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Ductless Cold Climate Heat Pumps for Multifamily Applications

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Executive Summary

Introduction

Air source heat pumps (ASHPs) are expected to be a key technology necessary to support achievement of energy efficiency and decarbonization requirements and goals within federal legislation, local governmental policy, and utility programs. It is anticipated that these programs and initiatives will significantly boost the number of ASHP installations in the coming years. Federal tax credits for energy efficiency and electrification are expected to increase interest in ASHPs installation nationally ("Inflation Reduction Act: For Consumers" 2023). Locally, many Minnesota electric utilities have modified their existing heat pump programs, conducted cold climate ASHP pilots, and incentivized ASHP installations. There has been considerable progress to raise awareness and transform the market to increase heat pump installations.

Cold climate ASHPs (ccASHPs) have a much higher coefficient of performance (COP) than electric resistance heating and can deliver huge percentage reductions in energy use over these traditional electric heating systems. Newer generations of ASHPs, called cold climate ASHPs (ccASHP) can operate below 0°F. Many models can maintain their capacity and efficiency levels below Minnesota's cold heating design temperature, -11°F. In a 2017 CARD study, two ductless ASHP Minnesota field operated at temperatures as cold as -13°F.

Most work on ASHPs and particularly cold climate ASHPs in the Midwest has focused on single-family installations, particularly centrally ducted systems. However, similar potential for ccASHPs exists in electrically heated multifamily buildings. For these installations, the improvements come from the efficiency improvements of ccASHPs compared to traditional electrical heating systems. Detailed information about real applications is key to developing valuable energy efficiency programs based on realistic energy performance and customer acceptance to establish realistic expectations for the technology in Minnesota. Therefore, this project collected performance data, developed system design guidance and produced installation best practice information of appropriately designed and implemented ductless cold climate ASHPs in Minnesota's electrically heated multifamily buildings.

Methodology

Key questions addressed by this research are:

- What is the energy savings potential and appropriate application criteria and design guidance for ductless ccASHPs applied in multifamily buildings in Minnesota?
- Within Minnesota's climate, what impact does sizing guidelines and use of controls have of ccASHPs installed in multifamily buildings to reduce backup heating operation?

Best Practice Development

Best practice protocols are needed because the type of heat pump, configuration of components, system sizing, control methodology, and integration with the backup heating system all significantly impact performance and actual savings realized by the customer, utilities, and statewide programs. The project team used past research, manufacturer resources, and engineer design practices to install ASHPs for the project. Measured field performance of those systems were used to adjust, update, and improve the original guidelines and then final recommendations and best practices were recorded. Best practice areas included:

- Heat pump type and configuration
- System sizing
- Control and integration

Field Installation and Measurement

A total of twenty-seven multifamily buildings were considered for heat pump installations. All twenty-seven building were primally heated with electricity. Single heating sources were common in multifamily buildings, none of the sites considered here had alternative fuel sources for heating. Four buildings were selected for ASHP and instrumentation installation.

Table 5 shows the selection criteria for the final sites selected for heat pump installation and monitoring. These sites span the range of the selection criteria and are representative of MN's electrically heated multifamily buildings.

Table 1. Buildings selected for ASHP installation

Site	Monitorable	Occupant Participation	Location	Layout	ASHP Approach	Existing Heat	Building Size
MF_01	Yes	Yes	Metro	1 Bedroom	1to1 ductless	ER baseboard	2 stories | 6 units
MF_07	Yes	Yes	Metro	1 & 2 Bedroom	1to1 ductless	ER baseboard	2 stories | 13 units
MF_60	Yes	Yes	Suburban	2 Bedroom	PTHP	PTAC & ER baseboard	6 stories | 71 units
MF_61	Yes	Yes	Suburban	1 & 2 Bedroom	1to1 & 2to1 ductless	ER baseboard	3 stories | 6 units

Results and Recommendations

The ductless heat pumps installed and monitored in this research had annual COPs greater than 2.0. These systems reduced the energy use between 51% to 56% for the heating load that they could displace. ASHP displacement was overwhelmingly beneficial for improvements in energy use and operating costs in all cases. Table 7 shows the average ASHP COP measured at each building. However, the fraction of the load met varies based on the building characteristics and heat pump design. Particularly in electrically heated buildings, ASHP runtime and load displacement should be prioritized due to the overwhelming increase in efficiency compared to baseline systems.

Table 2. Summary of annual heating performance of heat pumps installed in each building

Building	Units	Avg heating COP	Fraction on heating load met by ASHP
MF_01	6 – 1to1	2.25	48%
MF_07	4 – 1to1	2.05	86%
MF_61	6 – 1to1 & 2to1	2.12	60%
MF_60	1 – PTHP	1.69	51%

Recommendations for Inclusion in ECO

ASHP installations have gained significant traction in recent years and installations are expected to continue to increase with more decarbonization programs, federal funding, and general awareness of the technology increasing. ASHPs should be a key technology for all efficiency, climate, and utility programs. This research demonstrated that while installations and momentum are increasing, the success of these efforts and savings potential is increasingly tied to good system design and installation.

ECO programs should also consider requirements and specifications to encourage optimized choices. Advancements in heat pump diagnostics will make implementation and enforcement of these types of programs feasible. Connected diagnostics and quality installation reporting mechanisms are being added to some new heat pump systems (Bellanger 2024). These reports can be set up to ensure program requirements are addressed during design and installation. Parameters such as cold weather switchover temperature, airflow, installed capacity delivered, and COP can be included in an installation report to ensure the heat pump will be optimized and deliver expected savings.

Introduction

Air source heat pumps (ASHPs) are expected to be a key technology necessary to support achievement of energy efficiency and decarbonization requirements and goals within federal legislation, local governmental policy, and utility programs. The Minnesota Energy Efficiency Potential Study: 2020–2029 (Nelson et al. 2018) identified cold climate air source heat pumps as the technology expected to provide approximately 25% of total residential electrical savings in the state in the coming decade. Further, it is anticipated that these programs and initiatives will significantly boost the number of ASHP installations in the coming years. Federal tax credits for energy efficiency and electrification are expected to increase interest in ASHPs installation nationally ("Inflation Reduction Act: For Consumers" 2023). Locally, many Minnesota electric utilities have modified their existing heat pump programs, conducted cold climate ASHP pilots, and incentivized ASHP installations. There has been considerable progress to raise awareness and transform the market to increase heat pump installations.

Cold climate ASHPs (ccASHPs) have a much higher coefficient of performance (COP) than electric resistance heating and can deliver huge percentage reductions in energy use over these traditional electric heating systems. CEE has verified manufacturer claims and documented cold climate ASHP performance in Minnesota. These systems saved an average of 55% of the energy used by electric resistance heating systems (Schoenbauer et al. 2017). Other research around the country (Ecotope Inc 2014; Amero et al. 2022) have also demonstrated that cold climate ASHPs can cut heating energy use by more than 50% in electrically heated single-family homes. These systems also have two to three times greater seasonal heating efficiencies than standard heating systems (Schoenbauer, Kessler, and Kushler 2017). Further, the cooling performance of these systems can save significant energy in the summer. Most cold climate ASHP systems have seasonal energy efficiency ratings (SEER) in the 18 to 25 range, while the most common air conditioners installed in Minnesota have SEERs of 13.

Further, newer generations of ASHPs, called cold climate ASHPs (ccASHP) can operate below 0°F. Many models can maintain their capacity and efficiency levels below Minnesota's cold heating design temperature, -11°F. In a 2017 CARD study, two ductless ASHP Minnesota field operated at temperatures as cold as -13°F. Further, these ccASHP can meet the load for most of the heating season.

Figure 1 shows the performance of one such system in Minnesota. The COP is a measure of efficiency showing the ratio of energy delivered by the system to the energy consumed to produce it, over the range of outdoor temperatures experienced in MN. This system delivered very high COPs at moderate temperatures and was still close to 200% efficiency when switching over to its auxiliary heat source at 10°F. These results on early ducted cold climate heat pumps demonstrated the technology's potential.

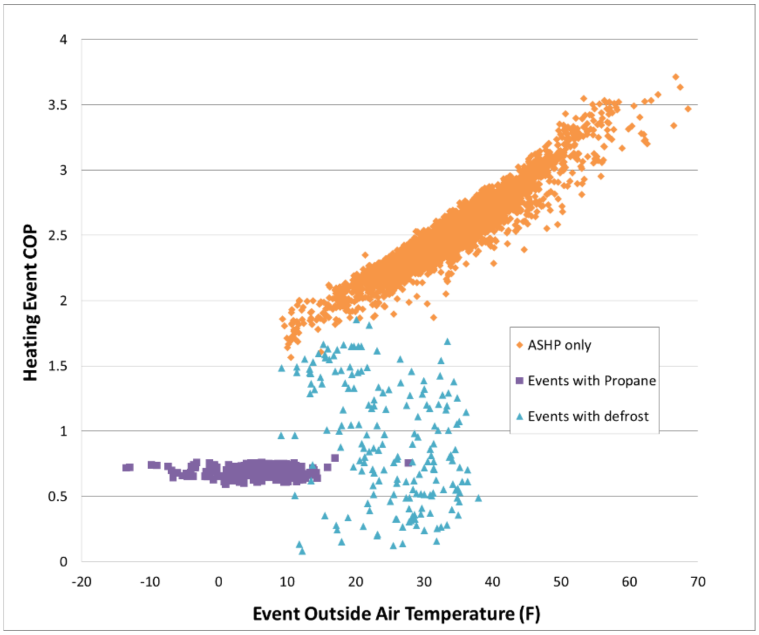

Figure 1. Efficiency of a centrally ducted residential ASHP installed as part of the 2015 CARD study

However, research in other climates has demonstrated that this energy savings potential can only be achieved with appropriate design and implementation (NEEA 2019). Further, application types have expanded, controls options have increased, and the landscape around heat pumps has continued to grow. Although there is verified energy savings potential, ever-expanding ASHP system types, performance, and installation requirements increase the difficulty of documenting installation best practices, characterizing savings, and understanding system operation.

Most work on ASHPs and particularly cold climate ASHPs in the Midwest has focused on single-family installations, particularly centrally ducted systems. However, similar potential for ccASHPs exists in electrically heated multifamily buildings. For these installations, the improvements come from the efficiency improvements of ccASHPs compared to traditional electrical heating systems. Detailed information about real applications is key to developing valuable energy efficiency programs based on realistic energy performance and customer acceptance to establish realistic expectations for the technology in Minnesota. Therefore, this project collected performance data, developed system design guidance and produced installation best practice information of appropriately designed and implemented ductless cold climate ASHPs in Minnesota’s electrically heated multifamily buildings.

While this project focuses on retrofits in electrically heating multifamily buildings, there is also considerable interest in fuel switching for buildings with natural gas heating. Lessons learned about sizing, equipment selection, performance, and customer acceptance in this research can also be applied to buildings undergoing full electrification or a retrofit design targeting a decarbonization through a flex fuel approach.

Opportunity in MN Multifamily

The CARD-funded Minnesota Potential study found 201,000 housing units within multifamily buildings with electric resistance heating (Nelson et al. 2018). Until recently the main option for electrical heat was electrical resistance. This is a low-cost simple heating type with limited opportunity for improvement. ccASHPs offer the opportunity to cut that electrical heating consumption in these homes in half.

Although there is opportunity for ccASHPs in multifamily buildings similar to single family homes, retrofit application of ccASHPs to multifamily buildings is distinctly different from that in single-family homes. These differences must be recognized and effectively addressed for ccASHPs to meet their savings potential in Minnesota. While similar types of equipment are used to heat and cool single-family and multifamily homes, the design, distribution of heating, and the zoning of these systems differ. These differences impact the interaction between a potential heat pump retrofit and the existing systems when they are used for backup. Many single-family homes have central ducts allowing for ducted heat pumps. Most multifamily buildings do not have large, centralized ductwork systems and rely on baseboards, radiators, point-of-use heaters (wall heaters or packaged terminal units), or systems with smaller ductwork (magic paks). These types of existing systems more often fit with ductless heat pump solutions.

Compared to single-family houses, multifamily dwelling units typically have lower loads and more open layouts. These lower loads allow a ccASHP to meet a higher fraction of the heating loads without requiring prohibitively large heat pump capacity. This allows the heat pumps to run for a larger fraction of the heating season, increasing seasonal heating efficiency and cost-effectiveness. These units that meet a high fraction of the load can be retrofitted at a substantially lower cost in multifamily buildings, using lower capacity ccASHPs with fewer heads. Multifamily applications with existing baseboard heaters also will not need a complex new backup system for low-temperature operation. These applications therefore present a very promising opportunity for cost-effective, high-savings retrofits in these previously hard-to-serve units.

This opportunity in multifamily buildings requires continued development and broad deployment of training materials, best practices, ASHP design guidance, and program specifications to ensure these upcoming ASHP installations deliver on their promise of energy efficiency to capitalize on this opportunity, particularly for utilities. These programs must also consider that implications of multifamily building layout and the range of ASHP retrofit options. These factors that need to be considered within a multifamily building include the operational temperatures expected for the ASHP design, the number of heating zones expected to be served by the ASHP, and heating load of the specific unit that the ASHP is installed in. Further to maximize energy savings, its important the Minnesota Technical Reference Manual (TRM) provide savings estimates for optimized cold climate ASHP to encourage program designs that require optimized heating performance. Ongoing improvements have been made to the ASHP TRM measures. However, the ever-increasing options in ccASHP installation applications and controls requires development of accessible and precise methodologies to capture savings and incentivize the best possible ASHP outcomes. Without these types of resources to support changes, such as within the TRM, this potential large-scale deployment of cold climate ASHPs in Minnesota may not deliver their full potential in Minnesota resulting in potential failure for quality installations, and therefore suboptimal performance, from a substantial fraction of the current installations, souring the market and creating additional barriers.

While this project focuses on retrofits in electrically heating multifamily buildings, there is also considerable interest in fuel switching for buildings with natural gas heating. Lessons learned about sizing, equipment selection, performance, and customer acceptance in this research can also be applied to buildings undergoing full electrification or a retrofit design targeting a decarbonization through a flex fuel approach.

Most work on ASHPs and particularly cold climate ASHPs in the Midwest has focused on single-family installations, particularly centrally ducted systems. Retrofit applications of cold climate ASHPs to Multifamily buildings are distinctly different from single-family homes. The differences must be recognized and effectively addressed for cold climate ASHPs to meet their large savings potential in this market.

COVID-19 Project Impacts

This project was funded prior to the COVID-19 pandemic. Field research projects in general, and this project specifically, have timelines to allow for data collection both prior to and after installation of a measure, such as an ASHP within this study. This project experienced significant delays due to the COVID pandemic, which limited field staff access to test sites and caused a huge disruption to ASHP supply chains.

When this project was conceived, ASHPs were an emerging technology only considered by early adopters and those pushing the market for energy efficient and environmental solutions. By the time this project completed, heat pumps became a key technology for nationwide decarbonization efforts, national goals for climate change, and the receipt of groundbreaking tax credits and rebates in upcoming years.

This level of change required some change to the research plan. Although the results were originally envisioned to increase installations, they now will support efforts to ensure the large number of installations coming are completed to the best possible performance, occupant satisfaction, and benefit.

Market Assessment

Interviews were conducted at the beginning of this project to evaluate the current market for air source heat pumps (ASHPs) in the state of Minnesota, particularly gathering information regarding cold climate air source heat pumps and applications for multifamily buildings. Various contractors and utility groups were asked about their involvement in current HVAC technology programs and their experience with ASHPs. Contractors were asked if they install this type of technology, what they know about it, how they learned about it, and if they would generally recommend it to their clients. Utility companies were asked about their rebate programs, the types of heating homeowners in their territories use, and if they are aware of ASHP technology.

Stakeholder interviews revealed a growing awareness and interest in ASHP technologies. The market for ASHPs in general exists and seems to function predominantly on the utility rebate incentive programs; however, cold climate ASHPs are still not as widely accepted due to the lack of knowledge around them, lack of rebate opportunities, and skepticism about the technology itself.

