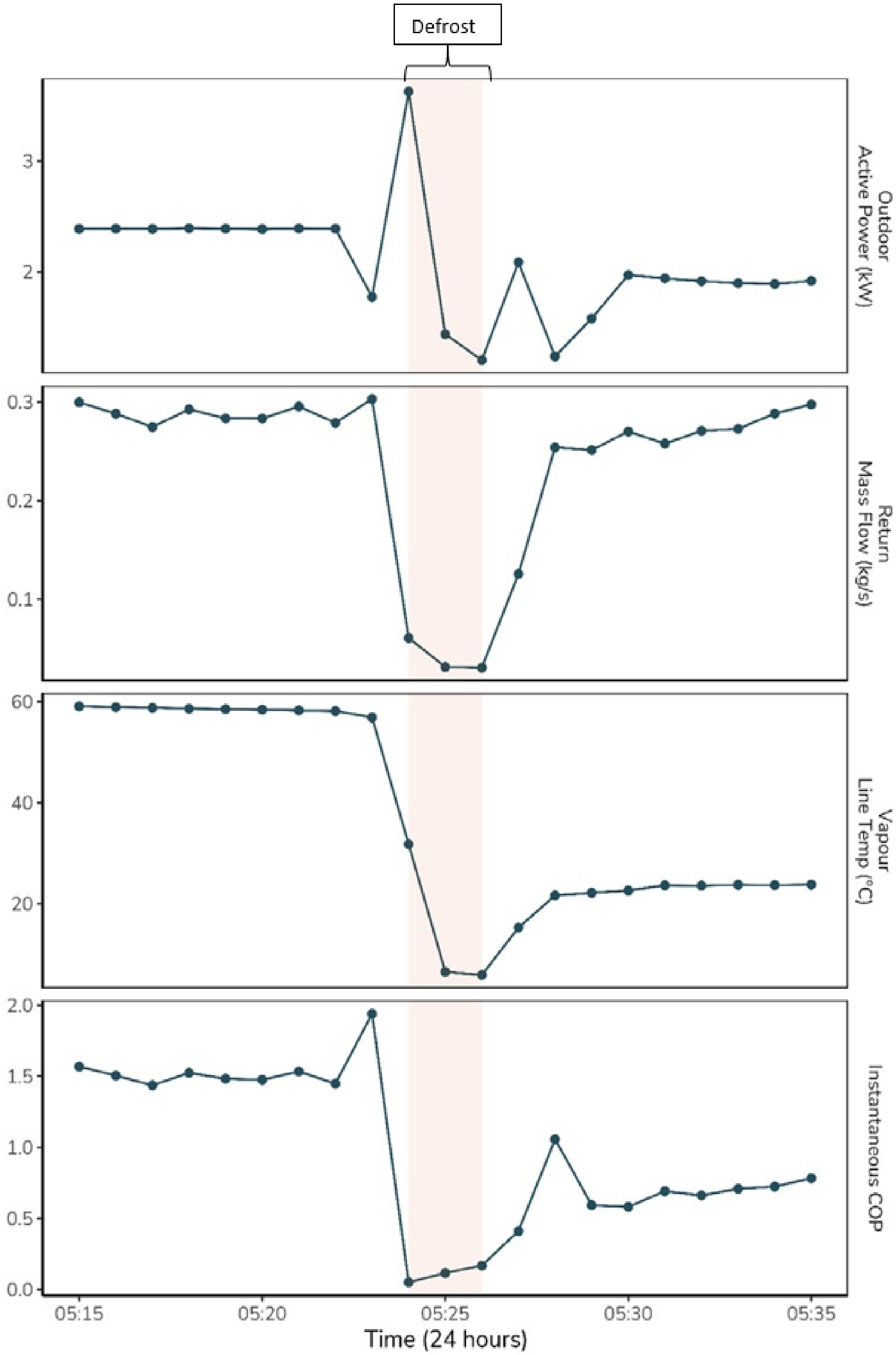
Defrost
3
2
Outdoor Active Power (kW)
0.3
0.2
0.1
Return Mass Flow (kg/s)
60
40
20
Vapour Line Temp (°C)
2.0
1.5
1.0
0.5
0.0
Instantaneous COP
05:15
05:20
05:25
05:30
05:35
Time (24 hours)

*Figure 9: Sample of data illustrating the change of a heat pumps system mode from active to defrost*

## Appendix A.8.3 Backup mode

Backup mode is easily identified when the heat pump’s auxiliary power data point is greater than 0, as shown in Figure 10 as the yellow shaded area.

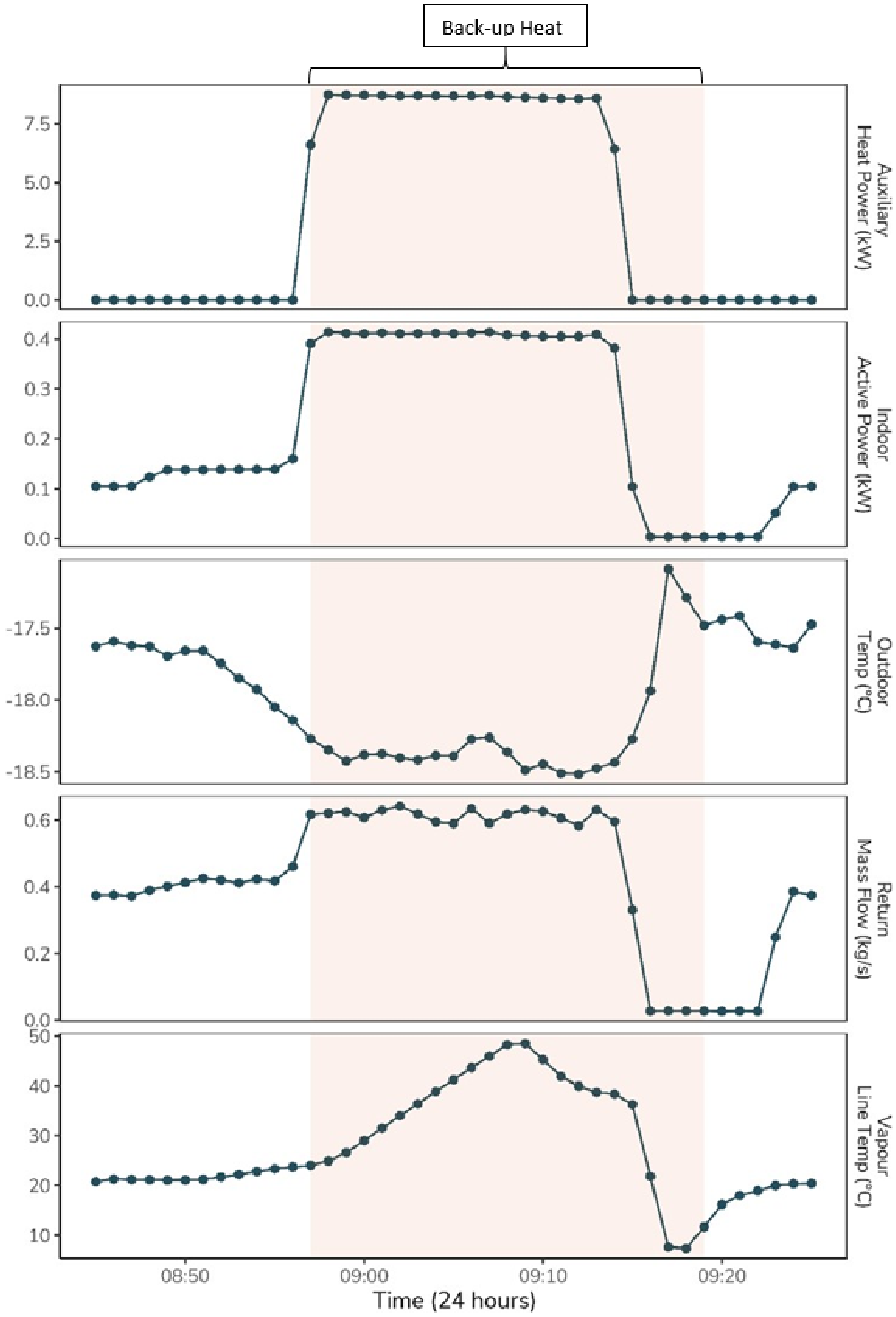

*Figure 10: Sample of data illustrating the use of back-up heat, indicated by the rise in auxiliary heat power above zero degrees Celsius.*

# Appendix B Data analysis

## Appendix B.1 Temperature and humidity profile

A daily average across all five heat pumps is shown in *Figure 11* using minute interval data for outdoor temperature and humidity.

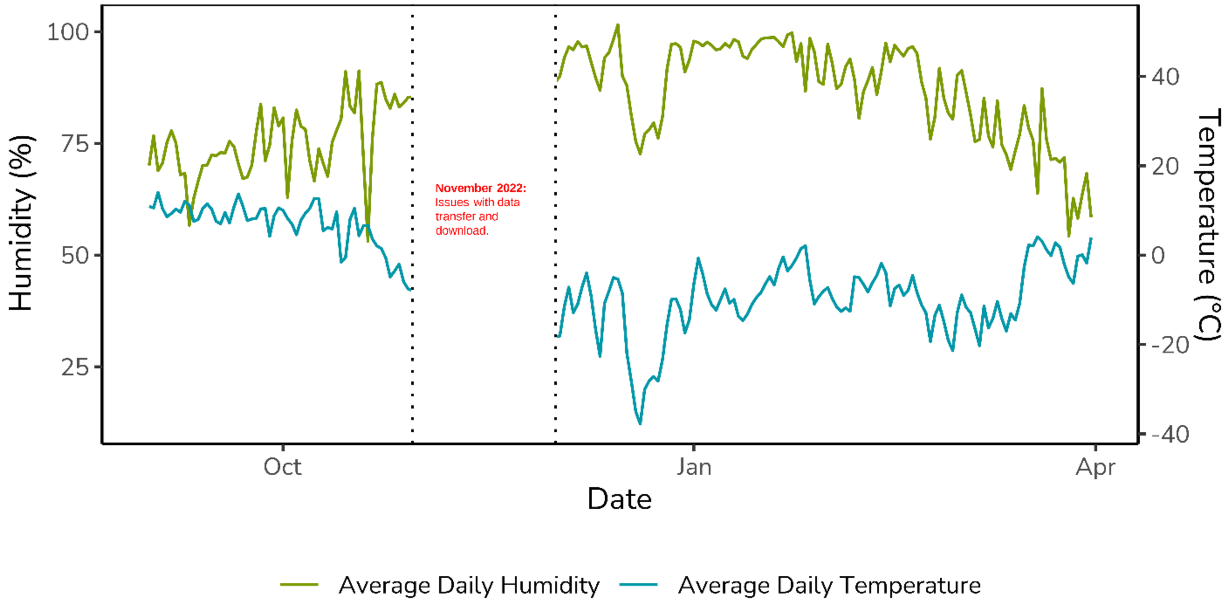

*Figure 11: Averaged daily outdoor temperature and humidity profile across four heat pumps for the last heating season.*

The lowest average temperature recorded was -40.4°C, and the lowest recorded temperature was -42.2°C. The Mitsubishi Zuba air-source heat pumps represented here are designed to switch to the backup heat source around -29°C. Overall, outdoor humidity increased over the winter months, but abrupt drops in humidity corresponded with steep decreases in temperature in December.

## Appendix B.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 kW of heat and draws 2 kW from the power supply, the heat pump has a COP of 5. This can be compared to an electric furnace, boiler or baseboard, all of which 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.

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 12).

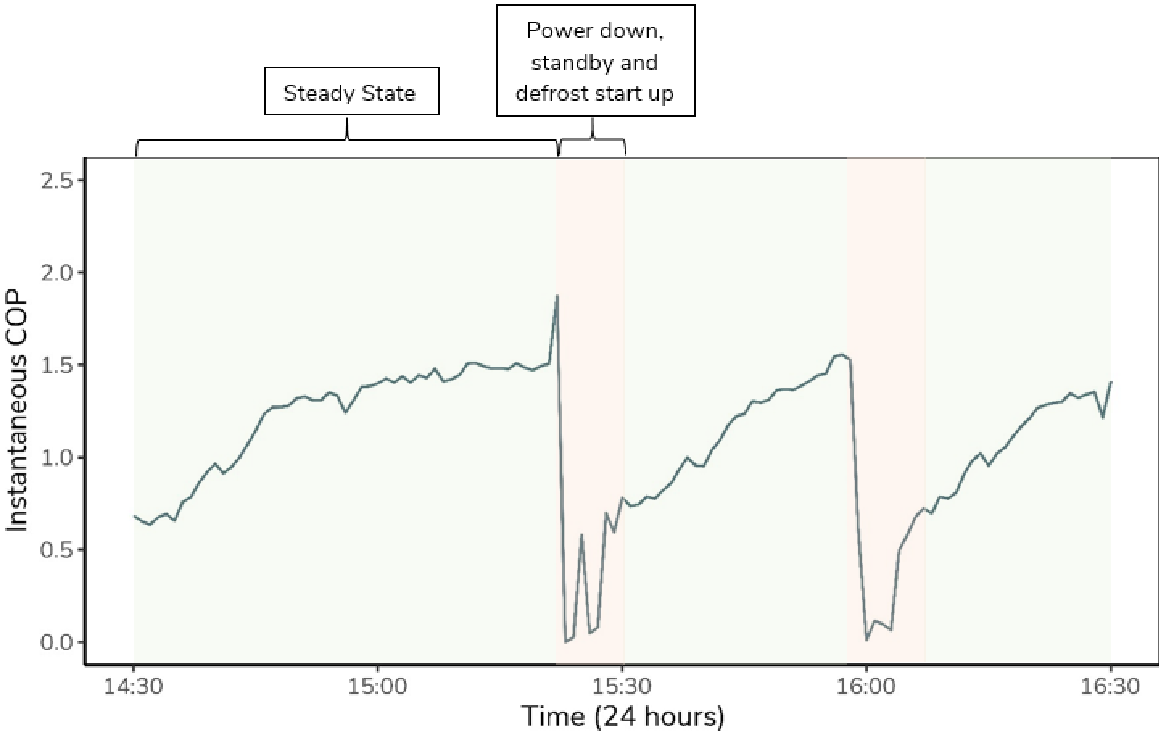

*Figure 12: COP of a heat pump over time at -12°C.*

Integrated COP (ICOP) is a measure of the efficiency of heat pumps that includes all system modes and, similar to COP, can be 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.

| Calculation | | Data points used | Formula |
|---|---|---|---|
| COP | $Q_{HP_{Active-on}}$ | (s) - Building Indoor Air Density<br>(v) - ASHP Return Mass Flow<br>(bf) - ASHP Supply Average Temp<br>(bg) - ASHP Return Average Temp<br>Other data:<br>Air density – 1.006 | FOR EACH TEMPERATURE BIN:<br>$Q_{HP_{Active-on}} = \sum (s) * 1.006 * (v) * [(bf) - (bg)]$ |
| | $P_{HP_{interior_{Active-on}}}$ | (bb) - ASHP Indoor Unit Active Power | FOR EACH TEMPERATURE BIN:<br>$P_{HP_{interior_{Active-on}}} = (bb)$ |
| | $P_{HP_{outdoor_{Active-on}}}$ | (bc) - ASHP Outdoor Unit Active Power | FOR EACH TEMPERATURE BIN:<br>$P_{HP_{outdoor_{Active-on}}} = (bc)$ |
| | COP | $Q_{HP_{Active-on}}$<br>$P_{HP_{interior_{Active-on}}}$<br>$P_{HP_{outdoor_{Active-on}}}$ | FOR EACH TEMPERATURE BIN:<br>$COP = \frac{Q_{HP_{Active-on}}}{P_{HP_{interior_{Active-on}}} + P_{HP_{outdoor_{Active-on}}}}$ |
| | 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 | $Q_{HP_{Total}}$ | $Q_{HP_{Active-on}}$<br>$Q_{HP_{Standby}}$<br>$Q_{HP_{BackUpHeat-On}}$<br>$Q_{HP_{Defrost}}$ | $Q_{HP} = \sum (s) * 1.006 * (v) * [(bf) - (bg)]$<br>FOR EACH TEMPERATURE BIN:<br>$Q_{HP_{Total}} = Q_{HP_{Active-On}} + Q_{HP_{Standby}} + Q_{HP_{BackUpHeat-On}} + Q_{HP_{Defrost}}$ |
| | $Q_{Aux_{Total}}$ | $P_{Aux_{Total}}$ | FOR EACH TEMPERATURE BIN:<br>$Q_{Aux_{Total}} = P_{Aux_{Total}}$<br>(ASSUMES 100% EFFICIENCY) |
| | $P_{HP_{interior_{Total}}}$ | (bb) - ASHP Indoor Unit Active Power<br>$P_{HP_{interior_{Active-on}}}$<br>$P_{HP_{interior_{Standby}}}$<br>$P_{HP_{interior_{BackUpHeat-On}}}$<br>$P_{HP_{interior_{Defrost}}}$ | FOR EACH TEMPERATURE BIN:<br>$P_{HP_{interior_{Total}}} = P_{HP_{interior_{Active-On}}} + P_{HP_{interior_{Standby}}} + P_{HP_{interior_{BackUpHeat-On}}} + P_{HP_{interior_{Defrost}}}$ |

| Calculation | | Data points used | Formula |
|---|---|---|---|
| ICOP | $P_{HP_{outdoor_{Total}}}$ | (bc) - ASHP Outdoor Unit Active Power<br>$P_{HP_{outdoor_{Active-on}}}$<br>$P_{HP_{outdoor_{Standby}}}$<br>$P_{HP_{outdoor_{BackUpHeat-On}}}$<br>$P_{HP_{outdoor_{Defrost}}}$ | FOR EACH TEMPERATURE BIN:<br>$P_{HP_{outdoor_{Total}}} = P_{HP_{outdoor_{Active-On}}} + P_{HP_{outdoor_{Standby}}} + P_{HP_{outdoor_{BackUpHeat-On}}} + P_{HP_{outdoor_{Defrost}}}$ |
| | $P_{Aux_{Total}}$ | (bh) - ASHP Backup Heat Power | FOR EACH TEMPERATURE BIN:<br>$P_{Aux_{Total}} = \sum(bh)$ |
| | ICOP | $Q_{HP_{Total}}$<br>$Q_{Aux_{Total}}$<br>$P_{HP_{interior_{Total}}}$<br>$P_{HP_{outdoor_{Total}}}$<br>$P_{Aux_{Total}}$ | FOR EACH TEMPERATURE BIN:<br>$ICOP = \frac{Q_{HP_{Total}} + Q_{Aux_{Total}}}{P_{HP_{interior_{Total}}} + P_{HP_{outdoor_{Total}}} + P_{Aux_{Total}}}$ |
| | 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. | |

## Appendix B.2.2 Results

The heat pumps' COP was observed to be above 1 at temperatures of -20°C or warmer, except for heat pump #3, which only experienced a COP above 1 at temperatures of -14°C or warmer.