HVAC Contractor Interview Summaries

Some contractors who were interviewed discussed utility rebates they participated in, from which most of their ASHP installations resulted. These rebates usually marketed ASHPs for air conditioning applications as opposed to heating applications, and many contractors interviewed have high confidence in the technology with this application in mind. Though ASHP technology used for air conditioning is more prevalent in the market, modern ASHPs, specifically cold climate ASHPs, can heat homes efficiently in low outdoor ambient temperatures. However, contractors generally felt that the cost is hard to justify, particularity for large-scale multifamily building retrofits. One-off or smaller unit-by-unit approaches were more attractive, but not typical for contractors interviewed. The majority did not recommend ASHPs to their customers, though the contractor's equipment installation was driven by each customer's fuel mix and the incentives offered by their utilities.

Customers were occasionally aware of ASHPs and requested them, but this this was less common according to the contractor interviews. The two major barriers for customers as reported by contractors were the customers' lack of knowledge about the technology and their skepticism due to poor performance ratings in the past. Contractors also reported they install ASHPs specifically for cooling and that the systems are sized predominantly to shut off at around 20°F in the shoulder seasons. Very few (generally less than 10% and often closer to 1%) of these contractors' ASHP installations were designed to meet most of the heating load, though a few were optimistic about the potential of newer models.

The market exists for multiple manufacturers, but some heat pump brands are used more frequently than others in Minnesota because the contractors are authorized dealers or retrofit applications from certain manufacturers are more practical. Contractor preference often involved ease of design and installation. For example, one contractor preferred Carrier because of the ease of installation and the thermostat. Many other manufacturers were mentioned in the interview process including Mitsubishi, Fujitsu, Daikin, and Goodman. Suppliers generally seem responsive to both utility rebates and contractor requests in their stocking practices.

Most contractors surveyed receive training from their local distributor, but not all take advantage of the classes offered. Training content focuses primarily on general maintenance, although one contractor received training to better market ASHPs and stated that trainings are beginning to cover different considerations for cold climate ASHP models. Training is also offered by manufacturers, especially for their authorized dealers. Most contractors receive training once a year, though some complete more than one and some fewer. One contractor spoke about belonging to a few independent knowledge-sharing groups that are focused on emerging technologies, including cold climate ASHPs, with some training opportunities.

Contractors estimated the typical incremental cost of ASHPs range from $1,000 to $3,500. The best utility rebates significantly reduce these costs. The difference in costs is almost entirely due to the equipment itself and material costs like line set length, controls, and risers. An extra hour or two of labor affects costs marginally. Long payback, as opposed to immediate, was a common complaint. For example, high-end systems were considered not cost-effective because they would not pay for themselves over the lifetime of the equipment. One contractor stated that this compels him to stick with middle-range ASHP models rather than the highest efficiency ratings.

Few survey respondents install electric heating systems other than ASHPs. One performs some electric boiler installs, but these are largely for comfort in garages and bathroom floors, as most of the homes he works on are too large to be heated with a boiler. Contractors do not typically have experience with electric resistance systems. These heaters have very few parts and simplistic designs, meaning they rarely malfunction or require replacement. Contractors typically only interact with them in new construction or when they are being removed.

All respondents took advantage of utility rebate programs for ASHPs and many suggested that ASHP projects are impractical without utility incentives. Dakota Electric's rebate program was the most highly regarded by respondents serving the utility's customers. Connexus, Wright-Hennepin, and Minnesota Valley's rebate programs were also highly regarded. All contractors with Xcel Energy customers were disappointed with the utility's low rebates. The one contractor with primarily Xcel Energy and CenterPoint customers says he would market ASHPs without utility incentives but considers them a nice perk.

Utility Interviews

Representatives from six utility companies in Minnesota were interviewed for this project. Over the course of the work, utility programs and markets for heat pumps changed significantly. Original interviews were conducted when fuel-switching was not allowed within utility energy conservation programs. Currently, legislation has been passed to allow fuel-switching measures and rebates and most electrical utility programs are evolving to capture efficiency improvements and system benefits from ASHP installs in homes with natural gas, propane, and electricity. Utility interviews did reveal that ASHP installations in electrically heated homes were seen favorably, but they were generally not a priority for utility programs due to the fraction of homes that are electrically heated and the lack of a clear pathway to recruit these homes. Utilities were very aware of the challenges of ASHPs, but also the potential to deliver savings and occupant satisfaction. Many utilities interviewed for this project are heavily involved in the Minnesota Air Source Heat Pump Collaborative, created to tackle barriers to proper ASHP installations in MN.

Utility representatives interviewed indicated similar barriers as the contractors interviewed within the ASHP market for multifamily buildings, though that multifamily buildings as a market contained unique challenges of its own. Unsurprisingly, the high capital cost to install these units is one of the largest barriers to implementation in multifamily buildings, but the challenge is particularly complex because of split-incentives that exist in this sector. Additionally, logistical issues arise in the multifamily market with homeowner associations and multi-owned buildings, as well as technical issues in placing the outdoor condensing units.

Split-incentives describe a transaction's implementation having unevenly distributed benefits between parties involved, and they arise often in the multifamily building sector especially in buildings where the tenant pays their own electric and utility bills. Many building owners are unable to justify large capital costs and payback periods for ASHPs because the benefits of their installation are generally in the form of energy efficiency and comfort, which are claimed by the tenant. Though ASHP technology provides the building owner with other benefits such as having modern, high-efficiency technology in their buildings to advertise to potential tenants, as well as a smaller carbon footprint, these benefits are hard to justify because they are not economic benefits. This barrier is less prevalent in buildings where electric and utility bills are evenly distributed and paid for among tenants in their rent. A potential way to overcome the split incentive barrier is to provide more rebate and incentives through utilities to offset high capital costs.

Large multifamily buildings (buildings containing ten or more units) often have either a homeowner's association or ownership among a group of individuals. Over the course of this project, we found that this arrangement creates a logistical barrier in the adoption of ASHPs in multifamily buildings. The installation of the ASHPs must have majority or unanimous agreement among individual decision makers who claim ownership of the building. Multiple individuals are required to approve the installation, which can extend the time to install or prevent implementing the technology at all. Many building owners often disagreed with implementation for aesthetic reasons such as how the line sets look on the exterior, while others could not justify the cost for reasons previously stated. In addition to disagreements, we also found that there was a high turnover rate in property managers that adds a layer of difficulty in the decision-making process.

Lastly, issues can arise when implementing ASHPs in larger multifamily buildings, especially in ductless mini-split applications. In large buildings, placement of the outdoor condensing unit presents barriers for technical reasons as well as aesthetic reasons. Often, building owners do not wish to have outdoor units mounted on the exterior walls and would rather they be installed on the roof or ground — however, this is not always achievable due to specifications with the line sets. The line sets that connect the outdoor condensing unit to the indoor head must maintain a certain length determined by the manufacturer and could result in loss of energy efficiency should the line set be installed at inappropriate lengths.

Field Test Methodology

Research Questions

Key questions addressed by this research are:

- What is the energy savings potential and appropriate application criteria and design guidance for ductless ccASHPs applied in multifamily buildings in Minnesota?
- Within Minnesota's climate, what impact does sizing guidelines and use of controls have of ccASHPs installed in multifamily buildings to reduce backup heating operation?

Because the performance of ccASHP in multifamily buildings depends on outdoor air temperatures, performance data was collected over a full season under real-world operating conditions.

This research provides insight into:

- Actual heating and cooling savings in multifamily buildings in Minnesota
- Important factors for quality installation of cold climate ASHPs in multifamily buildings
- Occupant acceptance in heating and cooling seasons

Installation Best Practices Development

Best practice protocols are needed because the type of heat pump, configuration of components, system sizing, control methodology, and integration with the backup heating system all significantly impact performance and actual savings realized by the customer, utilities, and statewide programs.

Heat pump type and configuration: CEE's previous CARD project examined single-head ductless solutions for electrically heated single-family homes. A typical two-ton ductless cold climate ASHP system is sized for 1,000 square feet of conditioned space and can only condition areas that the head's airflow can reach. Since single-head ductless systems are limited in the fraction of the heating load they can meet, this project considered these and two additional types of cold climate ASHP systems: multi-head ductless systems and short duct mini-splits. These additional types allowed the cold climate ASHPs installed within this field study to be sized more appropriately and meet a larger fraction of the home's heating load than relying on single-head systems alone.

System sizing: Cold climate ASHP capacity decreases under extreme cold conditions as it becomes more difficult to extract heat from very cold outdoor air. Typical cold climate ASHPs will not meet the heating load under these extreme conditions. The project used system performance curves to develop sizing guidance that balanced first costs and energy savings to optimize paybacks for Minnesota-specific homes and climates.

Control and integration: As shown by recent field work in Minnesota and the U.S. Northeast and Northwest, installation contractors do not sufficiently understand the critical interaction between the cold climate ASHP and the backup system. This results in suboptimal system performance and sharply reduced savings. Stakeholder engagement in Minnesota has shown growth in contractor knowledge and training. Many contractors are taking advantage of manufacturer providing trainings, utility program support, and other resources such as the Minnesota ASHP collaborative. Contractor feedback has shown an increased awareness of energy and efficiency related install and design concerns.

The two primary control methods currently seen in the field are — (1) operation of the backup system when low (but acceptable) supply air temperature is detected and (2) use of different thermostat setpoints for the heat pump and the backup (effectively preventing the heat pump from operating because the backup is already on) — have both been shown to use excessive backup heat. There are promising alternatives for control, including (a) lock-out of the backup heat at higher outdoor air temperatures and (b) delivered capacity control that uses knowledge of the cold climate ASHP performance curve, supply air temperature measurements, and system runtime to determine when the cold climate ASHP is not keeping up with the load, and only then boosts system performance with backup heat. Documented test cases and simple protocols are needed to gain contractor acceptance and program support. This project included sites with each of the most common configurations of existing electric heating systems to provide details on how to integrate the cold climate ASHP with existing components that will be retained as supplemental or backup heat. Guidance was developed on the proper integration of controls: how and when to use electric resistance (or other) backup at the lowest outside temperatures while maximizing the energy and cost savings benefits of the cold climate ASHP over as wide a range of outdoor temperatures as possible. Guidance includes procedures for testing and verification of control operation to eliminate unnecessary backup heating energy use while ensuring occupant comfort and minimizing callbacks.

Realistic savings calculations for the TRM: Traditional heating savings calculations, such as those currently used in the Minnesota TRM, assume that a heating system will deliver the full annual heating load at its rated capacity and rated heating efficiency. Both capacity and efficiency of cold climate ASHPs vary with outdoor air temperature, therefore annual energy use cannot be accurately estimated using these simple standard techniques. In addition, as noted previously, the cold climate ASHP does not carry the load under the lowest temperature conditions. This project addresses these issues and provides a methodology to accurately estimate electricity savings, carbon reductions, and cost-effectiveness of cold climate ASHPs in Minnesota.

Site Recruitment and Selection Criteria

Three main considerations were made for site recruitment. The site needed to be interested in working with the research team to allow for data collection. The total number of sites was not large enough to be statistically significant, but the units and buildings were selected to represent common Minnesota installations. This allowed the data collected to be useful for understanding how heat pumps will operate in similar situations. Finally, the living units had to be good fits for the intended heat pump solutions.

Site Selection Criteria

- Feasibility to install monitoring equipment and collect data was a yes or no criterion. This criterion required that the heat pump data collection package was able to be installed. The units electrical panel had to be accessible and large enough to install sensors. The location of the indoor unit (ductless) needed to be accessible for temperature and airflow measurements. Communications through cellular modem or homeowner Wi-Fi had to be possible.
- Occupant's participation was a yes or no criterion. The occupant and building owner/operator needed to be a willing and engaged participant in the work, allowing access for monitoring and troubleshooting, and be open to completing surveys.
- Building characteristics, considering building types, sizes, and number of units to represent the range of feasible installations was targeted. A specific sampling requirement was not made.
- Location of the building and electric service provider to represent a range of interested utility service providers and to capture any differences between rural, metro, and suburban opportunities was targeted. A specific sampling requirement was not made.
- Existing heat type to represent a range of the major types of existing electrical heating systems was targeted.
- Heating load to represent a range of loads were targeted. Heat pump capacity diminishes at colder temperatures. As such, ASHP sizing, performance, and energy savings may vary with the heating load. Initially, loads were categorized as small, medium, and large based on existing equipment sizes, unit size, the insulation level, the presence of any energy updates, and the location of the unit within the building. Utility bills were used when available to calculate a more accurate household heating and cooling load.

Site Selection Criteria Summary

Twenty-seven sites were identified for possible inclusion in the project. Data was initially collected at all 27 sites through communication with onsite staff and internet property searches. Based on the initial data, sites were screened based on the expected ASHP installation approach, building characteristics, and willingness of the building owner and occupants to participate. Fifteen sites passed the initial screening and site visits were scheduled for confirmation of collected data and evaluation for ASHP installation feasibility and monitorability. Table 3 summarizes the data collected for all buildings where a site assessment was completed. The final sites were selected based on willingness and accessibility of the building, the feasibility to install and monitor an ASHP system, and the desire to measure performance in buildings with a range of installation and building characteristics.

Table 3. Selection criteria summary

Site	Selected	Location	Existing Heat Type	Electric Utility	Unit Types	Number of Units	Heating Load per Unit[1]
MF_01	Yes	Metro	Electric Resistance Baseboard & Wall Heaters	Xcel	Studio	6	15,000 Btuh

MF_07	Yes	Metro	Infrared heaters, Electric Resistance Baseboards	Xcel	1B and 2B	13	7,500 Btuh
MF_60	Yes	Suburban	Electric Resistance Baseboards & Packaged Terminal (PTAC) Units	City of Buffalo Utilities	2B	71	8,000 Btuh
MF_61	Yes	Metro	Electric Resistance Baseboard	Xcel	1B and 2B	6	9,000 Btuh
MF_02	No	Suburban	Electric Resistance Cove Heaters and Wall Heaters	Dakota	1B and 2B	4	Medium
MF_03	No	SW MN	Ducted single stage heat pump	Worthington Public	>9 floorplans	108	Large range of loads
MF_04	No	SE MN	Electric Resistance Baseboard & Wall Heaters	City of Hastings	2B	20	Small
MF_05	No	Southern MN	Electric Resistance Baseboards & Packaged Terminal (PTAC) Units	Freeborn Mower Electric Cooperative	1B and 2B	25	Medium
MF_06	No	Suburban	Electric Resistance Baseboard & Ceiling panels	Dakota	1B	4	Medium
MF_08	No	Metro	Ducted single stage heat pump	Xcel	Studio, 1B, 2B	230	Small to Medium
MF_09	No	Northern MN	Electric Resistance Baseboard & Wall Heaters	MN Power	Studio, 1B, 2B	56	Small
MF_10	No	Northern MN	Electric Resistance Baseboard	MN Power	1B and 2B	20	Medium
MF_12	No	Central	Electric Resistance Baseboard & Cove Heaters	Small Municipal	1B and 2B	14	Small
MF_13	No	Suburban	Electric Resistance Baseboard	Dakota	1B, 2B, and 3B	35	Medium
MF_59	No	Northern MN	Electric Resistance Baseboard	MN Power	1B and 2B	12	7,500 Btuh

1. Heating loads were estimated to be small, medium or large based on existing heating systems, unit size, and building envelop. Each building has a range of loads based on the units' properties and location within the building. More accurate load estimation wasn't possible until the building was selected, or the analysis began.

Heat Pump Design and Selection

The specific heat pump equipment selection, design, and installation were determined based on the building and unit parameters and the initial best practice guidance. The project was open to the best cold climate heat pump approach and application suited to each instance. Ductless cold climate ASHPs were to be specified for the electrically heated buildings included in this project. Both single-head and multi-head systems

Single-head systems consisted of one outdoor unit (ODU) were considered.

The ductless cold climate ASHPs selected for this project were all:

- Variable speed equipment capable of delivering heating and cooling at a range of capacities by modulating system operation (airflow, compressor speed, etc.).
- Designed to maintain capacity at cold temperatures.
- Capable of delivering reasonable efficiency (coefficient of performance or COP) at cold temperatures.

and one indoor unit or head. Multi-head systems paired one ODU with multiple indoor heads. Some multi-head systems could have as many as three or four heads per outdoor unit, but this study focused on 2 to 1 installations. Figure 2 shows a diagram of a multi-head system.

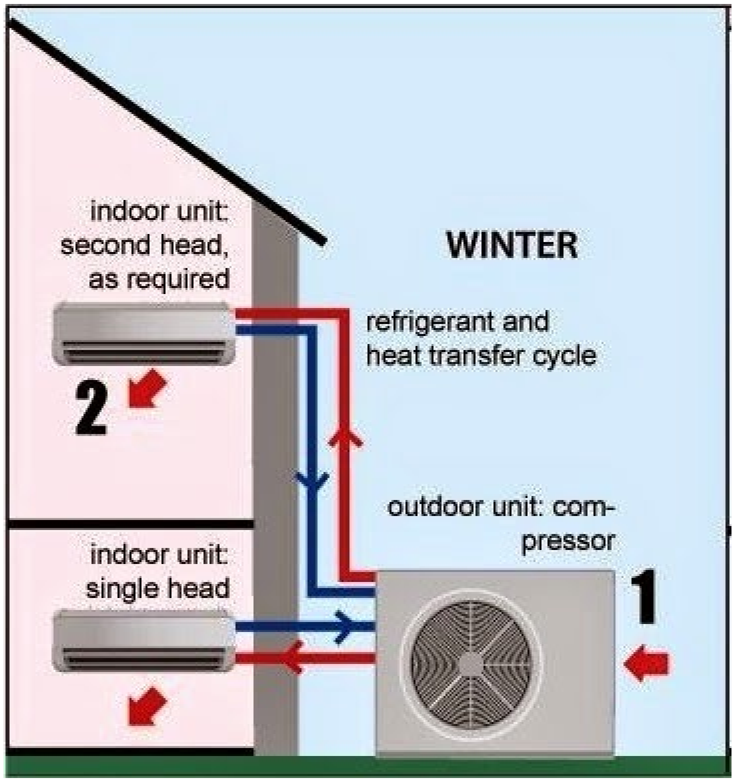

Figure 2. Multi-head ductless heat pump

Field Measurements

Instrumentation and Testing Procedures

Instrumentation packages were initially deployed for a baseline monitoring period of six months to one year. Packages consisted of an energy use logger and ambient temperature sensors. Baseline systems were monitored, and data collected for one heating season. Data collected during this period was used to determine the heating load of a home and analyze general baseline system operation.

Following the baseline period, heat pumps were installed and monitored for one to two heating season(s). Within the first week of a heat pump being installed, instrumentation packages were deployed. Each site had these main components: electrical use logger, thermocouple for supply and return temperature, and current transistor sensors for parts such as supply fan, refrigerant line, and compressor.

The field ASHP measurement package was designed to capture real-world data and characterize the in-field performance of heat pumps, including system energy use, delivered capacity, operating efficiency, and operational characteristics and sequences. These measurements were used to characterize the system's performance, but also to understand opportunities for improvement.

To determine the overall performance of the ASHP, data was collected from system operation in all operating conditions. The measurement package collected all energy input to the system. This was the electrical consumption used for the system to operate. Consumption was disaggregated into several system components including the indoor unit, outdoor unit, and the distribution fan. Field measurements were also taken to collect the energy output from the system. Supply air and return air temperature and system airflow rates measurements were made to capture the delivered energy of the system. All measurements were collected at one-second resolution, then post processed and rolled up for analysis. High-resolution data ensure that transient conditions, key to evaluating in-field performance, were captured with enough detail for evaluation.

The baseline measurement package consisted of the power meter installed in the electrical panel (**Error! Reference source not found.**. This meter measured the true power of all heating and cooling related circuits in the panel. Communications hardware was needed as necessary to support connection to unit or building Wi-Fi or to add cellular communication. An e-gauge power meter was used for all installations. This meter has been found to be robust, reliable, and accurate. For baseline measurement, the power readings were supplemented with some standalone HOBO temperature loggers within the occupied space. In baseline, all the primary heating systems were electric resistance and assumed to be 100% efficient. That meant that all the energy consumed by these devices was dissipated into the space as heat.

The panel-based power meter was also used in the heat pump period. Current transducers were added for the heat pump circuits to collect power data for the heat pump in addition to all other heating and cooling circuits.

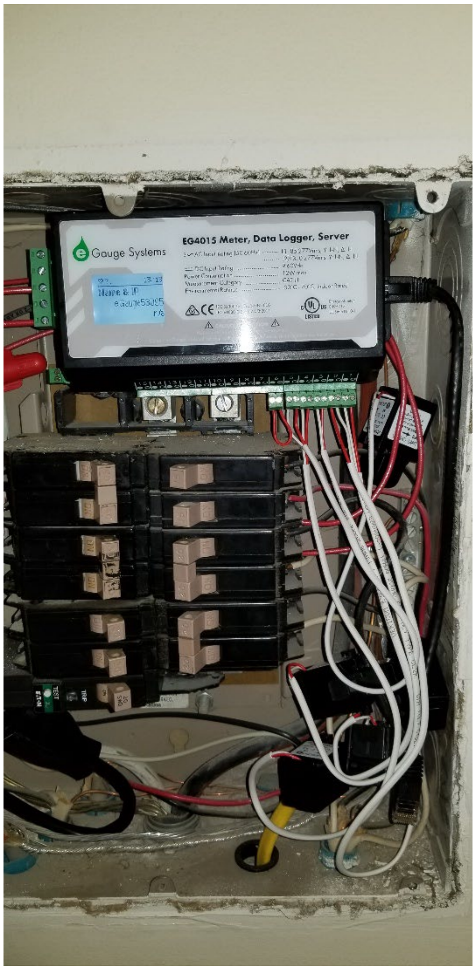

Figure 3. Example installation of data logger used for heat pump and baseline energy consumption

A second data logger was installed near the heat pump outdoor unit, during the heat pump monitoring period (Figure 4). This Campbell Scientific based monitoring package was deployed to collect data used to characterize the energy delivered by the installed ASHP. These loggers were configured to collect data remotely and transmit it to a centralized server for analysis using onsite Wi-Fi. Data was collected and transmitted continuously and regularly checked for completeness, and values were compared to pre-selected reasonable ranges. This quality control process ensured usable data was being collected and highlighted potential problems early to minimize data loss. The energy output of the system cannot be a direct measurement but was rather a calculation based on the data that could be directly measured. Thermocouples measured supply and return temperatures by using multi-sensor arrays. These arrays were designed and installed in such a way to measure the average air temperature delivered to the space. Airflow data was measured via a proxy variable, supply fan power. The supply fan power (or indoor head power) was then correlated to airflow using a calibrated fan measurement methodology. This process has been used by CEE and others for many years (Schoenbauer, Kessler, and Kushler 2017). The Campbell logger was also used to collect some additional system data, such as the status of the reversing value to better understand defrost operation, a temperature sensor in the outdoor unit, and others.

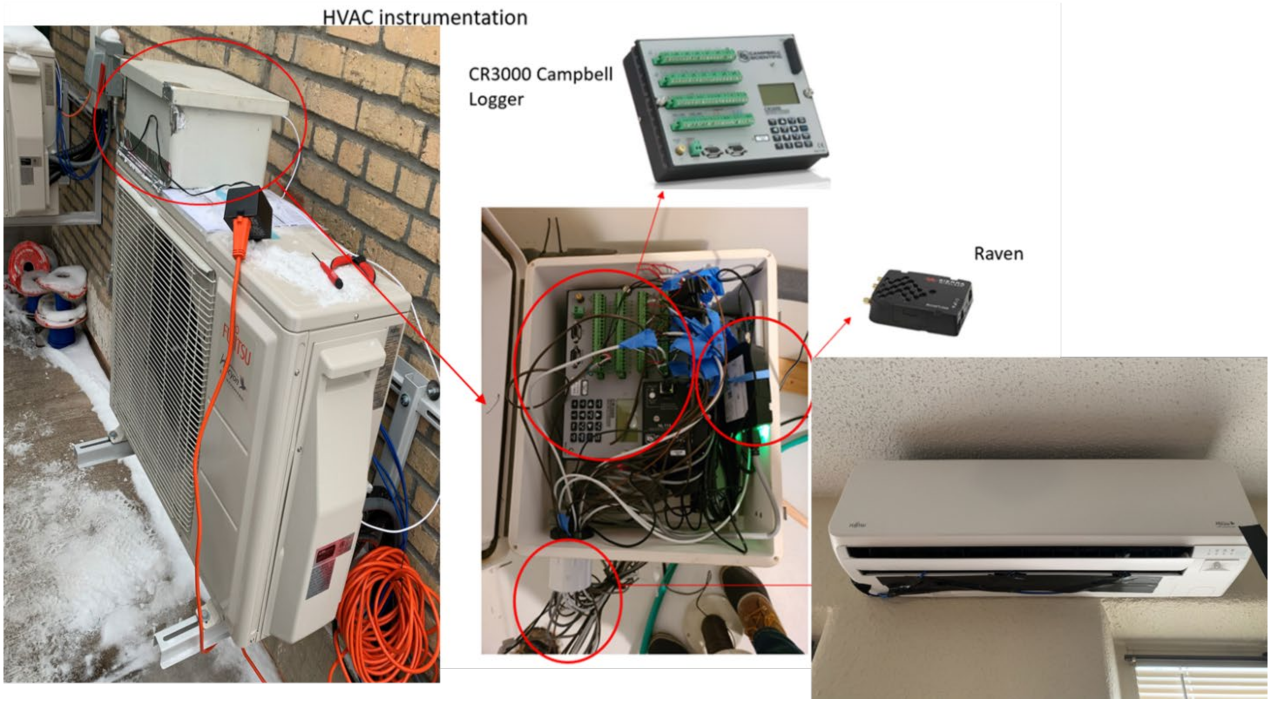

Figure 4. Data logger and sensors used for heat pump delivered energy monitoring

Installing the data logger near the outdoor head, required the sensor wiring to be passed through the thermal envelope to the indoor unit. The wire was run during installation, while line sets were also being routed through the envelope. With multi-head systems, wires were run along the refrigerant line sets to each of the indoor heads.

Occupant Surveys

Occupant surveys were administered in each unit where ASHPs were installed. Surveys were designed to assess the occupants' satisfaction with their HVAC systems in both winter and summer conditions before and after the heat pump installations. Questions were asked about the system performance and comfort levels, which included questions about the space temperatures, noise levels, and comfort under extreme weather conditions. Occupants were also asked questions about how they used their thermostats or ductless controllers and how familiar they were with the heating and cooling technologies in their homes.

Comparing occupant responses across all seasons in both modes before and after heat pump installation was difficult in multifamily buildings. Occupancy turnover was higher in multifamily buildings than in single-family homes and direct communication with occupants was more difficult in some cases. Survey results were not expected to be statistically significant and instead were conducted to provide anecdotal feedback about these systems.

Analysis

Extensive instrumentation packages were deployed days within heat pump installations, and data was collected onsite and transmitted and saved for processing and analysis. Data from each logger were run through rigorous quality control (QC) checks for any data discrepancies. Detailed analyses on each heat pump installed during the project confirmed the importance of various installation and design considerations, helped identify and redefine details that needed adjustment and improvement, and gave insights on heat pump performance in cold climates.

Data Collection and Quality Checking

Modems were connected to the data loggers to allow for remote data collection and limit times needed for site visits. Data was downloaded and compiled daily or weekly to ensure data would not be lost due to the loggers' memory limitations. To maximize the data return during test periods, the project team created a robust QC protocol that integrated and merged data across the multiple data logger sources, filtered the data for repeated or omitted timestamps, and applied a parameter range check to monitor sensor failures. This QC check produced reliable and high-quality data that was later used for more detailed analyses.

Data collected from the primary loggers (electrical use and thermocouple sensor array) and supplemental data from secondary loggers (temperature and humidity sensors) were merged with external data such as NOAA from local weather stations. CEE's project teams used the RStudio integrated development environment and R to develop code, which allows us to create single data files by merging all the data sources into one file. The merged data files were checked for consistency within the timestamps at the one-second time intervals that were set when the instrumentation packages were deployed. Data with empty, omitted, or duplicative timestamps were filtered out of the data set to ensure only complete data was processed for analysis.

Once a compiled data frame has gone through a timestamp continuity check, a simple range check is done to establish accuracy among the other parameters being monitored for the study. Past field measurement experience has shown that most instrumentation failures cause data readings to spike outside the acceptable ranges for given parameters — therefore, a simplistic range check was created to catch most errors in the data. For example, a temperature sensor on the return side of a heat pump system would read temperature ranges between 50–90°F. If the sensor is out of this range, usually it indicated a sensor failure. The code developed for range checking was used frequently (weekly or daily) at the project's start-up period to provide ample time to catch any sensor-reading errors, irregular data, and other issues that arose. Once data appeared to be steady, this range-checking process was then used less frequently (monthly) or as needed.

Finally, when the data was collected, reviewed, and processed with confidence in the quality of the collection, the files were then stored for future analyses. Only the merged files that have undergone range checking and timestamp continuity were used to ensure that only the highest quality data is presented in this final report.

Heating Loads and Coefficient of Performance

The primary analysis of this project was to determine the correlation between heating/cooling energy use and outdoor air temperature (OAT). For each site, the energy use data from the baseline system was plotted against the OAT. Linear regression analysis was then applied to determine the heating and cooling loads of the site. Generally, a unit used more energy in periods of extreme temperature ranges and very little to none during times with moderate temperatures. This behavior causes two distinct load curves that define the home's heating and cooling loads where energy use is a function of OAT.

These load curves also gave us insight regarding the balance point for each site. The balance point is the temperature range, usually within five degrees, in which a home switches from heating use to cooling or vice versa. This balance point occurs in moderate temperature ranges usually in the shoulder seasons (spring and autumn) where there is a blend of cool and warm weather and low energy usage (1–3 kWh). Determining the balance point, which varies by each site, allows the load curves to be fit precisely. The heating/cooling loads along with the balance points allowed the research team to find the best cold climate ASHP to install based on capacities, switchover points, and general sizing specifications.

Runtimes of the baseline system were analyzed to optimize eventual heat pump installation. Each system monitored produced an electrical current signature that could easily be identified using the electrical use logger data. Code was developed that would input raw data (continuous data that was collected initially), identify these electrical current signatures, and indicate that a system was on if that use was above the electrical current signature threshold. Likewise, the system would be considered off when the use was below the threshold. With this information, a new data frame was created that would indicate actual runtimes of the system.

When looking primarily at the baseline heating systems, the team found that these systems would often run for significant amounts of time ranging from a few hours to a day at a time. This implies that the original system installed in the home was undersized and unable to meet the heating load. A system running continuously signifies it being undersized because the heat delivered to the space never reaches the temperature setpoint on a thermostat, whereas a system that is sized properly will eventually meet the temperature setpoint after some duration of being on. Using this information, the team referenced the heating load at its maximum use and compared it to the proposed heat pump capacity during contractor bidding. This confirmed a successful QI procedure because real data provided on a home allowed accurate system sizing.

The primary focus of analysis on the installed heat pumps was their performance in cold climates, specifically, determining their coefficient of performance (COP). COP is the ratio defined as the heat delivered to a space over the heat input to provide it.

$$COP\ = Energy\ delivered/energy\ input$$

Determining this ratio for the heat pumps installed during the project was important because heat pump COPs are unique compared to other HVAC systems. Traditional HVAC systems such as furnaces and boilers create heat through combustion or electric resistance. These systems have low COPs because they use more energy than they output due to the processes they use to provide heat. In other words, the delivered heat (or energy) to the space is less than the energy used to provide it resulting in a ratio less than 1. A heat pump, by contrast, moves heat from the outdoor air to the indoor space while adding additional heat through the heat exchanger. This process allows COPs for heat pumps to be higher than 1 without breaking the Laws of Thermodynamics because the heat of the system is being transferred, not undergoing a thermodynamic change.