Figure 13 compares the COP data from all five heat pumps units against the manufacturer specified rated capacity. Aligning with the results from the previous year's report, overall heat pump performance was lower than manufacturer specifications, with gaps ranging from 39% for the lowest performing heat pump (#3), to no difference for the best performing heat pump (#5).

The difference between manufacturer specified COP and calculated COP varies based on temperature; at warmer temperatures, gaps tend to close for all heat pumps, whereas during colder days, gaps increase. This trend indicates that cold climate air source heat pump efficiency gradually reduces as temperatures decrease.

It is also worth noting that heat pump #5 demonstrated COP values matching manufacturer specifications between -12°C and -15°C (the coldest temperature tested by the manufacturer) and above 6°C. Additionally, heat pump #1 met or exceeded manufacturer specifications at temperatures above 1°C.

Underlying reasons for heat pumps performing below a COP of 1 at cold temperatures are not yet confirmed. However, it is hypothesized that when temperatures drop, the unit spends a greater amount of time in defrost mode. This may cause the heat pump to expend more energy in order to remain operational.

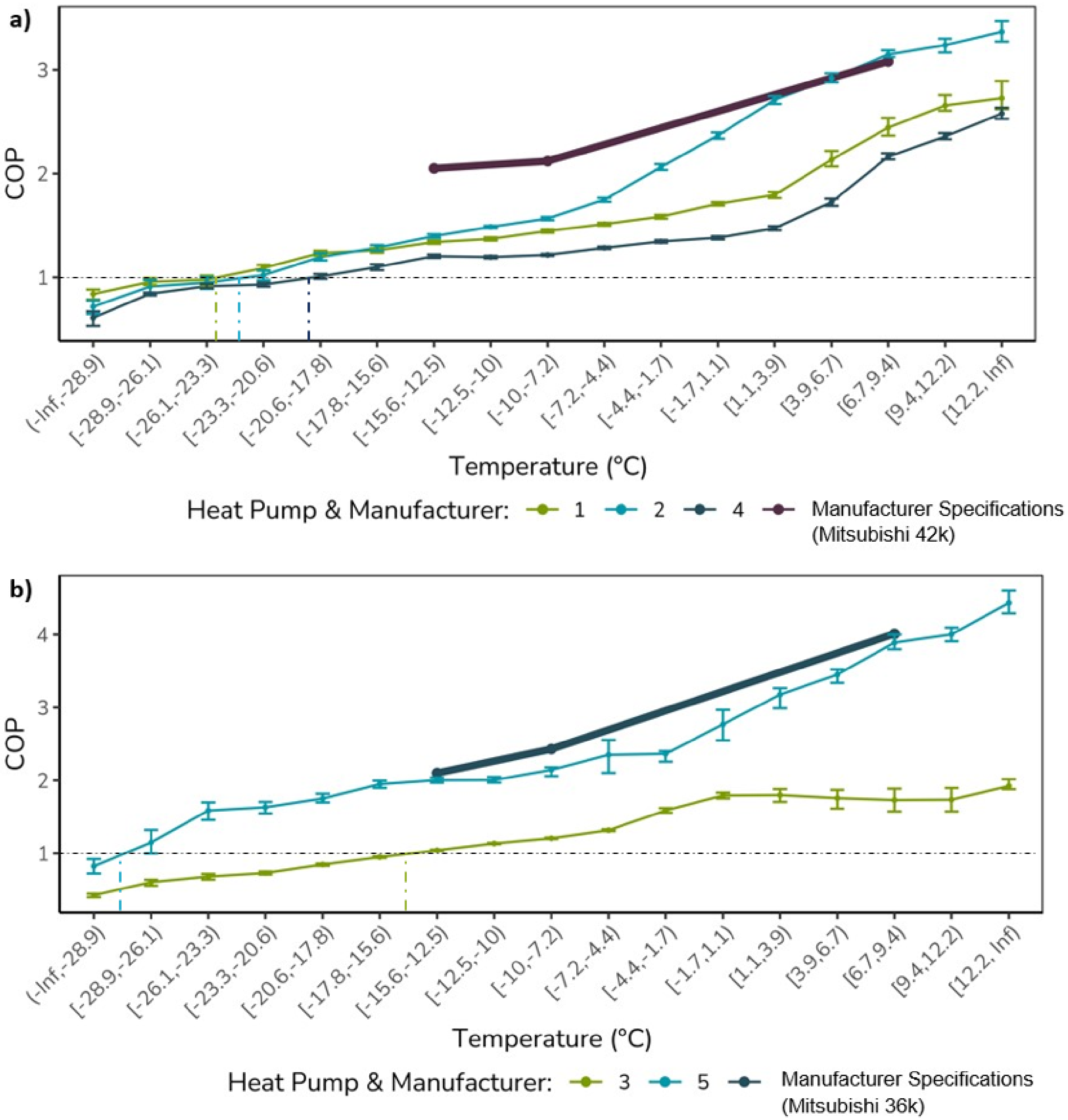

*Figure 13: Comparison to manufacturer specifications a) (42,000BTU/hr) with heat pumps #1, #2 and #4, and b) (36,000BTU/hr) with heat pumps #3 and #5.*

The integrated COP was also calculated to provide information on heat pump performance across all modes. Figure 14 demonstrates ICOP results for the 42,000 BTU/hr units and the 36,000 BTU/hr units separately.

The three larger units (42,000 BTU/hr) exhibit ICOP values above 1 at temperatures warmer than -14°C, but heat pumps #1 and #2 dip below an ICOP of 1 again once temperatures reach 11°C. This may be attributed to units short cycling with more frequency during times of low heat demand. These results indicate that units #1 and #2 perform best and provide net energy benefits within the -14°C to 11°C range.

The two smaller units (36,000 BTU/hr) display diverging results, with heat pump #5's ICOP values rising above 1 at -26°C, while heat pump #3's ICOP values only reach 1 above -11°C. The underlying reason for the observed differences is unknown; however, the interruption in heat pump #3's data collection in December/January may influence these results. Neither of the small units experienced a drop in ICOP values at warmer temperatures, suggesting that slightly under-sizing units is preferable to oversizing.

It is important to note that wood heating was also used throughout the winter with heat pumps #1, #2 and #5. Wood heat was only minimally relied upon for heat pump #2, and only at temperatures below -25°C. The use of wood heating may increase ICOP values; it is not captured in the analysis and any heat provided by the wood stove would appear to be the heat pump's output. COP and SCOP values remain unaffected, as only the heat pump data during active mode is incorporated in the analysis.