The equation used to calculate the COP of the heat pumps is provided below:

$$COP = \frac{Q_{out}}{Q_{in}}$$

Where Q_{out} is the energy output of the system and Q_{in} is the energy input of the system. These quantities were calculated using the equations below:

$$Q_{out,Btu/h} = CFM * 1.08 * (T_{Supply} - T_{Return})$$

$$Q_{in,Btu/h} = Sum\ of\ heat\ inputs$$

For Q_{out}, the CFM in the equation is the CFM determined by the regression analysis of experimental airflow found during site visits, 1.08 being the specific heat of air and the average temperature of the supply and return from the sensor array. Q_{in} is the sum of the energy input of the complete system.

Much like the methodologies described for the baseline system, the heat pump runtimes were analyzed; however, heat pumps, especially variable capacity systems, have more complex thresholds that are identified by their energy use. The energy input threshold can vary slightly depending on the heat delivery needed in the system, and heat pumps have defrost modes that reverse the heating cycle to take warm air to the heat exchanger to melt ice built up on humid days. These variations make the thresholds more complex than traditional HVAC systems, which can have on/off modes, and the COPs can vary for each of these modes. COP was calculated at these different stages using the threshold methodologies described for the baseline system. In general, COPs ranged from 3–6 and were higher than the rated COPs provided by the manufacturers.

These various COPs were plotted against OAT to determine what temperature ranges the system was most efficient, and the team found that the heat pumps within this project could produce COPs as high as 3 at -15°F.

Results

Site Characteristics and Selection

A total of twenty-seven multifamily buildings were considered for heat pump installations. All twenty-seven building were primally heated with electricity. Single heating sources were common in multifamily buildings, none of the sites considered here had alternative fuel sources for heating.

Electric resistance baseboards (ER baseboard) were the most common type of existing heating system with approximately 70% of sites using this system. Other distributed electric resistance heaters like cover heaters, wall heaters, and radiant panels were observed in some units. Slightly over 10% of the screened buildings had through wall vertically packaged systems, sometimes referred to by one of the larger manufacturers of systems, Magicpaks.

The buildings considered had an average of 23 units per building. Two buildings had 100 units and the smallest buildings had four units each. The characteristics of the individual units were expected to impact the ASHP performance more than the overall building size or number of units. These unit characteristics include, the layout, existing systems, heating zones, and heating load. However, some factors such as heating load were still likely affected by the scale of the building.

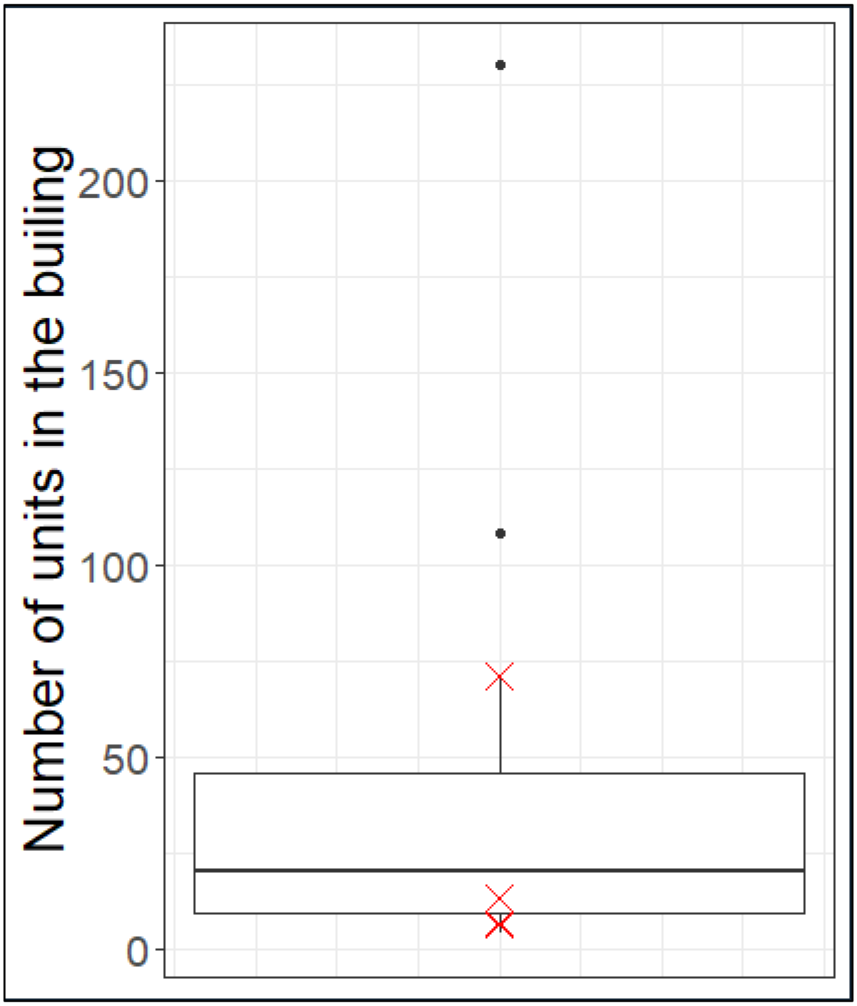

Figure 5 shows the distribution of building sizes and the selected buildings.

The selection process attempted to identify and install heat pumps in buildings that would be representative of the electrical heat multifamily building in Minnesota. Due to the scope of the project and the costs to do detailed monitoring, the selected sites were not going to be a statistically significant sample of multifamily buildings. Still, the selection represents a range of the characteristics considered most important for ASHP operation. The detailed data collected at the buildings can be considered representative and used in future evaluations of possible heat pump installs in a wider array of buildings.

Site selection and installations on this project were hampered by the timing of the COVID 19 pandemic. Three buildings that were in the process of selection with ASHP installations being installed had to be dropped from the project due to the pandemic. These buildings were unable to allow access to non-essential workers during the pandemic due to the high-risk nature of many of the building occupants. An additional two potential properties were removed from consideration due to ongoing complications around the supply chain and other COVID 19 complications. This caused significant delays to the project as well as more broadly applied screening criteria.

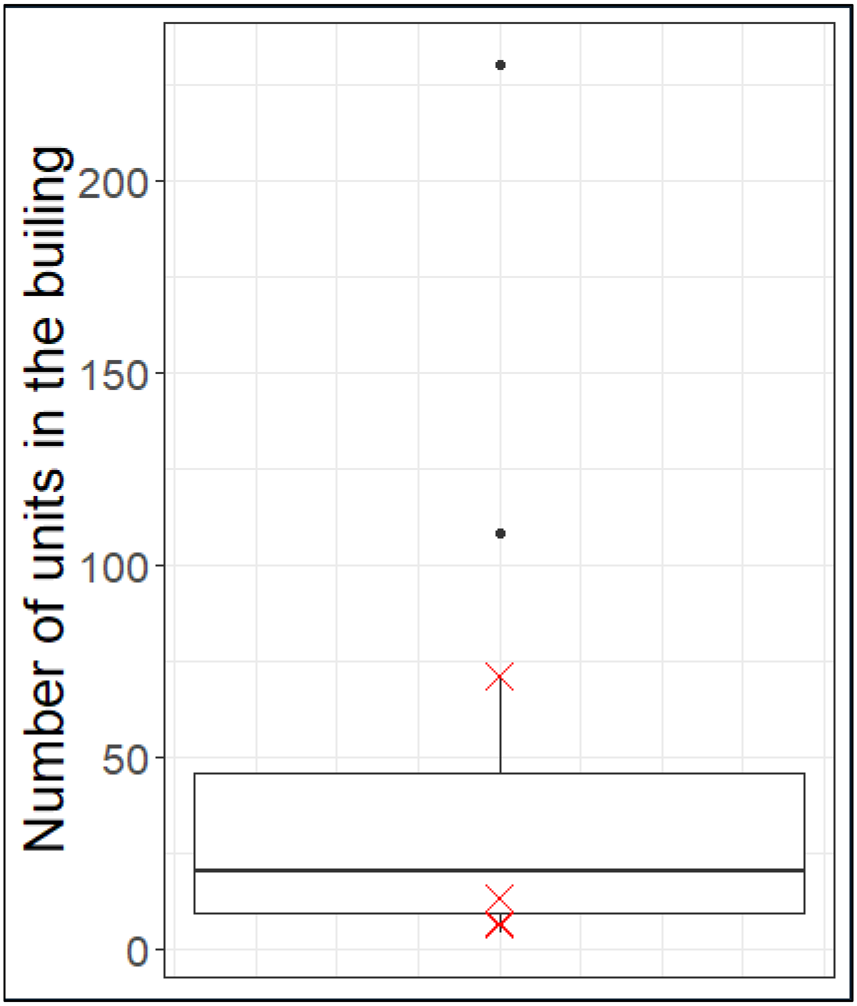

Figure 5. Distribution of the number of units per building screened

Of the twenty-seven multifamily buildings considered, only three were excluded from the project for reasons related to the heat pump installation. One building had a historically classified brick façade and the owner was hesitant to consider any system that could impact the exterior aesthetics. A second multifamily building used electric furnaces and a centrally ducted air handler system. This system type could have been replaced by a centrally ducted ASHP, more common in single-family homes. The system size and ductwork attached were smaller than many single-family systems, but this installation was deemed out of scope of this work which focused on ductless solutions. A final building used a water source heat pump as its existing system. These units were also deemed out of scope.

Nine buildings were contacted to evaluate. Although screening evaluation started on all nine buildings, the communications slowed or stopped before buildings were fully assessed or ASHP installation bids were developed. Of these nine sites, three dropped out due to lost interest from the owners. All three indicated that installation cost or cost-effectiveness of cold climate ASHP installation was a factor in their hesitation to participate.

Table 4. Final recruitment breakdown of all 27 buildings considered

Selected/Not Selected – Reason for non-selection	Number of Buildings
Not selected - Unable to recruit. Lost communication with owner/operator.	9
Not selected - COVID 19 related reasons	6
Not selected - Buildings that were too like selected buildings	2
Not selected - Buildings with instrumentation issues related to electrical panel	2
Not selected - Buildings that were not ideal fit for ductless heat pump applications	4
Selected	4

Selected Sites

Table 5 shows the selection criteria for the final sites selected for heat pump installation and monitoring. These sites span the range of the selection criteria and are representative of MN's electrically heated multifamily buildings.

Table 5. Buildings selected for ASHP installation

Site	Monitorable	Occupant Participation	Location	Layout	ASHP Approach	Existing Heat	Building Size
MF_01	Yes	Yes	Metro	1 Bedroom	1to1 ductless	ER baseboard	2 stories | 6 units
MF_07	Yes	Yes	Metro	1 & 2 Bedroom	1to1 ductless	ER baseboard	2 stories | 13 units
MF_60	Yes	Yes	Suburban	2 Bedroom	PTHP	PTAC & ER baseboard	6 stories | 71 units

MF_61	Yes	Yes	Suburban	1 & 2 Bedroom	1to1 & 2to1 ductless	ER baseboard	3 stories | 6 units

Building Installations

Site MF_01

MF_01 was an 1895 building with six housing units. This building was formerly a very large (4,800 square foot) residence that had been divided into six units. Anecdotally, this building type is not uncommon for metro area electrically heated multifamily buildings. When a residence is divided into several units, splitting the utilities can be difficult. A simple and low-cost solution is to install distributed electric heaters in each unit. This simplifies issues with modifying ductwork to deliver heat uniformly to newly created units.

Two of the six units in this building were selected for ASHP installation and monitoring. Each of the selected units had one bedroom, one bathroom, a kitchen, and living room space. The units had slightly different floor plans with some connection between the living and dining spaces. Unit 3 had a more open concept layout. During the installation process, the heating design loads of these units were estimated to be approximately 10,000 Btu/hr. each.

Cold climate ASHP ductless units were specified for each unit with a one indoor head and one outdoor unit configuration. The heating load of the units were deemed too low to justify the increased cost of a multi-head solution. Existing electric resistance heaters were left in place in bedrooms and bathrooms. The indoor head was placed in the largest space in both units, the living room with some airflow access to the connected kitchen space.

Site MF_07

MF_07 was a 13-unit multifamily building. Six units were monitored and had cold climate ASHP systems installed. MF_07 was a more traditional purpose build multi-family building. The owner of this property was in the process of fully replacing the heating system of this property. The ASHP installations on the first floor were included in this project, but the building planned to complete replacements in all 13 units.

Five of the six units selected were one-bedroom units, with the final unit having two bedrooms. Ductless cold climate ASHPs were installed in each unit. Due to the size and expected heating load, one-ton outdoor units were paired with a single one-ton indoor head to be placed in the main living room and/or kitchen space of each unit.

Figure 6. MF_07 exterior

Site MF_60

MF_60 was a 71 unit, six story condominium complex. The property had a range of units, sizes, and layouts. The building was electrically heated with a mixture of electric resistance baseboards and packaged terminal air conditioners (PTACs). Figure 7 shows the PTAC installed in the living space of the unit that was selected for monitoring. This unit delivered electric heating and cooling for the living space. A second PTAC was installed in the bedroom. Electric resistance baseboards were also used to heat the units. PTACs are a common inexpensive HVAC solution, most used in hospitality settings, but also in multifamily buildings. Heat pumps have historically been available for this form factor but were not equipped to be installed in cold climates. Recently, a couple manufacturers have developed cold climate units with variable speed compressors and defrost cycles that allow the unit to heat at colder temperatures. One of these cold climate variable speed packaged terminal heat pumps (PTHPs) was installed in this unit.

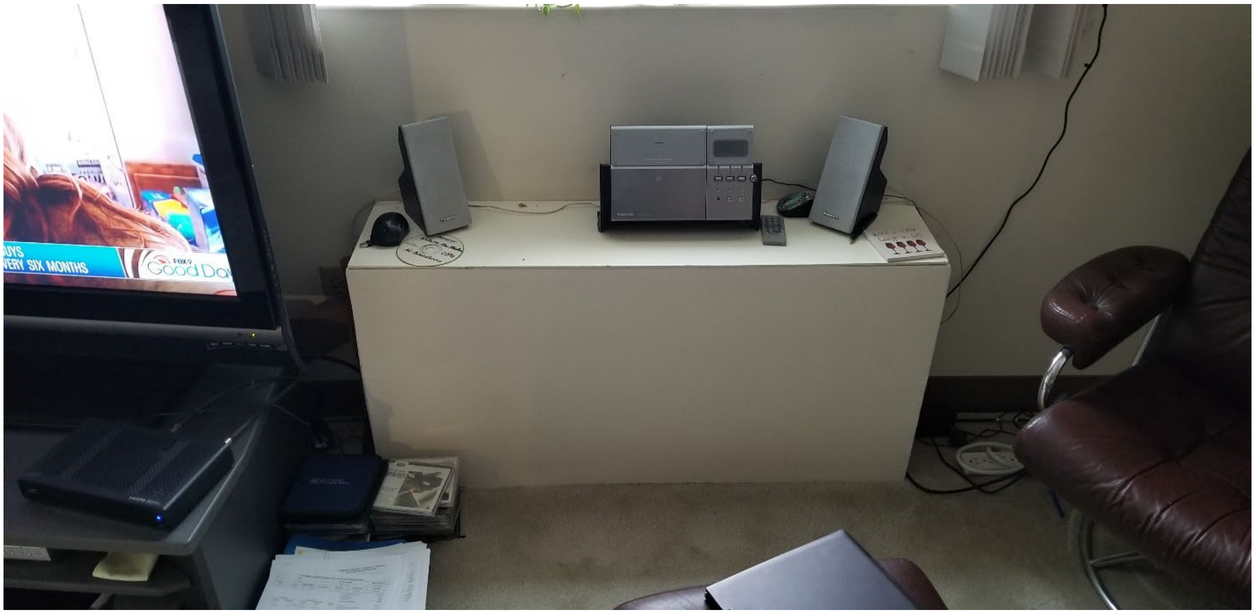

Figure 7. The existing PTAC heating system in the living space of MF_60

Site MF_61

MF_61 is a three story six unit electrically heated multifamily building in suburban St. Paul. This property is an affordable housing complex with two-bedroom units. Two units had multi-head systems with an indoor unit in the living/kitchen space and a second head in the larger bedroom. The four units on the upper levels had single one-to-one ductless systems installed with the head in the living/kitchen space. Upper units had smaller heating load calculations than the lower units.

Heat Pump Specifications

ASHPs were selected, designed and installed based on the installation best practices developed based on previous heat pump research, manufacturer documentation, and the market assessment. Each heat pump installation was intended to offset as much electric resistance heating load as feasible considering installation costs and expected system operation. Table 6 summarizes the heat pumps installed and their rated performance metrics.

Table 6. Specifications for the installed heat pumps

Site	Units	HP Type	SEER	HSPF	EER	Rated Heating Capacity (Btu/h) @47F	COP at Max. Capacity at 5F

MF_01	3 & 6	1 to 1 Ductless	20	10.3	13.3	25,000	2.09
MF_07	102, 103, 104, 105, 106, & 107	1 to 1 Ductless	29.4	13.8	15.2	16,000	2.13
MF_61	Unit 1	2 to 1 Ductless	21	10.5	12.5	19,000	1.97
MF_61	Unit 2	2 to 1 Ductless	21	10.5	12.5	19,000	1.97
MF_61	3, 4, 5, & 6	1 to 1 Ductless	23	10	9	19,000	1.97
MF_60	Unit 1	PTHP	11.95*	6.45*	N/A	10,200	1.64

Installation Observation

Outdoor unit location

Cold climate ASHPs were installed in four buildings. Three of those buildings had standard heat pump outdoor units and one had a through the wall packaged heat pump (PTHP). The multifamily buildings included in the project were two and three stories tall. This building size allowed for all outdoor units to be installed at ground level. Ground level installations were preferred by contractors due to ease of access. Installations off the ground for non-ground level units would have decreased refrigerant line set length, but would require lifts, scaffolding, or other means to install and service. Wall mount and roof installations were considered for larger buildings. These alternative installation locations should not impact the performance of the ASHP significantly but could increase installation costs. Although rooftop and high wall installations were not completed as part of this project, ground level wall mounted systems were installed with no measurable performance difference from ground mounted systems. Based on the installation practices observed in this project and experiences with installing contractors, there is no technical reason to expect off-the-ground installations to impact system performance. And no measurable impact on impact was found based on the sites monitored within this work.

Many ductless heat pumps have ground mounting and wall mounting options. For this project, one installer chose to set the outdoor units on a pad at the ground level (Figure 8), while the other two multifamily buildings had units wall mounted just off the ground. Figure 9 shows this installation of the outdoor units at MF_61. At this site, the contractor chose to wall mount the units at about eye level. This installation type allowed for easy ground level access and limited the amount of ground preparation work because it did not require adding a ground pad as a ground mount install would have. Figure 10 shows a similar wall mounted installation at MF_7.

Figure 8. Outdoor unit installation at MF_01

Impact of In-Unit Zoning

Heating and cooling systems require a distribution system to move the heat from the HVAC system to the different occupied spaces in a home and housing unit. In a single-zone system, all distribution is connected, and any time heating and cooling is delivered to one space it is delivered to all spaces. In a multi-zone system, the distribution is broken into different sections, which can then be heated and cooled independently. Multi-zoned approaches are common in electrically heated multifamily buildings when baseboard units are often controlled with their own thermostat in each room or pair of rooms. Zoning added an additional level of load calculation and heat pump sizing in some of the multifamily units. MF_01 was particularly difficult as units were small and floor plans were not standard due to the buildings past use as a single-family building. In constructing the multifamily units, heating zones were created in which a single circuit and thermostat could include radiators in multiple rooms. For example, in MF_01 unit 3, a single circuit was used to write the bedroom and kitchen baseboard heaters. Installing a heat pump in the living room where it could offset the living room and kitchen energy use may cause issues in the bedroom, when the kitchen circuit was satisfied, but no heat was able to be circulated to the bedroom. These challenges in layout and zoning make advanced control, displacement, sizing, and wiring difficult to optimize. These issues were maximized in the less traditional layouts of MF_01 but were felt in all the smaller unit floor plans.

Consideration for Operation of the HP systems

Occupancy Impacts

Several properties monitored in this research were rentals for income-qualified renters (MF_01, MF_07, and MF_61). In these properties, occupants typically change annually (or more often). These frequent changes in occupancy had some impacts on the heat pump operation and performance. Heat pumps are relatively new HVAC systems and are often controlled with different types of thermostats and remotes than traditional heating systems. Based on a few interactions with tenants that moved into units after the ASHPs were installed, we observed that new occupants were unsure of the heat pumps' operation and how they should control and interact with it.

Communications and Control

Newer and more advanced heat pumps, thermostats, and controls are more likely to rely on internet connections to fully utilize all their features. This can include access to heat pump setpoints and operating modes, control methods that rely on internet connection to get local weather information, and third-party control devices that connect to one another through local Wi-Fi.

In multifamily buildings, consistent Wi-Fi connections and reliable communications can be difficult. In buildings where occupants are responsible for their own Wi-Fi, change of occupancy requires the heat pump, thermostat, or controller to be set up with the new Wi-Fi credentials. This introduces an opportunity for interruption of control and/or inaccessibility of these advanced features. In properties with building-wide Wi-Fi or communications, some spaces may have poor signals or/and connections may be inconsistent. Any programs or system that relies on these internet-based features needs to consider these issues.

Spit incentives

In multifamily buildings, the occupants typically are not the owners of the unit or building. As such, they may have different incentives than an owner. These incentives should be considered during design and installation of the heat pump. This applies to the system payback and first cost justification, but also to operation of the heat pump. For example, if a unit is not sub-metered so that the occupant pays their own heating cost directly, convenience might be a higher priority than system efficiency. That may lead them to running the electric resistance heater with a simple dial thermostat over a more efficient system. In this project, the owner of one building, MF_07, had supplied portable infrared (IR) heaters to all the units and asked tenets to use these heaters for point source heating in heavily occupied areas, instead of the electric resistance heaters that would heat the full zone. These heaters were the convenient and preferred method of heating for occupants at the time of the ASHP installation. Occupant training was required to ensure the more efficient ASHP was prioritized over the IR heaters.

Figure 9. Outdoor unit placement at MF_61

Figure 10. ASHP outdoor units at MF_7

Installed Performance

The buildings monitored in this project were not statistically significant sample of the entire Minnesota multifamily building stock. However, they were selected to represent Minnesota's multifamily buildings. The analysis and performance of the heat pumps at each site should be considered for the implications of the performance of these systems in the wider population of Minnesota multifamily buildings; therefore, methods and best practices followed for installation should be considered for future program use. Analysis and installed performance should be considered for implications on savings calculations and assumptions used for program performance and expectations of these systems in the field. Due to unique conditions present at each site, installed performance from each site should be considered as part of the framework under which it was installed and operated.

MF_01

The heat pumps installed in MF_1 were monitored over an extended period including data from two different heating seasons. Efficiency and capacity were monitored and mapped for dependence on outdoor air temperature. System efficiency largely met expectations. Figure 13 shows the daily COP of the one-to-one ductless mini split installed in unit 3 at this property. The system runtime and required heating load placed on the heat pump significantly affected the efficiency of the system. There were several days where the heat pump efficiency was below 1.0. However, on these days the average daily capacity delivered was less than 1,000 Btu/hr. This indicated that the heat pump had limited runtime on these days and when it was operating, the calls for heat required capacities below the minimum operating range of the system. On days that averaged 6,000 Btu/hr. or above the heat pump showed much higher efficiencies. On these days, the heat pump was running more frequently, and the heating load was within the operating capacity range of the one-ton system.

Zoning played a large impact on the heat pump runtime in this building. When the heat pump was operational and reached a steady-state efficiency for a significant part of the daily runtime the daily efficiencies were more than double (COP > 2.0) baseline heating system. However, the heat pump could only deliver heat to a fraction of the unit, due to the airflow pathways from the single head (Figure 11). Figure 12 shows that the heat pump ran across a wide range of operating temperatures, including operation on days below 0°F. But the baseboard heaters were in zones where the heat pump's indoor head was not installed (H1 and H2) — the heat pump could not offset heating loads in the zones and the backup baseboards were needed to meet the setpoints (H1_kW and H2_kW). As such, the heat pump was limited in the amount of heating load it could offset.