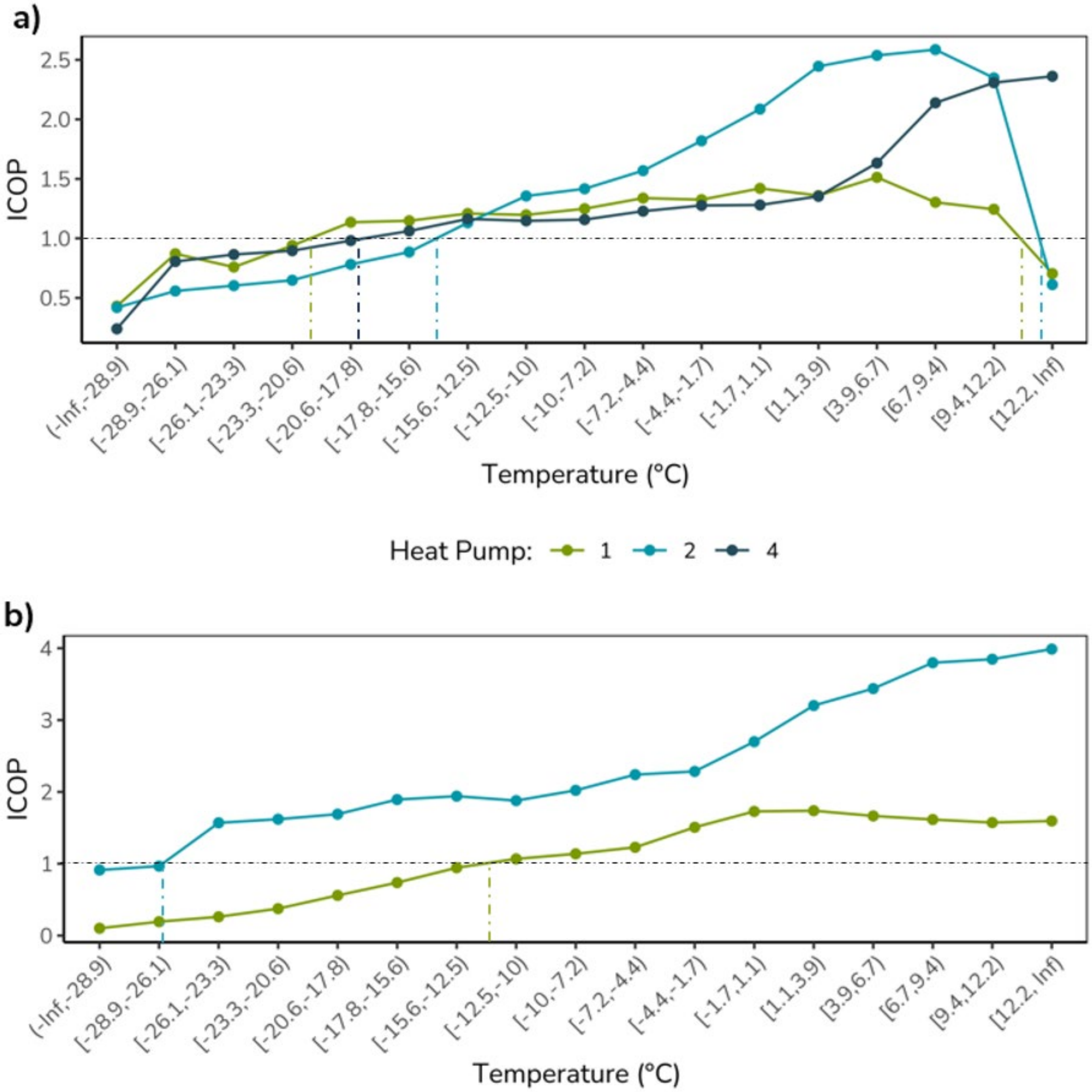

*Figure 14: Comparison of ICOP data from a) 42,000 BTU/hr heat pump units and b) 36,000 BTU/hr systems. Heat pump #4 had a broken coil during operation and data from before (dashed line) and after (solid line) is presented for completeness.*

SCOP values shown in Table 11 provide insight into average heat pump performance through the season. Heat pumps 1, 2, 4 and 5 all demonstrated improvements in their SCOP when compared to the previous winter, potentially attributable to adjustments, troubleshooting and lessons learned from the past.

However, heat pump #3 had a slightly lower SCOP in this season. The reason for heat pump #3's lower SCOP in this heating season is not known; however, data for about one month is missing which may have impacted results.

| # | **20/21**<br>Apr 1 2020 –<br>Mar 31, 2021 | **21/22**<br>April 1, 2021 –<br>March 31, 2022 | **22/23**<br>April 1 2022 –<br>March 31, 2023 | Average |
|---|---|---|---|---|
| 1 | 1.16 | 1.02 | 1.20 | 1.13 |
| 2 | 1.36 | 1.34 | 1.54 | 1.41 |
| 3 | 1.34 | 1.43 | 1.10* | 1.29 |
| 4 | 1.47 | 1.16 | 1.45 | 1.36 |
| 5 | Not yet installed | 2.41 | 2.51 | 2.46 |

*Table 12: Seasonal Coefficient of Performance (SCOP). Note that Heat Pump #3's network connection was accidentally unplugged between December 2022 to January 2023, which may contribute to the low SCOP.*

## Appendix B.3 Heat pump performance

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. Typically, standby mode will draw power without producing heat, therefore reducing efficiency. However, this analysis records all data points with a power draw under 0.2 kW as "standby," meaning that when the heat pump is powered off and other, unmonitored forms of heating are being used, such as wood stoves, the heat pump will still register as standby.

### Appendix B.3.1 Method

System mode calculations found in Appendix A were performed to determine the heat pump's mode at any given moment during the monitoring period. To further calculate the percentage each heat pump spent in each system mode, the following formula was used (see Table 12). Heat capacity and airflow analyses were also performed for the 2021-2022 heating season to evaluate performance, but the analysis was not repeated for the 2022-2023 heating season as system mode provides better insight into performance.

| Mode | Data Points Used | Formula |
|---|---|---|
| Heat | COP<br>Temperature Bin | FOR EACH MINUTE OF DATA:<br>IF $COP$ > 0.1, system mode = Active – On<br>FOR EACH TEMPERATURE BIN:<br>$\% \, Active \ mode = \frac{Data \ points \ in \ Active \ mode}{Total \ data \ points \ for \ all \ modes} * 100$ |
| Secondary Heat | $P_{Aux_{Total}}$ | FOR EACH MINUTE OF DATA:<br>IF $P_{Aux_{Total}}$ > 0, system mode = Backup heat - On<br>FOR EACH TEMPERATURE BIN:<br>$\% \, Backup \ heat \ mode = \frac{Data \ points \ in \ Back \ up \ heat \ mode}{Total \ data \ points \ for \ all \ modes} * 100$ |
| Defrost | (u) - ASHP Return Volumetric Flow<br>(y) - ASHP Vapour Line Temp | FOR EACH MINUTE OF DATA:<br>IF (u) < 0.05 AND (y) <10, AND IF ($P_{outdoor} \geq 0.2$), system mode = Defrost<br>FOR EACH TEMPERATURE BIN:<br>$\% \, Defrost = \frac{Data \ points \ in \ Defrost \ heat \ mode}{Total \ data \ points \ for \ all \ modes} * 100$ |
| Standby | Combination | FOR EACH MINUTE OF DATA:<br>All other data points, system mode = Standby<br>FOR EACH TEMPERATURE BIN:<br>$\% \, Standby \ mode = \frac{Data \ points \ in \ Standby \ mode}{Total \ data \ points \ for \ all \ modes} * 100$ |

Table 13: As formulated in Appendix B.2 for the SCOP calculation, defrost is identifying when the fan speed of the heat pump was below 0.05m3/s and the heat pump vapour line temperature was below 10°C.

## Appendix B.3.2 Results

Figure 15, Figure 16 and Figure 17 show the percentage of total time each heat pump spent in active, standby and backup modes respectively at each temperature range.

In Figure 15, heat pumps #2, #3 and #4 spent 25% to 90% of time in active mode at most temperature bins, specifically between the -26°C to 1°C range. Conversely, heat pump #1 and #5 spent less time in active mode, ranging between just below 25% to 60% for all temperature bins. The difference observed is likely linked to the homeowners of both heat pump #1 and #5 burning 2-3 cords of wood over the winter. This reduced the need for the heat pumps to be in active mode. Despite the varying SCOP values between heat pumps #2, #3 and #4, the percentage of time spent in active mode was relatively similar, indicating that active mode may not be a direct representation of heat pump performance. It is also worth noting that heat pump #4 continued to spend on average 75% of its time in active mode up to -28°C.

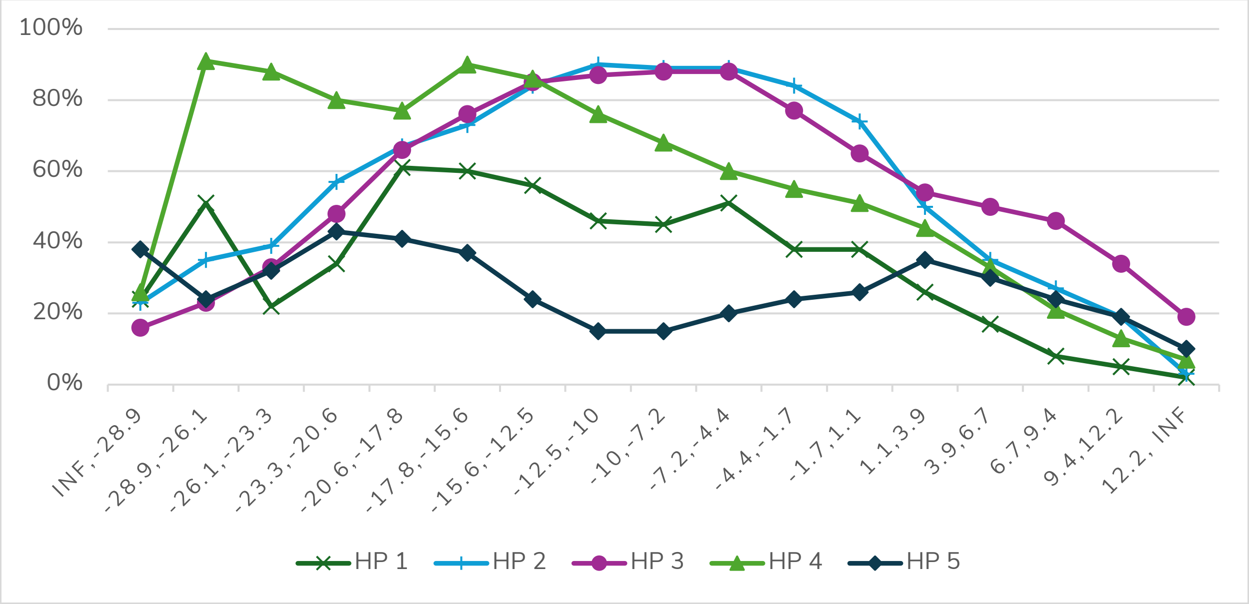

*Figure 15: Percentage of time each heat pump spent in active mode in different temperature bins.*

Figure 16 shows the significant time that heat pump #1 and #5 spend in standby mode at all temperature bins. This includes time spent with the heat pump off while the wood stove is being used. Integrated COP values may be affected by the wood stove, with artificially enhanced performance as wood heat efficiency is not being factored in the analysis (Figure 14). However, COP and SCOP remain unaffected. Both heat pumps also follow a similar disparity in heat load to heat output ratio, and while they both spent similar lengths of time in active and standby mode, heat pump #5 maintains a better SCOP.

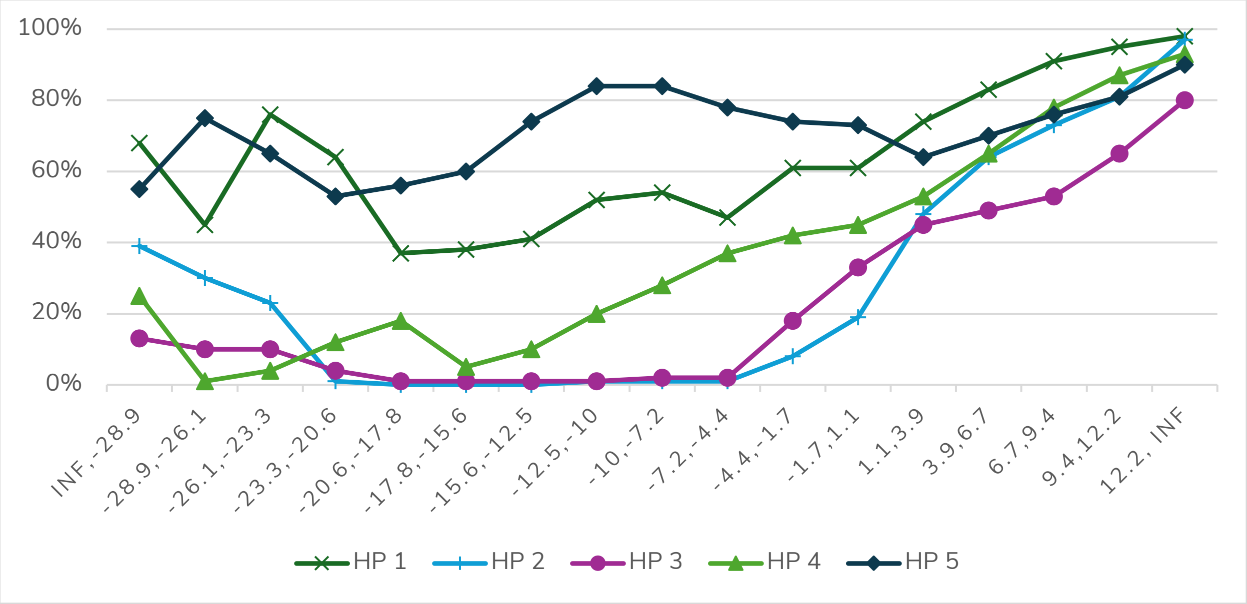

*Figure 16: Percentage of time each heat pump spent in standby mode in different temperature bins.*

Time spent in backup mode is also represented in Figure 17. Backup heating for all five homes is only operational for very small percentages of time once temperatures reach -15°C or higher. At colder temperatures, backup heating for heat pumps #3 and #4 increases gradually, matching the increase in heat requirement and decrease in heat pump COP. The same increase is not observed for heat pumps #1 and 5, although this is likely when wood heating was relied upon the most, therefore being recorded as standby rather than backup. To a lesser degree, heat pump #2 also worked in conjunction with wood heating at temperatures below -25°C, thus exhibiting a smaller increase in backup heating at cold temperatures when compared with heat pumps #3 and #4.

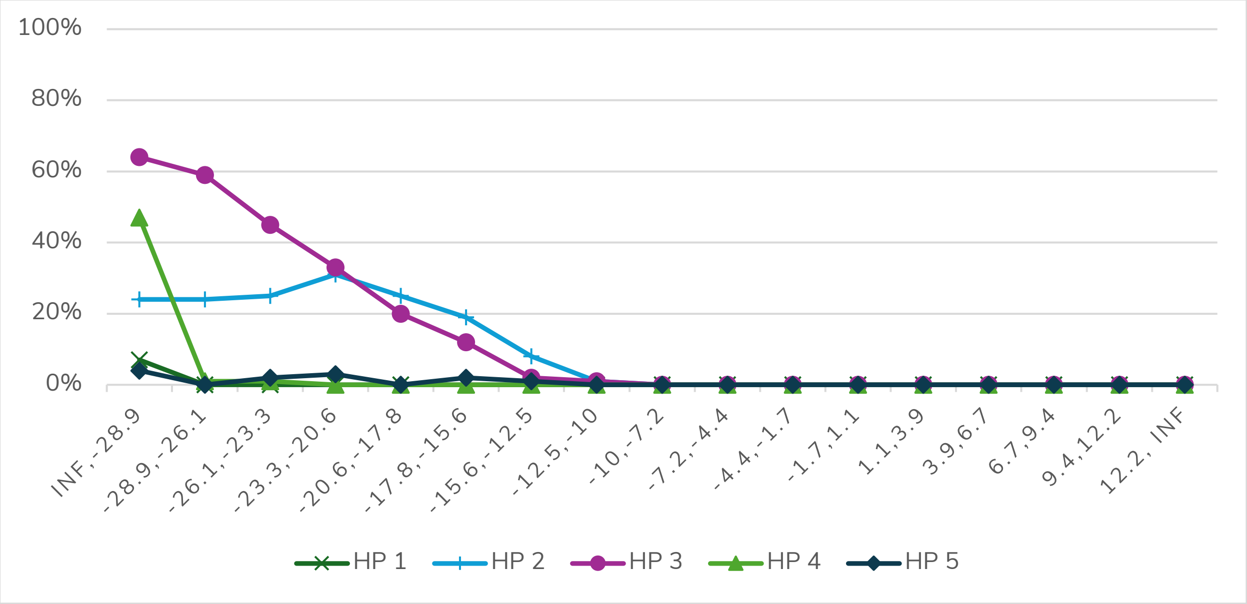

*Figure 17: Percentage of time with the backup heat operational. Lower values indicate that the heat pump is operational*

Table 13 lists the house heat load, selected heat pump size and percentage overall that each heat pump spent in each system mode throughout year.

The largest gap between house heat load and selected unit size is observed for heat pump #5 followed by heat pump #1. This has not impacted performance though as the unit has the highest SCOP (2.51, see Table 11), suggesting other factors in installation may play a larger role than unit sizing.

Heat pump #3 spent the most time in defrost mode, although this result may be due to the month of missing data. During the previous heating season, heat pump #4 spent a significant amount of time in defrost mode, likely due to a broken coil. The 2022-2023 heating season saw a change in time spent in defrost mode for heat pumps #1, #4 and #5, which likely contributes to the higher SCOP values observed in Table 11.

| # | House heat load (NRCan sizing tool) | Selected unit size | Unit size minus heat load | Active mode (%) | Standby mode (%) | Back-up heat | Heat Pump |
|---|---|---|---|---|---|---|---|

| # | House heat load (NRCan sizing tool) | Selected unit size | Unit size minus heat load | Active mode (%) | Standby mode (%) | Back-up heat | Heat Pump |
|---|---|---|---|---|---|---|---|
|  | [BTU/h] | [BTU/h] | [BTU/h] | [%] | [%] | [%] | [%] |
| 1 | 34,087 | 42,000 | 7,913 | 34.5 | 64.1 | 0.2 | 1.2 |
| 2 | 42,617 | 42,000 | -617 | 63.8 | 24.7 | 5.0 | 6.5 |
| 3 | 37,874 | 36,000 | -1,875 | 74.1 | 10.2 | 7.0 | 8.7 |
| 4 | 39,171 | 42,000 | 2,829 | 50.6 | 45.8 | 0.8 | 2.8 |
| 5 | 27,297 | 36,000 | 8,703 | 23.8 | 74.8 | 0.3 | 1.0 |

*Table 14: Heat pump system mode results*

## Appendix B.4 Defrost consumption / ice build-up and damage

In previous years, it was noted by participants that outdoor units produced high levels of defrost water. While fewer complaints were received compared to previous seasons (potentially indicating growing familiarity with the heat pump), water run-off and ice build-up still required additional maintenance. Following the analysis from the 2021-2022 technical report, a review of defrost consumption was repeated to identify where changes may have occurred.