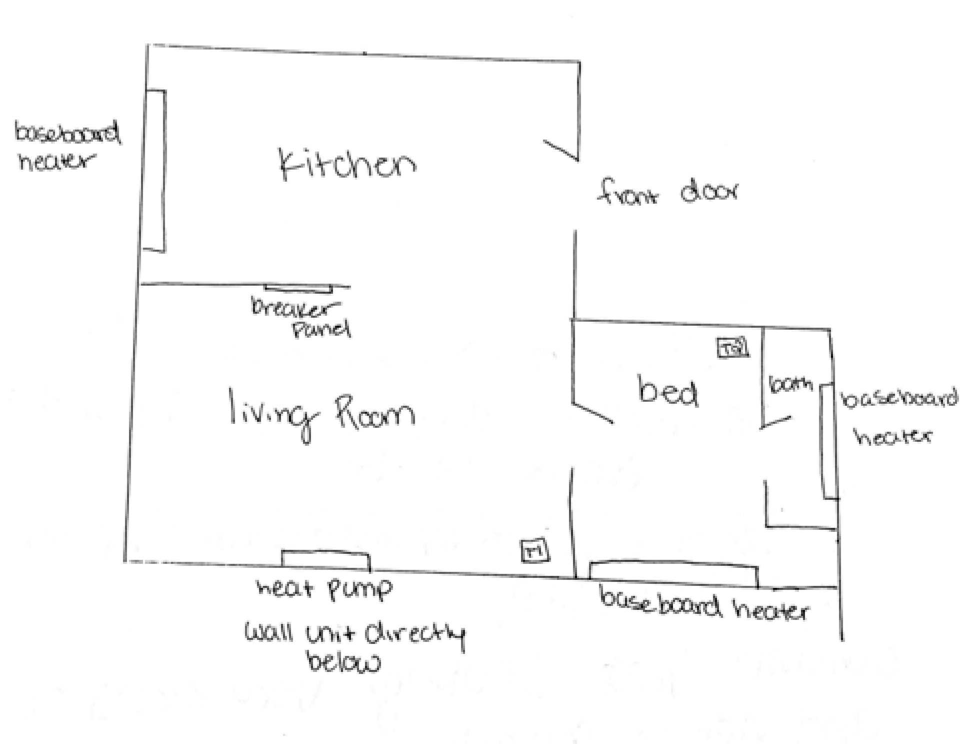

Figure 11. Diagram of MF_01 Unit 3 layout

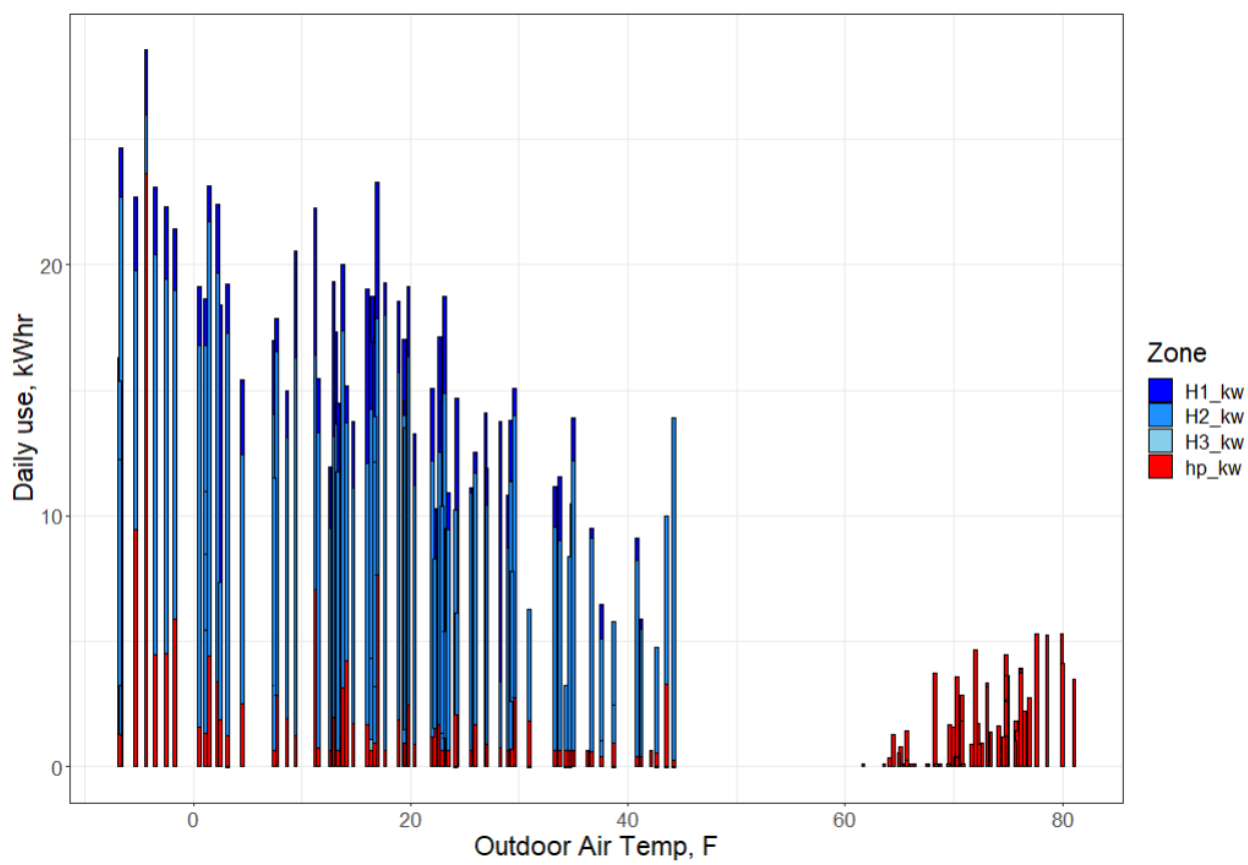

Figure 12. Daily heating and cooling circuit energy use at MF_07 Unit 3

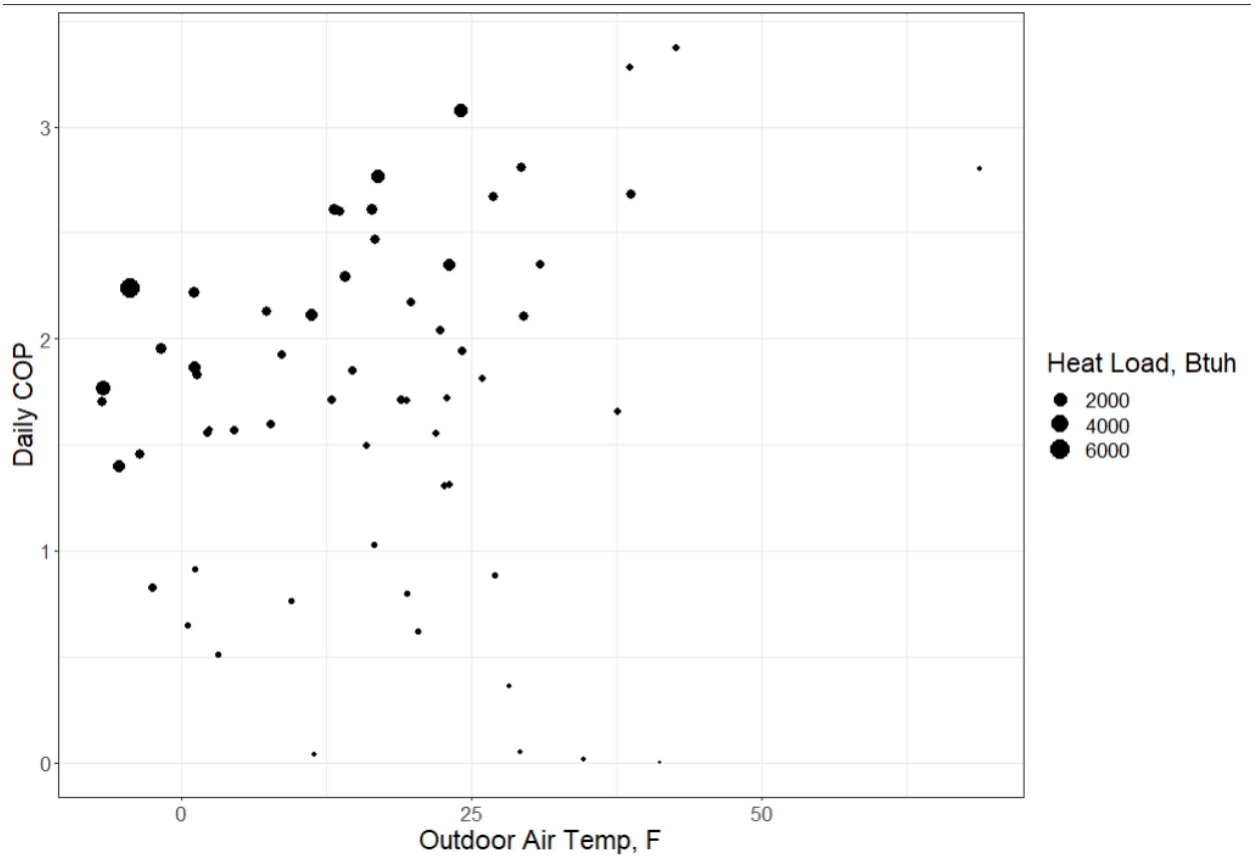

Figure 13. Daily COP at MF_01 Unit 3

MF_07

Heat pumps were installed in six units at MF_07. Five of the units were small one-bedroom apartments. The final unit was a small two-bedroom unit. The design heating loads of each unit were about 5,000 Btu/hr. Figure 14 shows the heating energy use in one of the single bedroom units in the baseline mode. The total unit used 4,800 Btu/hr. at the design heating load of -11°F. For this unit, the zone containing the baseboards in the living room and kitchen accounted for slightly less than half of the unit's total heating load. The circuit with the IR heater accounted for the other half of the heating energy used, with infrequent use from the bedroom and bathroom baseboard circuit.

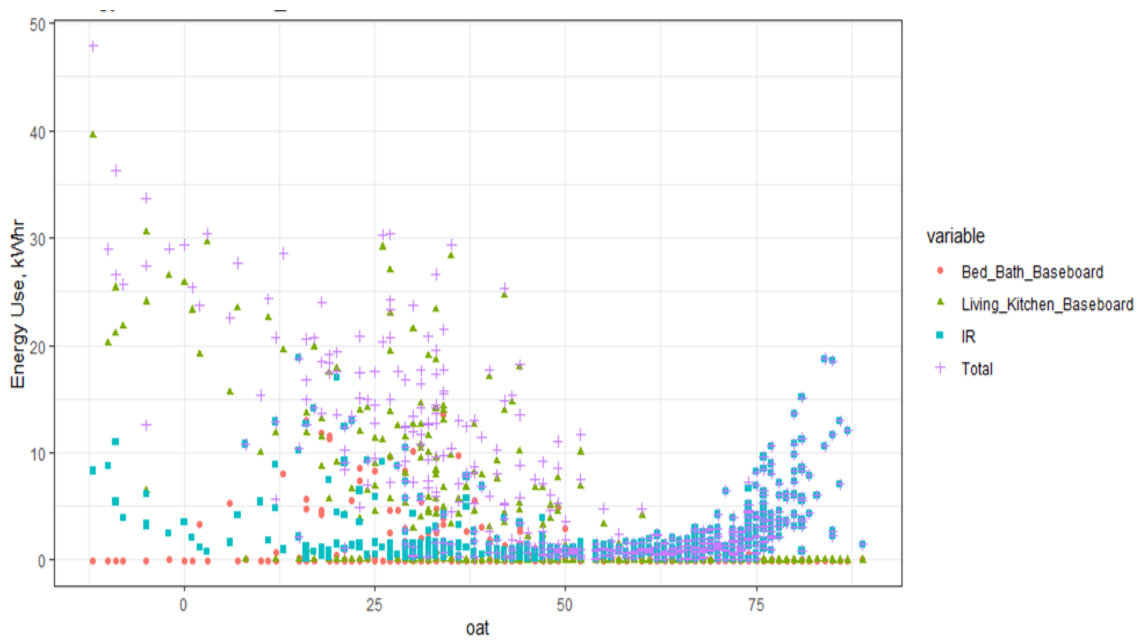

Figure 14. Energy used by heating circuit in baseline mode to capture total unit and zone heating loads

After heat pump installation heating and cooling energy use was reduced for each unit. Figure 15 shows the total unit energy use by outdoor temperature in Unit 103 before and after heat pump installation. Heating energy reductions were greater in the shoulder heating season where the heat pumps had higher efficiencies and could displace a larger fraction of the heating load. As outdoor air temperature dropped, heat pump capacity was reduced, and more backup heating was required. Heat pump efficiencies also decreased as temperatures reduced, such that even when the heat pump was operational at cold temperatures, the efficiency improvement over the baseline system was smaller. Less runtime and reduced efficiency meant that as temperatures continued to decline the total unit heating energy use approached baseline levels.

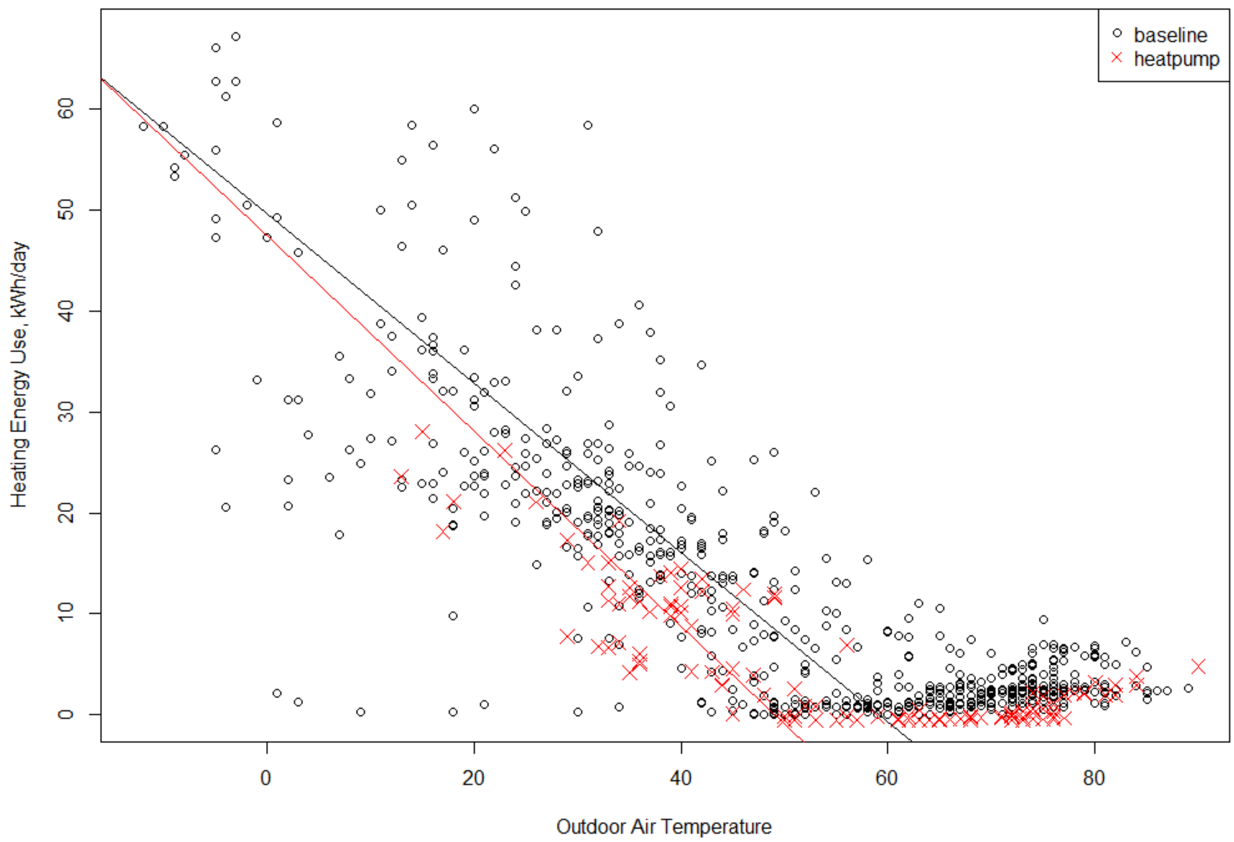

Figure 15. Energy use in Unit 103 in baseline and heat pump mode

MF_61

MF_61 was a three-story building. Heat pumps were installed on two units per floor. Larger multi-head systems with two indoor heads were installed on the ground floor where heating loads were larger. The larger multi-head heat pumps could deliver more capacity and were installed to serve a larger space inside the unit (two-point sources of heat compared to one). The middle and upper floor units had lower heating loads than the ground floor units. Figure 17 shows the total daily heat delivered for different units in the building. On average the ground floor units required 12,000 Btu/hr at design temperature to maintain occupant space temperatures, while upper floor units only require 8,750 Btu/hr.

Despite the differences in capacity and design the system COPs were statistically the same between the one to one and two to one units installed in MF_61. Figure 16 shows a comparison of the event efficiencies for the heat pumps installed in these units.

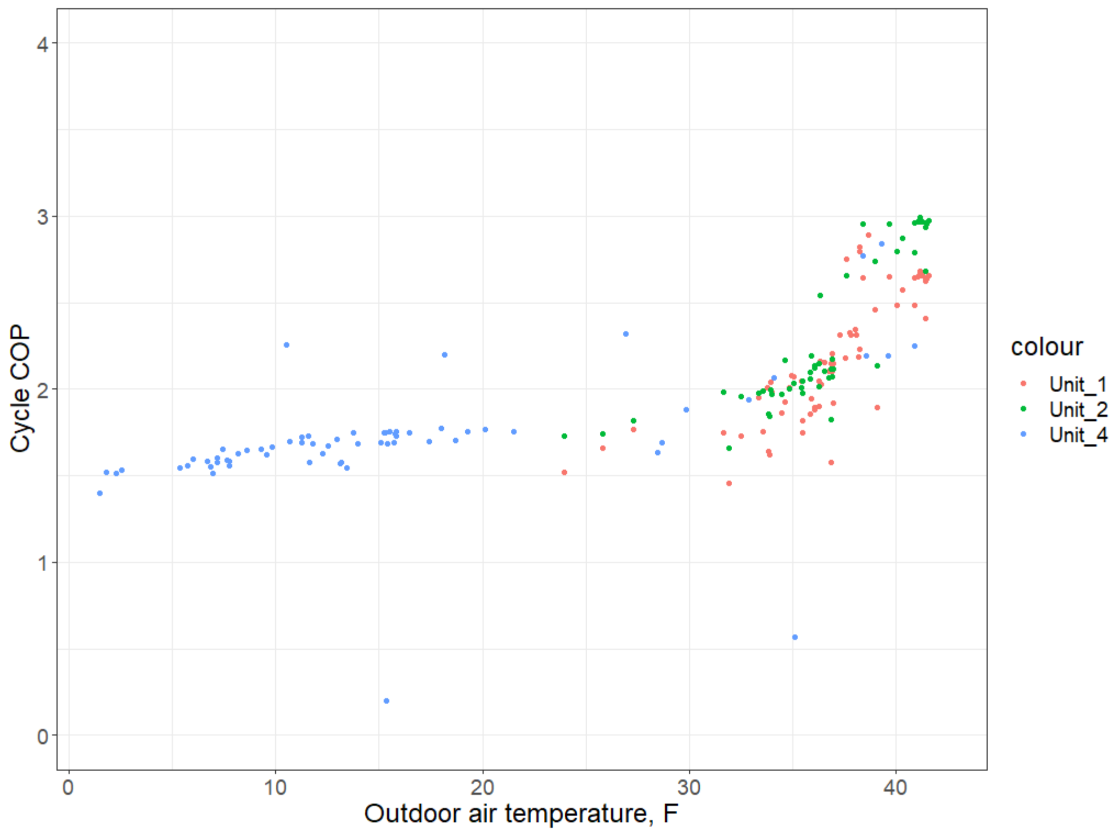

Figure 16. Comparison of the event efficiencies for two units with multiple heads (Unit 1 and Unit 2) to a single head system (unit 4).

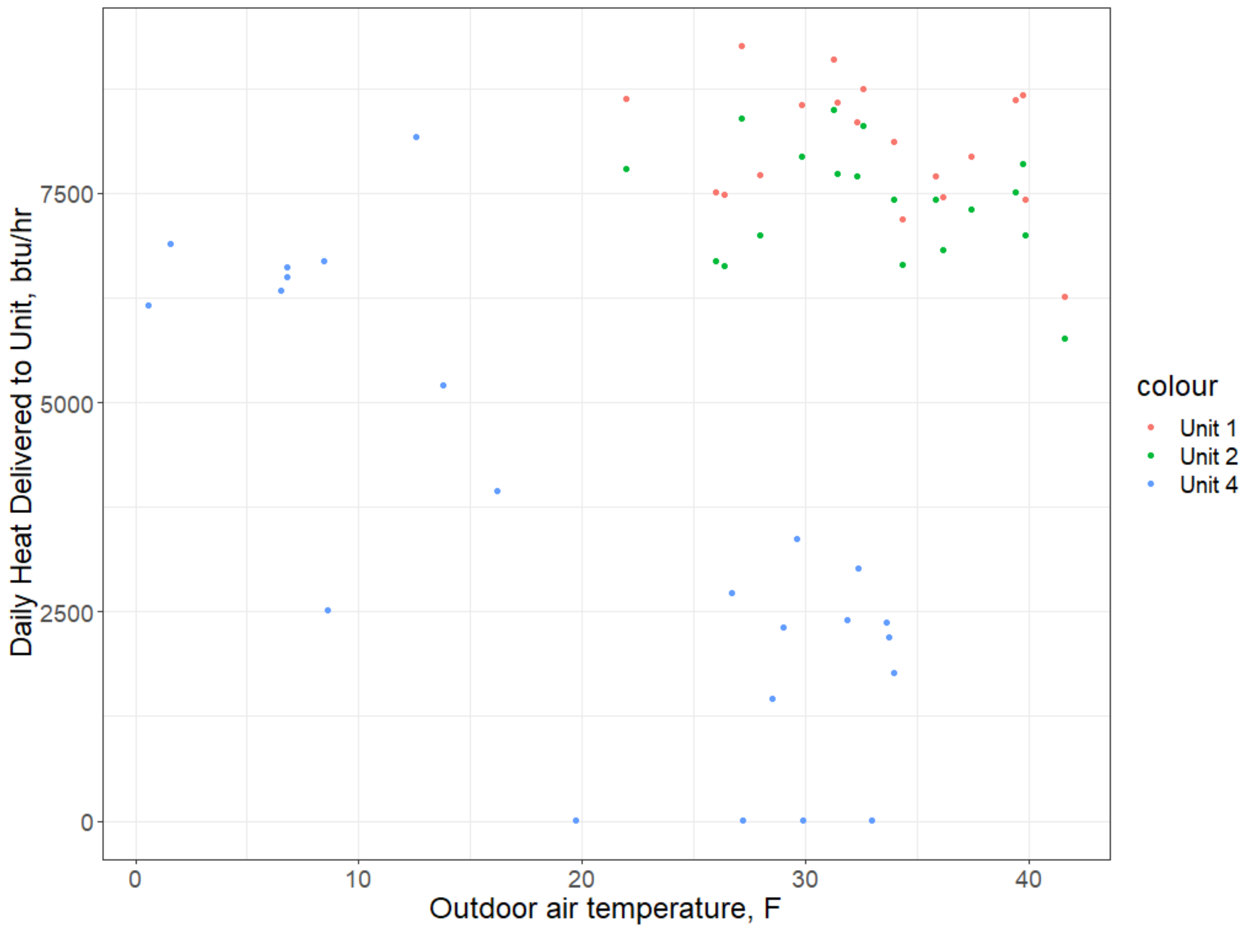

Figure 17. Total daily delivered heat (heat pump plus backup) for each unit

MF_60

The PTHP installed at unit MF_60 was one of the first generations of heat pumps to use a variable speed compressor. This model was one of the few designed for cold climate applications. As such, the refrigeration cycle and compressor had less history and generations of design and improvement when compared to a ductless heat pump system. Despite the lack of history and generations, the PTHP performed quite well with a seasonal heating COP of 1.69. Figure 18 shows the COP of each heating cycle the PTHP delivered heat to the unit at MF_60. Generally, COPs are slightly below that of the cold climate ductless units, but it still delivered significant improvement over electric resistance heating.