### Appendix B.4.1 Method

Table 14 details the methodology to calculate defrost consumption and percentage of total heat pump consumption. Improvements to the formula were made to prevent the incorrect classification of data points with less than 0.2 kW of power draw.

| Calculation | Data Points Used | Formula |
|---|---|---|
| Total heat pump consumption | $P_{HP_{interior_{Total}}}$<br>$P_{HP_{outdoor_{Total}}}$ | $p_{HP_{Total}} = \frac{(P_{HP_{interior_{total}}} + P_{HP_{outdoor_{total}}})}{60}$(kWh) |
| Total defrost consumption | $P_{HP_{outdoor_{Defrost}}}$ | $P_{HP_{outdoor_{defrost}}} = \sum \frac{P_{HP_{outdoor_{defrost}}}^{*}}{60}$(kWh) |
| Defrost % | $P_{HP_{Total}}$<br>$P_{HP_{outdoor_{Defrost}}}$ | $Defrost\,\% = \frac{P_{HP_{outdoor_{defrost}}}}{P_{HP_{outdoor_{defrost}}}} * 100$ |

*Table 15: 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.*

## Appendix B.4.2 Results

Using the formula in Table 14, results of power consumption and defrost analysis are shown in Figure 18 and in Table 15. Figure 18 indicates energy consumed by heat pumps on a daily basis in kwh, at different temperatures throughout the monitoring season. Heat pumps #1 and #5 consumed the least amount of energy, even at the coldest temperatures. This is likely due to both participants relying on biomass heating in addition to the heat pump, thus reducing the need for electricity. Heat pumps #2, #3 and #4 all consumed on average a similar amount of energy on a daily basis, with no significant difference identified between them.

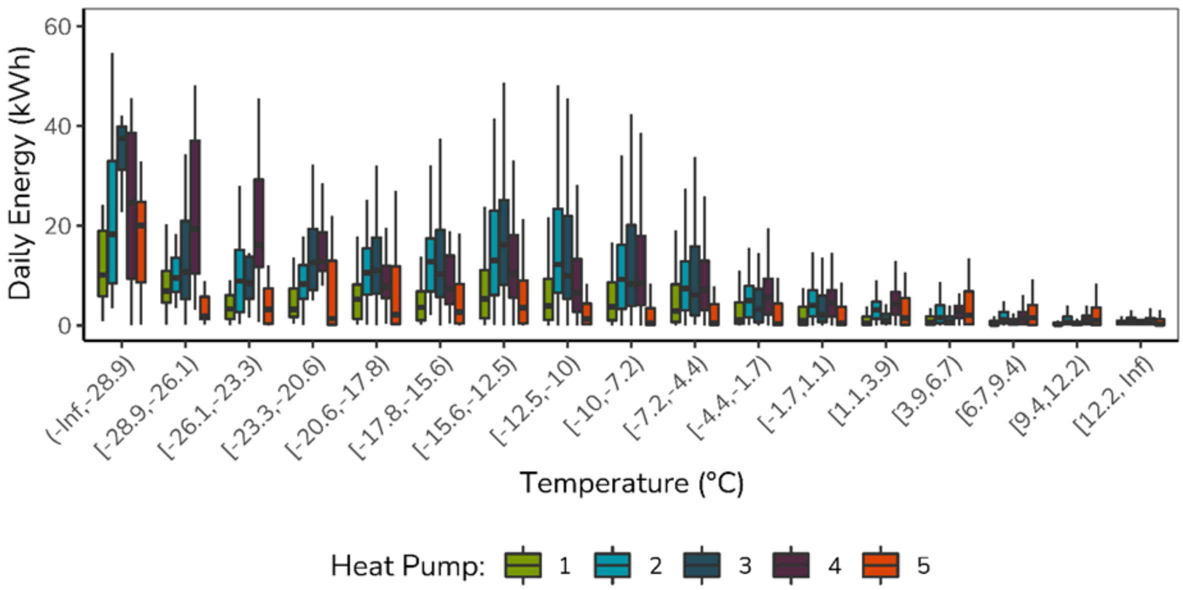

*Figure 18: Daily energy consumption for each heat pump based on temperature*

These results were further broken down to demonstrate the consumption proportion going towards defrost. Three of the five analyzed heat pumps had under 5% of their total consumption going towards defrost, while heat pumps #2 and #3 were just over 5%, but below 10%. These results indicate that while ice buildup was identified along the outdoor units of these heat pumps, defrost mode does not contribute significantly to the power usage of the heat pumps.

Additionally, several participants reported that ice buildup was minimal in comparison to previous years, partly due to mitigation strategies including adding wind baffles, a shed roof, and ensuring proper settings. Results were compared with defrost consumption percentage from previous years, and a slight decrease was identified for heat pump #4, while no significant change is seen for the other four heat pumps.

| # | Heat Pump Consumption | Defrost Consumption | Defrost 2022/2023 | Defrost 2021/2022 |
|---|---|---|---|---|
|  | [kWh] | [kWh] | % | % |
| 1 | 3,915 | 106 | 2.7 | 3.0 |
| 2 | 7,427 | 570 | 7.7 | 7.3 |
| 3 | 6,074 | 363 | 6.0 | 4.6 |
| 4 | 5,610 | 206 | 3.7 | 8.8 |
| 5 | 2,983 | 81 | 2.7 | 2.5 |

*Table 16: Defrost consumption results*

Previously, defrost consumption had been high for heat pump #4 in comparison with other units. However, this current year saw improvements heat pump #4’s defrost consumption, likely resulting from the repair of a broken coil that occurred in January 2022. This broken coil had caused improper drainage and therefore higher ice build-up during the winter 2021-2022.

# Appendix C Unit and duct airflow

## Appendix C.1 Method

A review of commissioning test data was completed with a focus on the following data points in Table 16.

| Data points reviewed | Formula |
|---|---|
| ASHP Return Volumetric Flow – (u)<br>Manufacturer Flow Rate Specifications | FOR EACH 24HR TEST PERIOD IDENTIFY:<br>Maximum volumetric flow rates |

*Table 17: Commissioning test data methodology. 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.*

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 17).

| Data points used | Formula |
|---|---|
| $QHPTotal$<br>$QAuxTotal$<br>Outdoor Temp - (z) | FOR EACH MINUTE OF DATA GRAPH:<br>Scatterplot |
| *Manufacturer Specifications Sheet (42,000BTU/hr unit)* | PLOT ON SCATTERPLOT:<br>At -25°C Rated Heat Cap is 11.25kW<br>At -15°C Rated Heat Cap is 14.07kW At -8°C Rated Heat Cap is 14.07kW<br>At 8°C Rated Heat Cap is 15.82kW |
| Manufacturer Specifications Sheet (36,000BTU/hr unit) | PLOT ON SCATTERPLOT:<br>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<br>At 8°C Rated Heat Cap is 11.72kW |

*Table 18: Heat capacity data methodology. 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.*

## Appendix C.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 18). Each flow rate measurement was verified using multiple pieces of equipment (see Appendix A.3). Airflow was likely reduced in part due to inadequate duct sizing.

Figure 19 to Figure 23 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 appear 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 19 is a sample heating capacity graph with four specific areas are highlighted.

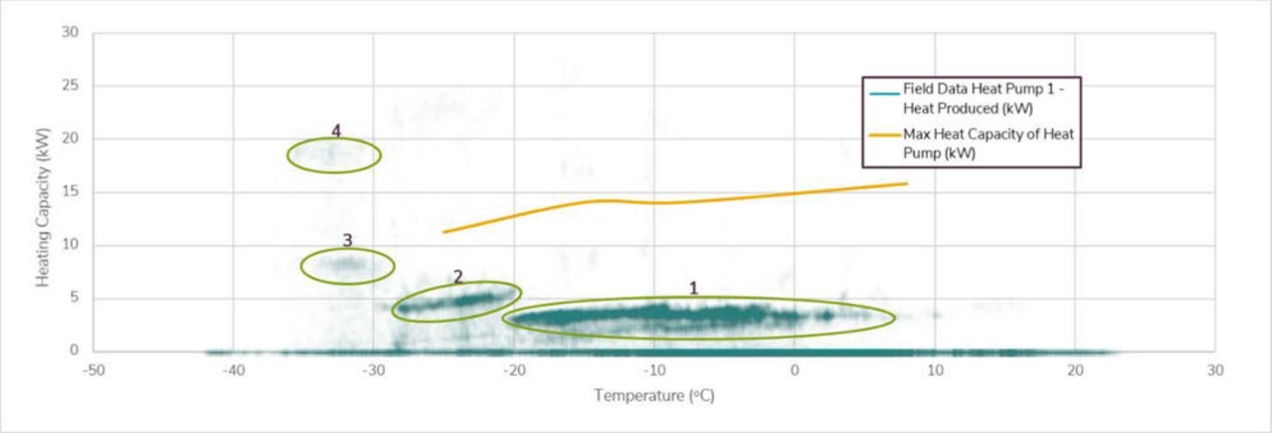

*Figure 19: Sample heating capacity for all data points across all temperature ranges with sections highlighted for explanatory purposes. Maximum capacity of heat pump unit included.*

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.
- A normally 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.

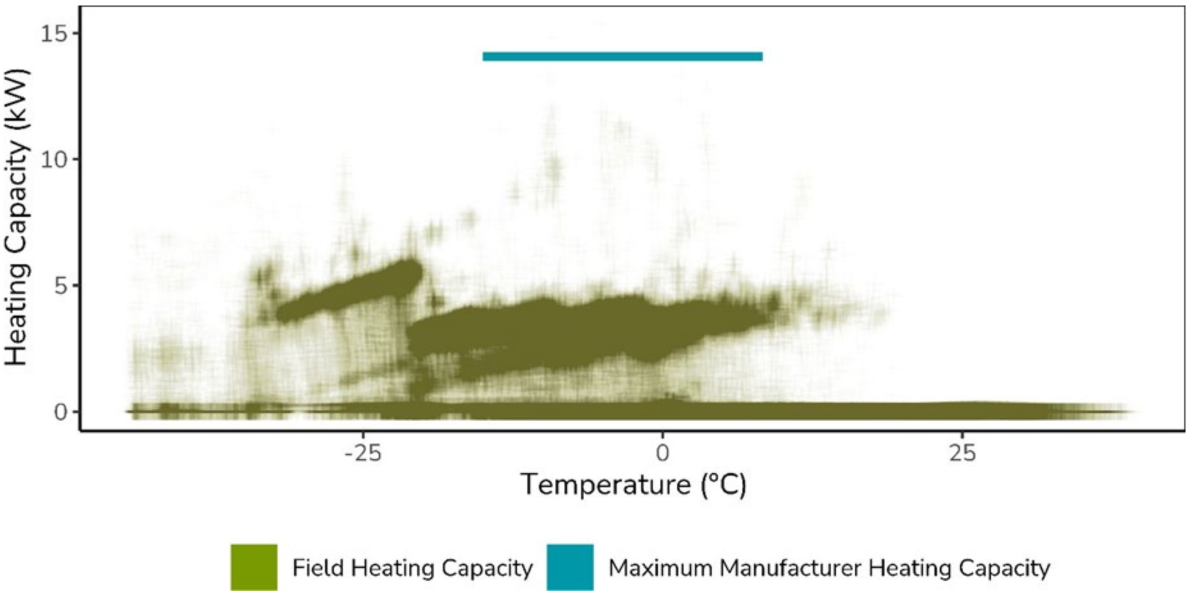

*Figure 20: Heating capacity for all data points across all temperature ranges for heat pump #1. Maximum capacity of heat pump unit included.*

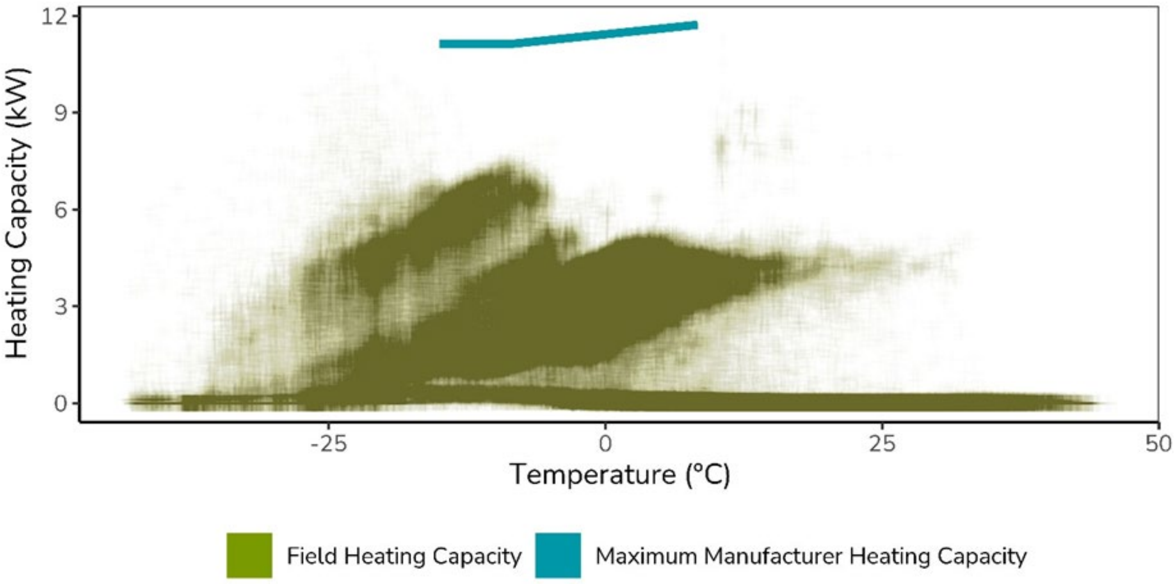

*Figure 21: Heating capacity for all data points across all temperature ranges for heat pump #3. Maximum capacity of heat pump unit included.*

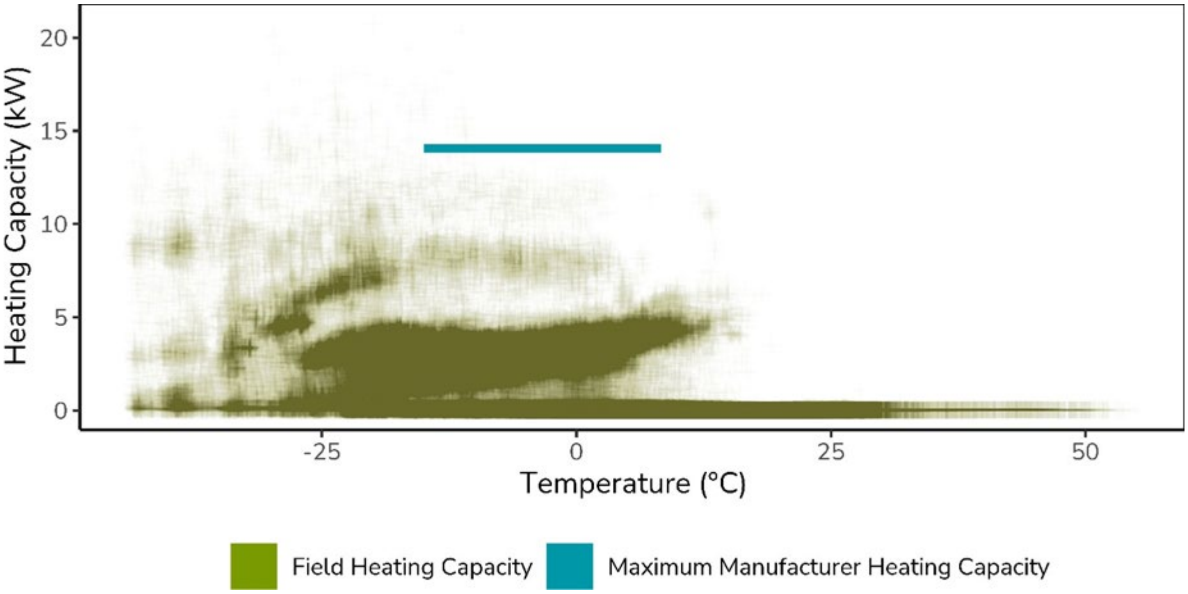

*Figure 22: Heating capacity for all data points across all temperature ranges for heat pump #4. Maximum capacity of heat pump unit included.*

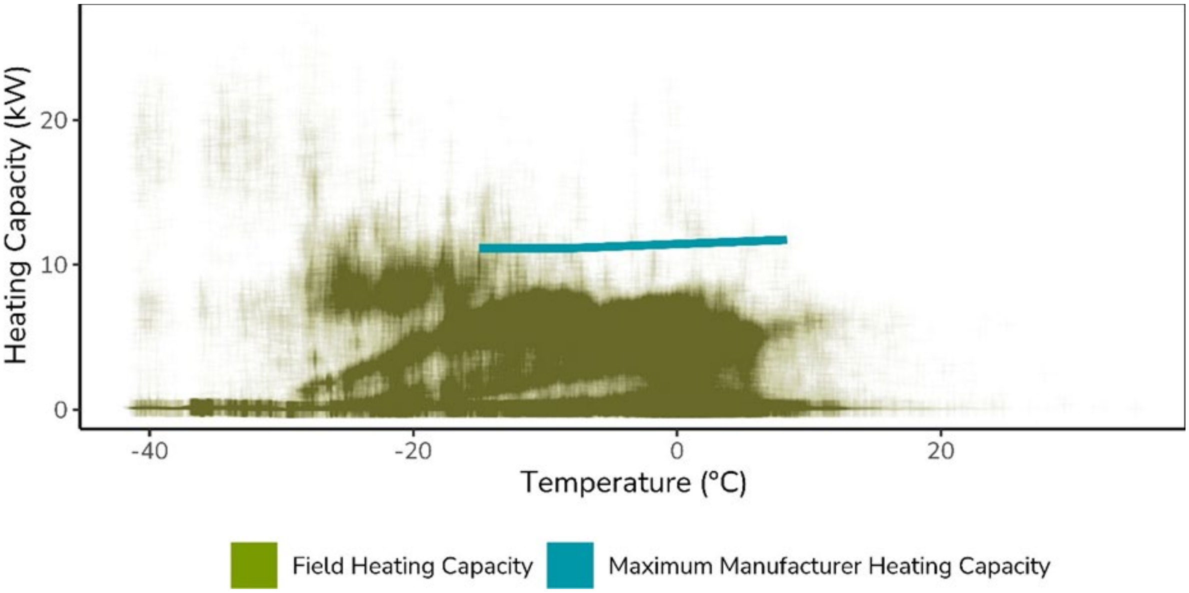

*Figure 23: Heating capacity for all data points across all temperature ranges for heat pump #4. Maximum capacity of heat pump unit included.*

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.