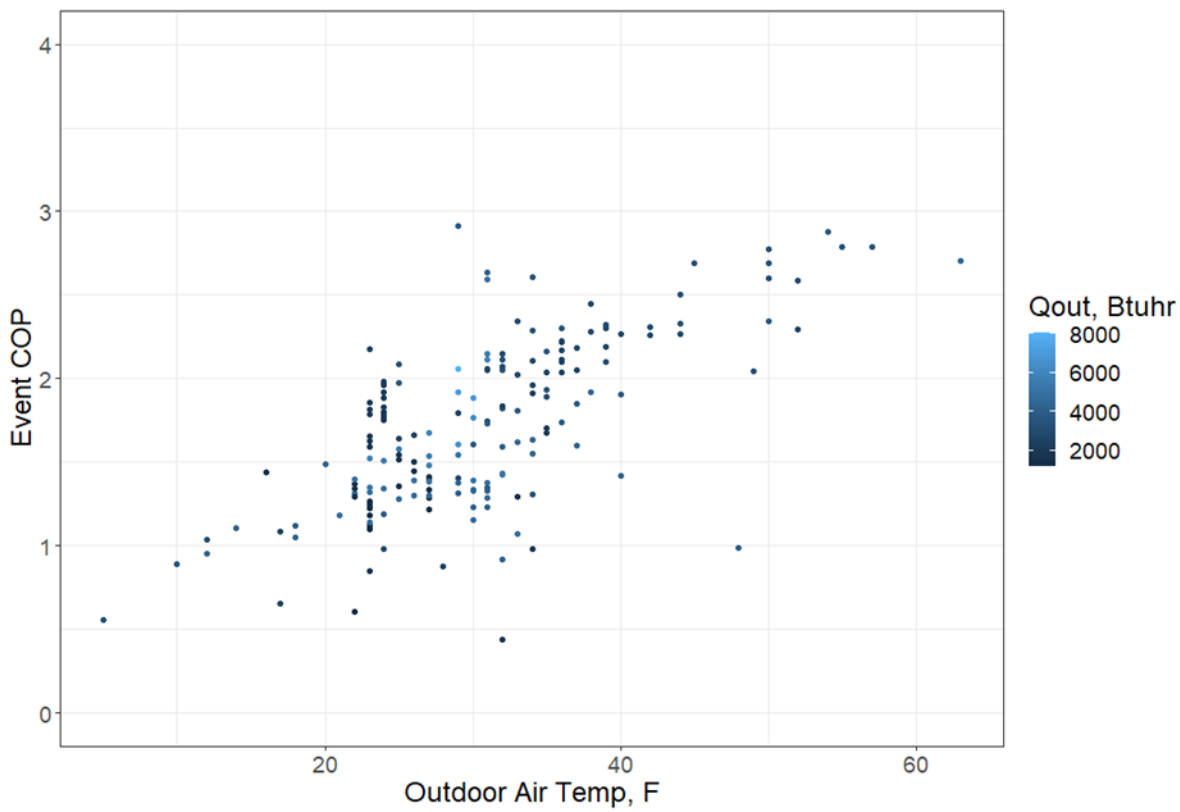

Figure 18. COP of heating cycles for the PTHP system install at MF_60

The PTHP unit had a rated capacity of 8,100 Btu/hr. with a range from 3,000 to 10,000 btu/hr. The system typically operated in the lower end of that range, with an average cycle delivered capacity of 3,800 Btu/hr. At 17°F the PTHP systems was rated to deliver between 3,000 and 5,200 Btu/hr. In the field, the system delivered between 2,500 and 4,500 Btu/hr. (Figure 19). Real-world dynamic conditions often cause field system performance to be lower than rated performance. The actual delivered system capacity indicated that the system was operating well and meeting expectations in the field.

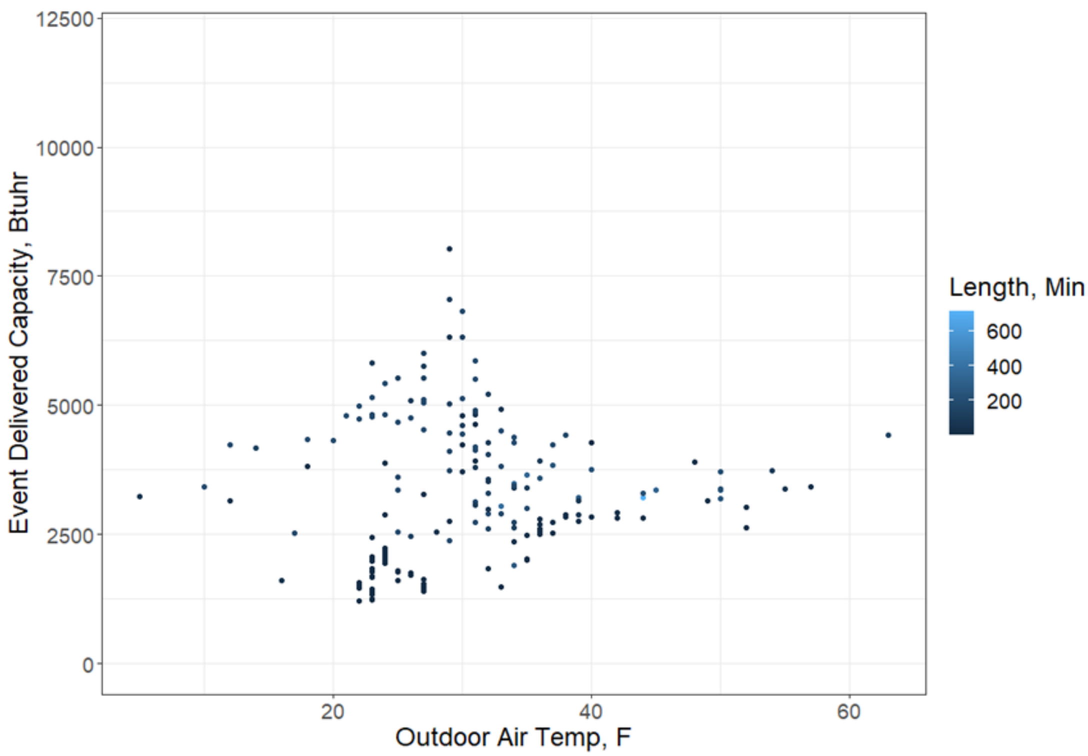

Figure 19. Delivered capacity of the PTHP unit

The PTHP delivered just over half the heat needed by the unit in the monitored period. 50.6% of the total heat energy delivered came from the heat pump. Figure 20 shows the energy consumption split between the two systems (heat pump and electric resistance) for each day in the monitoring period.

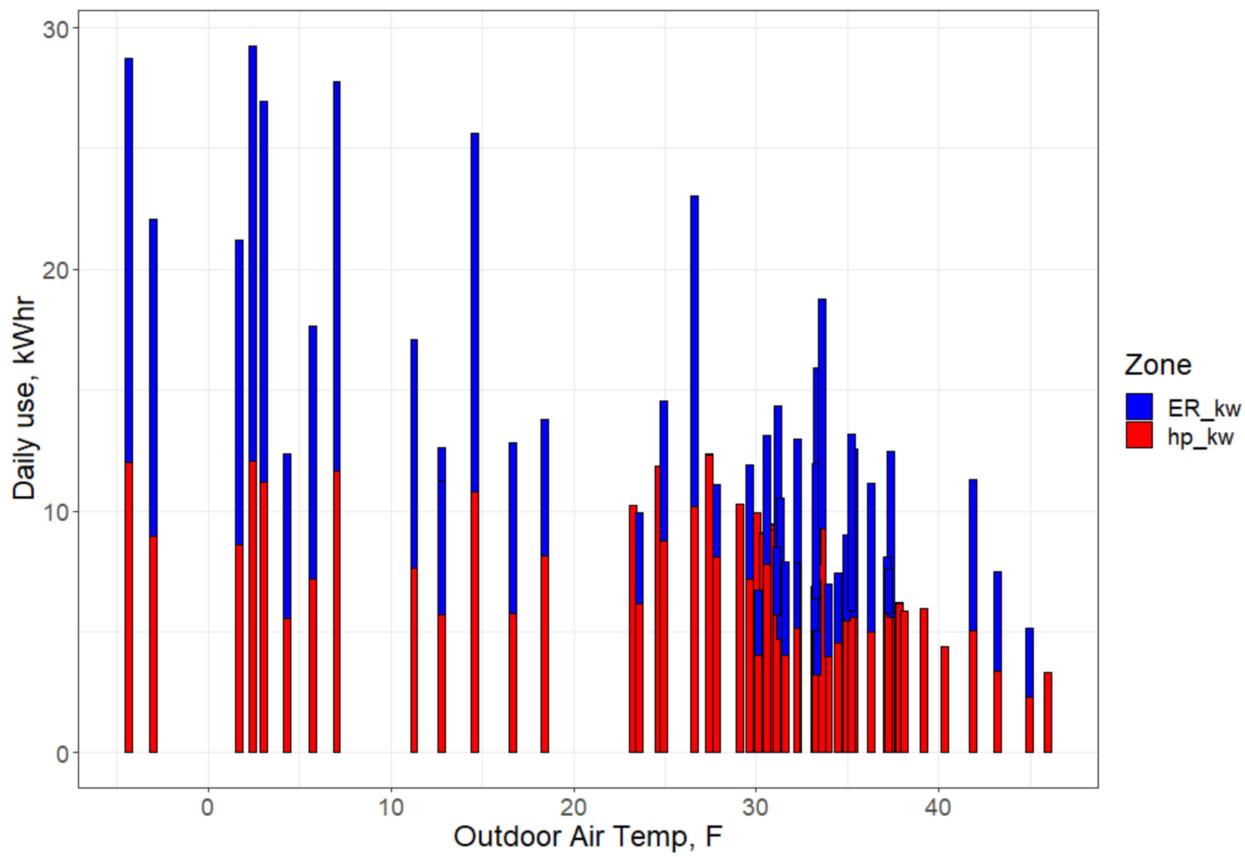

Figure 20. Energy used for heating at MF_60 in the unit with the PTHP

Heat Pump Performance by Building

The ductless heat pumps installed and monitored in this research had annual COPs greater than 2.0. These systems reduced the energy use between 51% to 56% for the heating load that they could displace. ASHP displacement was overwhelmingly beneficial for improvements in energy use and operating costs in all cases. Table 7 shows the average ASHP COP measured at each building. However, the fraction of the load met varies based on the building characteristics and heat pump design. Particularly in electrically heated buildings, ASHP runtime and load displacement should be prioritized due to the overwhelming increase in efficiency compared to baseline systems.

The PTHP system installed in MF_60 had a slightly lower annual heating COP than the ductless systems. This lower COP matched expectations due to the slightly earlier generation heat pump being used in these new to the market heat pump types. As this market and application mature, it is expected the heat pump performance will improve to match that of the ductless systems measured.

Table 7. Summary of annual heating performance of heat pumps installed in each building

Building	Units	Avg heating COP	Fraction on heating load met by ASHP
MF_01	6 – 1to1	2.25	48%
MF_07	4 – 1to1	2.05	86%
MF_61	6 – 1to1 & 2to1	2.12	60%
MF_60	1 – PTHP	1.69	51%

Surveys and Customer Feedback

The project team attempted to conduct three rounds of surveys, the first after completing the baseline, a second after heat pump installation, and a third at the end of the project. Due to COVID19 which extended length of monitoring because of delayed heat pump installation and higher than expected occupant turnover in some units and buildings, these surveys were not able to be collected at all sites. For example, due to the mission and occupancy types at the affordable housing property, MF_61, the project team was not in direct communication with the occupants in each unit. The building operators coordinated access for the necessary field work and communications with the site. These arrangements made conducting surveys impractical. Due to the limited number of sizes and the lack of complete responses, these surveys should not be taken as representative of ASHP installations but may provide some anecdotal feedback. Interesting and illustrative comments include the following.

Surveys were sent to tenants at three of the four properties. Some survey responses collected from each building about tenant experiences before and after heat pump installation, but the project team was unable to gather completed pre and post surveys from the same tenants in any of the units monitored except the tenant in MF_60 where the PTHP was installed. Both MF_01 tenants completed surveys about their heat pump performance. Four of the six tenants completed baseline system surveys at site MF_07, but three of the tenants moved out before the post installation survey could be completed. The remaining tenants did not complete the formal survey for the post installation period.

Highlighted trends and responses from the heat pump systems:

- Occupants noted that heat pumps had long runtimes during cold outdoor air temperatures.
- Several occupants responded that the heat pump had a noticeable noise when operating, but that it was quiet, not loud.
- Occupants who responded indicated acceptance and maintained comfort with the heat pump.

- Two occupants who were not living in the apartment when heat pumps were installed mentioned lack of familiarity with the controls and indicated they did not receive instructions on how to use the heat pumps.

Discussion of Results

Statewide Impact Estimates

The statewide average multifamily space heating energy use was assumed to be 4,600 kWh per unit per year. This assumption is supported by the 4,576 kWh per unit per year average space heating use per unit in Seventhwave's CARD funded Minnesota multifamily characterization study (Scott Pigg et al. 2013). Additionally, the 2018 Minnesota potential study (Nelson et al. 2018) calculated that there are 201,000 electrically heating multifamily units in Minnesota and these units use 946,700 MWh per year. That is an average of 4,709 kWh per unit per year. This project found electrical heat use that ranged between 5,673 to 10,688 kW-hrs per year, which was higher than the statewide average. Table 8 shows the reductions in heating energy use that can be expected, based on the baseline heating energy used prior to heat pump installation and the savings percentage for the heat pump.

Table 8. Statewide savings estimates for ASHP installations in MF buildings

		Heating Energy Reduction from HP installation						
		5%	15%	25%	35%	45%	55%	
Annual baseline Heating Energy Use, kWhr	3,500	175	525	875	1,225	1,575	1,925	
	4,600	230	690	1,150	1,610	2,070	2,530	Assumed state wider average
	5,673	284	851	1,418	1,986	2,553	3,120	Lowest load unit in this project
	7,500	375	1,125	1,875	2,625	3,375	4,125	
	10,688	534	1,603	2,672	3,741	4,810	5,878	Largest load unit in this project

The site selection and screening process for this project considered 27 buildings for installation. All these buildings were primarily heated with electricity. A more detailed characterization of the electrically heated building stock is needed to draw detailed conclusions, but less than 10% of the buildings were screened out due to lack of ASHP options. Some buildings were expected to have higher costs associated with HP installs than others and 7% of the buildings screened had heat pump options that were out of scope for this work (water source HPs and centrally ducted ASHPs). However, the screening process indicated that there was a viable ASHP option for around 90% of electrically heated units.