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.

| # | 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) |
|---|---|---|---|---|---|---|---|
| | [in] | [BTU/h] | | | | [cfm] | [cfm] |
| 1 | 11 by 24 | 42,000 | Basement | Vertical | Single, gap underneath | 1450<br>1200<br>1000 | 640 |
| 2 | 10 by 20 | 42,000 | Basement | Vertical | Single, gap underneath | | 878 |
| 3 | 18.25 by 20.25 | 36,000 | Basement (in utility room) | Vertical | Single, gap underneath | | 672 |
| 4 | 17 by 8 | 42,000 | Basement | Vertical | Single, small 2" gap underneath | | 730 |
| 5 | 16 by 8 | 36,000 | Crawl-space | Horizontal | Single, open underneath | | 1098 |

*Table 19: Commissioning test results*

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. It is unknown how much of the success of heat pump #5 is attributed to the horizontal indoor unit since it is a new build, however it likely plays a hand in the improved COP.

# Appendix D System mode calculations

| Variables | Updated algorithm for determining system mode |
|---|---|
| $D_{indoorAir}$ – Building Indoor Air Density | For each minute of data $i$:<br>**Defrost State Calculation**<br>Note that $\Delta x = x_i - x_{i-1}$ |

[kg/m^3]

$F_{returnVolumetric}$ – ASHP Return Volumetric Flow [m^3/s]

$P_{outdoor}$ – Outdoor active power [kW]

$P_{indoor}$ – Indoor active power [kW]

$P_{backup}$ – ASHP Backup Power [kW]

$Q$ – Quantity of heat delivered [kW].

$SH_{air}$– Specific heat of air. Assumed to be 1.006 [kJ/kgC]

$T_{vapourLine}$ – ASHP Vapour Line Temp [C]

$T_{returnAvg}$ – ASHP return average temperature [C]

$T_{supplyAvg}$ – ASHP supply average temperature [C]

$t$ – Time [minute by minute]

**Calculate the slope of the vapour line temperature.**

$$T_{vapourLine_{slope}} = \frac{\Delta T_{vapourLine}}{\Delta t \cdot 60 \cdot 60 \cdot 24}$$

**Note when the slope of the vapour line temperature falls below or above threshold.**

```
IF ( $T_{vapourLine_{slope}} < -1000$){ $T_{vapourLine_{start}} = 1$}
ELSE {$T_{vapourLine_{start}} = 0$}

IF ($T_{vapourLine_{slope}} > 1000$){ $T_{vapourLine_{end}} = 1$}
ELSE {$T_{vapourLine_{end}} = 0$}
```

**Assume the first vapour flag instance is 0.**

Set $T_{vapourLine_{flag_{i=0}}} = 0$

**Check whether previous vapour flag is active, implying a large negative change in vapour line temperature slope. If active, then check if there has been a large positive change in vapour line temperature slope. If so, then set vapour flag to inactive. Otherwise maintain the vapour flag as active. The inverse holds true.**

```
IF ($T_{vapourLine_{flag_{i-1}}}$ == 1) {
    IF ($T_{vapourLine_{end}}$ == 1) {
        $T_{vapourLine_{flag_i}}$ = 0
    }
    ELSE {
        $T_{vapourLine_{flag_i}}$ = 1
    }
}
ELSE IF ($T_{vapourLine_{flag_{i-1}}}$ == 0) {
    IF ($T_{vapourLine_{start}}$ == 1) {
        $T_{vapourLine_{flag_i}}$ = 1
    }
```

```
ELSE {
    $T_{vapourLine_{flag_i}}$ = 0
}
}
```

Apply a rolling window across $T_{vapourLine_{flag}}$ of width 7, if there is at least a single value of 1 set all values in window to 1.

**Calculate slope of the volumetric return flow.**

$$F_{returnVolumetric\ slope} = \frac{\Delta F_{returnVolumetric}}{\Delta t * 60 * 60 * 24}$$

**Note when the slope of the volumetric return flow falls below or above threshold.**

```
IF ( $F_{returnVolumetric_{slope}} < -100$){ $F_{returnVolumetric_{start}} = 1$}
ELSE { $F_{returnVolumetric_{start}} = 0$}

IF ( $F_{returnVolumetric_{slope}} > 100$){ $F_{returnVolumetric_{end}} = 1$}
ELSE { $F_{returnVolumetric_{end}} = 0$}
```

**Check whether previous return flow flag is active, implying a large negative change in volumetric return flow slope. If active, then check if there has been a large positive change in volumetric return flow slope. If so, then set return flow flag to inactive. Otherwise maintain the return flow flag as active. The inverse holds true.**

```
IF ($F_{returnVolumetric_{1flag_{i-1}}}$ == 1) {
    IF ($F_{returnVolumetric_{end}}$ == 1){
        $F_{returnVolumetric_{1flag_i}}$ = 0
    }
    ELSE {
        $F_{returnVolumetric_{1flag_i}}$ = 1
    }
}
```

```
ELSE IF ($F_{returnVolumetric_{1flag_{i-1}}}$ == 0) {
    IF ($F_{returnVolumetric_{start}}$ == 1) {
        $F_{returnVolumetric_{1flag_i}}$ = 1
    }
    ELSE {
        $F_{returnVolumetric_{1flag_i}}$ = 0
    }
}
```

**Flag return volumetric air flow if it falls below 0.2 m^3/s.**

```
IF ($F_{returnVolumetric} < 0.2$){ $F_{returnVolumetric_{2flag}} = 1$}
ELSE {$F_{returnVolumetric_{2flag}} = 0$}
```

**Flag outdoor active power if value is greater than or equal to 0.2 kW.**

```
IF ($P_{outdoor} \geq 0.2$){ $P_{outdoor_{invertedFlag}} = 1$}
ELSE {$P_{outdoor_{invertedFlag}} = 0$}
```

**Check if the vapour line temperature flag, the two volumetric return air flow flags, and the inverted outdoor active power flag are all active simultaneously. If so, then assign the defrost state to be active. Otherwise defrost state is inactive.**

```
IF( $T_{vapourLine_{flag}} + F_{returnVolumetric_{1flag}} + F_{returnVolumetric_{2flag}} + P_{outdoor_{invertedFlag}} = 4$){
$defrostState = 1$}
ELSE{ $defrostState = 0$}
```

**Standby Mode Calculation**

**Calculate heating capacity.**

$$Q = SH_{air} \cdot D_{indoorAir} \cdot F_{returnVolumetric} \cdot (T_{supplyAvg} - T_{returnAvg})$$

**Flag outdoor active power if value falls below 0.2 kW.**

| | |
|---|---|
| | IF ($P_{outdoor} < 0.2$){ $P_{outdoor_{flag}} = 1$}<br>ELSE {$P_{outdoor_{flag}} = 0$}<br><br>**Flag heating capacity if value falls below 0.2.**<br>IF ($Q < 0.2$){ $Q_{flag} = 1$}<br>ELSE {$Q_{flag} = 0$}<br><br>**Check if the outdoor active power flag, OR the heating capacity flag is active. If so, then set the standby mode state to active.**<br>IF( $P_{outdoor_{flag}}$ \| $Q_{flag}$ == 1) { $standbyState = 1$}<br>ELSE{ $standbyState =\ 0$}.<br><br>**Backup Mode Calculation**<br><br>**Check auxiliary power to determine if backup mode is on.**<br>Apply a rolling window across $P_{backup}$ of length 6, if there is at least a single value greater than 0 set $backupState = 1$. Otherwise set $backupState = 0$.<br><br>**System Mode Calculation**<br><br>**Check the various system modes, in order of backup, defrost, standby. Active mode is assumed to be the state when all other modes checked, in their specific order, are inactive.**<br>IF ($backupState = 1$){ $systemMode$ = "Backup"}<br>ELSE IF ($defrostState = 1$){ $systemMode$ = "Defrost"}<br>ELSE IF ($standbyState = 1$){ $systemMode$ = "Standby"}<br>ELSE { $systemMode$ = "Active"} |