Installation Best Practices

Most installation best practices for single-family applications hold true for installations targeting multifamily buildings. Best practices for load calculations, selecting the heat pump operating parameters, setting up thermostats, outdoor door unit locations selection, and refrigeration charge and system airflow checking all hold true. Appendix B contains the single-family best practices developed for the 2024 CARD project titled, "Optimized Installations of Air Source Heat Pumps for Single Family

Homes." However, a few additional priority areas that impact performance were identified to consider during installations in multifamily buildings.

Sizing and Layout

Load calculations and heat pump sizing best practices developed for single-family applications should be followed for multifamily installations. The Minnesota ASHP collaborative (MN ASHP Collaborative 2024) and Northeast Energy Efficiency Partnerships (NEEP 2020; 2024) have developed good references and tools for sizing and installing ASHP systems. These tools and approaches can be used to implement best practices for single-family and multifamily buildings in Minnesota.

Multifamily units are typically smaller than single-family properties, both in terms of overall square footage of finished area, but also in the size of specific heating zones. Due to the smaller sizes and corresponding smaller loads in multifamily buildings, it is particularly important to consider the minimum capacities for heat pump equipment. Oversizing heat pumps can significantly impact their overall efficiency. Figure 21 shows the impact of cycle length on the COP of the heat pump in a multifamily unit. The transient periods, especially at the start of a heating cycle, have a bigger impact on the overall efficiency of the system for shorter cycles. These transient periods tend to be less efficient than steady-state operation. The figure shows that cycles less than 30 minutes in length are likely to be at a lower COP than cycles longer than 30 minutes at similar outdoor air conditions.

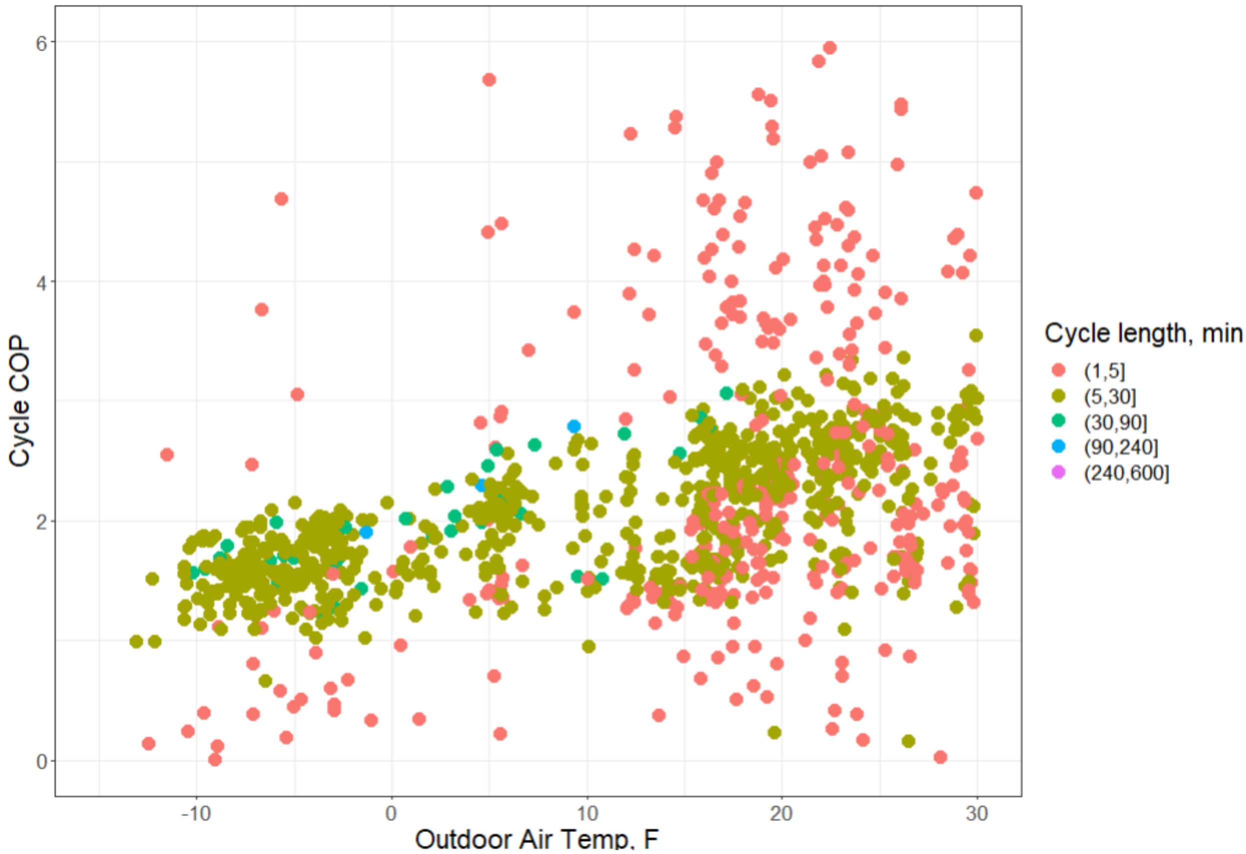

Figure 21. Impact on cycle length on COP at MF_01 Unit 3

Applications

Multifamily buildings have different existing systems and installation criteria than single-family properties. Ductless mini splits of various types were found to be very good applications for multifamily buildings with distributed heat emitters such as electric resistance baseboards and wall heaters or hydronic radiators. However, ductless heat pumps would be less ideal in multifamily buildings with other heating systems, such as MagicPaks or packaged terminal heaters.

It is anticipated that multifamily heat pump applications will continue to evolve. Measurement and verification of installed performance will be needed for new heat pump applications as they are deployed into the marketplace. Further, technical reference manual (TRM) and other savings estimation metrics will need to be updated, and installer best practices will need to be adjusted.

Data from a newly developed PTHP for cold climate applications was used to demonstrate the potential of this new application for MN's multifamily buildings. These systems have much higher efficiencies than traditional PTACs and can deliver savings and comfort in MN.

Conclusions and Recommendations

TRM Recommendations

The Technical Reference Manual (TRM) provides standard methodologies and assumptions for calculating energy savings and cost-effectiveness of efficiency improvement measures used in energy efficiency programs in Minnesota. The TRM has had a measure for residential central air conditioners and air source heat pumps (ASHPs) since version 1.0 of the document. In 2023, version 4.0 of the TRM ("State of Minnesota Technical Reference Manual for Energy Conservation Improvement Programs" 2023) included a significant update to the previous version of the ASHP measure. Version 4.0 split the previous measure into separate measures for air conditioners and ASHPs. The ASHP measure was updated to include adjustments to the assumed heat pump efficiency based on the weather conditions during heat pump operation. The heat pump operation numbers were also updated to align with more recent field-monitored values and heat pump installation considerations, such as if the heat pump was designed for replacement (minimal or no auxiliary heating) or partial replacement (a significant part of the home's heating load is still expected to be met by the existing or auxiliary heating system and not the ASHP).

The recent updates to the TRM methodology for ASHPs are a good estimation for typical heat pump installation and operation. The calculations adjust for the most common reasons that field performances deviated from ratings-based performance, and result in good program-level savings estimates. However, detailed monitoring data on optimized ASHP installations show potential for high levels of savings from high-quality installations.

Several key areas of ASHP system design, installation, and control decisions highlighted in the "Optimized Installations of Air Source Heat Pumps for Single Family Homes" research project can significantly impact the installed performance of an ASHP system. Although there are differences between ASHP applications in single family and multifamily homes, the implications and recommendations for the Minnesota TRM are the same.

ASHP product selection. Heat pumps come in many styles, cost categories, and performance ranges. Heat pump selection greatly affects performance. Variables to consider include the type of system, whether it is a centrally ducted system, ductless one-to-one, or multi-head ductless system, as well as the category of heat pump including single-stage, multi-stage, variable speed, or cold climate. These different categories of heat pump have their own advantages and disadvantages. The capacity and efficiency performance of these systems can vary quite drastically. Ideally, product-specific performance data is available. Recent work by NEEA (Bruce Harley et al., n.d.) demonstrates that even products with similar specifications and ratings can have different performance characteristics when installed and operated in real buildings.

Integration with auxiliary, back-up, or supplemental heat. Despite significant advancements in the cold climate capability of ASHPs most installations in Minnesota require auxiliary or back-up heating to meet the heating load at very cold heating conditions. The fraction of load met by the heat pump can vary widely depending on the installation, design, and operation of the system. Advanced heat pumps in a very small fraction of installations in homes with high-performance envelopes may be able to meet the full load of a home. These installations are rare and current program design should not focus on them. However, they illustrate the wide range of system designs. A dynamic approach to modeling these scenarios or a more detailed look-up table or mode-based methodology will allow for more accurate performance estimates and better differentiate the performance of optimized systems.

Controls and thermostat settings. Similar to integration with other heating systems, how the heat pump is controlled, and which system is favored provide additional opportunities for optimization and enhanced savings. Even energy modeling will struggle to capture the vast array of control options, but some high-level choices can be analyzed for performance impact across a range of installation scenarios. Recommendations include thermostats with simple switchover, multiple point switchovers that allow for simultaneous operation, staged controls, system runtime based on energy cost data or emissions, and third-party controls.

Decisions made in each of these areas are likely to increase (or decrease) energy savings, cost-effectiveness, and emissions from an ASHP system.

The current TRM calculations rely on how heat pumps are installed today and some of the assumptions around typically installed ASHPs. There is a subset of systems being installed today that use higher performance cold climate heat pumps, whose performance is less impacted by cold weather than typical heat pumps. There are systems being installed with advanced controls that increase the fraction of heating load met by the heat pump by eliminating unnecessary back-up heating. These are a couple of examples of heat pump installations that will deliver more energy savings and emissions reductions than typical installations. Current TRM methods may not capture all those additional savings.

The recent field research project did not have enough test sites to sufficiently cover the range of variables and characteristics needed to recommend savings calculations and input assumptions for the wide range of installation and design choices that can be made. The work did indicate the potential for achieving these savings. Field measurement and verification for the number of sites needed is cost prohibitive. However, energy modeling offers a good solution.

Building energy modeling is a good option for the TRM to incorporate additional savings from high-performance ASHPs. Existing off-the-shelf modeling tools are not currently capable of modeling all the scenarios and cases needed for full dynamic savings calculations. However, there are several efforts underway to create tools capable of quantifying these savings, such as NREL's ResStock Tool (NREL 2024) and NEEA's Advanced Heat Pump initiative (NEEA 2024). The TRM could either allow savings calculations from an accepted tool or program or conduct an analysis with an energy model to develop an updated version of the calculations and spreadsheets to be used for a future version of the Residential ASHP measure.

Enhanced solutions with energy models should consider:

- The forced air distribution system including location of heat pump heads for ductless and ductwork for central systems and the relative sizing of each zone, heat pump, and auxiliary heat system.

- The performance characteristics of the specific heat pump or the heat pump class if specific data is unavailable.
- Any controls that integrate heat pumps and supplemental, auxiliary, or back-up heating systems, including thermostat controls, on-board heat pump controls, and any third-party sensors used.

Utility Recommendations

Heat pump applications for multifamily buildings have advanced considerably in the past five years. Like other heat pump applications, the advancement of variable speed compressors has unlocked additional potential for heat pumps in cold climates. These advancements have benefited installations in multifamily buildings. But additional opportunities are available for multifamily building specific installations.

Design and installation considerations remain the biggest barrier for having ASHPs meet their expected or potential performance in multifamily buildings. All heat pump installations need to consider:

- The whole unit heating load, but also the loads of the specific zone or area where the indoor head of distribution will deliver conditioning.
- Currently, cold climate ASHPs for multifamily building applications require some auxiliary or back-up heating source. For retrofit installations, it is cost-effective to use the existing heating source for supplemental heat. In multifamily buildings, these systems are typically independent of one another. Understanding occupant use and behavior and how to prioritize the heat pump, weather through controls or system design was key to heat pump utilization.

Future Research and Development Needs

Continued field research and validation work is needed as ASHP technologies, applications, and controls continue to evolve. This project (and past research) has shown that installed performance of ASHP systems is dependent not only one the equipment specifications, but also on the design and installation of the system. As ASHP performance continues to advance field research and verification is needed both for the system performance itself, but also to continue to optimize installation and design criteria.

- Over the course of this research project the DOE ASHP challenge (DOE 2022) has challenged manufacturers to develop systems that can maintain higher delivered heat capacities at temperatures down to -5 °F.
- This project collected installed performance data on multihead systems with two indoor heads. This type of application continues to expand with more indoor heads (3 to 1) and other indoor unit types, like ducted mini-splits systems and multihead systems that combined ducted air handlers and mini-split style indoor heads (Mitsubishi Electric HVAC 2024).
- PTHPs and variable speed window mounted heat pumps were additional applications that saw significant development over the course of the project. These units have large potential in multifamily buildings and condominiums through direct replacement of older equipment that was previously without alternatives or to be accessible for existing units where installation of

other heat pump types was difficult. This technology had the ability to raise the heating efficiency by 1.5 to double the efficiency current systems.

When these and other innovative applications become available, research will be needed to verify those capacities in real world conditions and to update design guidance around design, sizing, backup system integration and operation.

Due to the wide range of heat pump application types and design considerations, heat pump models and engineering calculations are needed to truly evaluate the savings and environmental potential of all the options. Energy models need good baseline on performance and operation to increase the accuracy of their analysis. Field evaluations should be designed to support inclusion of these new technologies, applications, controls and innovations into modeling efforts through the development of performance maps and characterization of controls and sequencing.

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Appendix A: Participant Surveys

Contact Information

Name:

Phone/Email:

Preferred method of contact: Phone Email

Today's Date:

Please consider your heat pump system and answer the following questions

Winter Questions

1. In general, how well do you think your heat pump heats your home in the winter? (1=very poor, 10=excellent)

   1 2 3 4 5 6 7 8 9 10

2. On particularly cold days, are there regions in your home that feel colder than others? If so, where?

3. In general, are you comfortable in your home during the peak of winter when it is particularly cold?

   (1=not comfortable, 10=extremely comfortable)

1 2 3 4 5 6 7 8 9 10

4. How frequently does your heat pump turn on in one day? How long does it stay on?

5. When the heat is on, do you feel the air is warmer in the space?

6. How do you feel about the noise of your heat pump?

7. How would you rank the noise level of your current system?

   (1=loud, 10=do not notice)

-
- 1 2 3 4 5 6 7 8 9 10

Thermostat Questions

1. Thermostat settings **Please note that some questions may not be applicable to your thermostat, and you can just indicate "NA"**

   a. Do you have "at home" or "away" settings on your thermostat you utilize?

Yes No NA

b. What temperature do you set your thermostat at when you are home?

c. When you're away?

d. Do you set the temperature to a different setting at night than you do during the day?

Technology and Utility Questions

1. Do you think your heat pump has improve your home's comfortability?

   Yes No

2. Comfort comments
   a. If yes, please describe in what ways do you feel more comfortable?

   b. If no, please describe how the heat pump has not met your expectations?

c. Any other comments about the comfort of your home?

3. Do you think you spend a reasonable amount of money on utility bills?
- (1=not reasonable/expensive, 10=reasonable/fair price)
-
- 1 2 3 4 5 6 7 8 9 10

FOR MINI-SPLITS ONLY

1. Did you find your mini-split controller easy to operate?

   (1 = difficult to understand, 10 = easy to operate)

- 1 2 3 4 5 6 7 8 9 10

2. Did your heat pump contractor show you how to use your heat pump controller?

   Yes No

3. Some mini-split controllers have multiple control options. Which, if any, of the following settings do you use? (Please note this is a sample of options that may be available, but may not be applicable to your system)

MODE	FAN	STOP
ECO MODE	VANE/SWING	START
SMART SET	SLEEP	TURBO

Summer Questions

Please consider your heat pump in cooling mode and answer the following questions.

NA (Please circle if you do not have a system that provides cooling to your home in the summer)

1. In general, how well do you think your current system cools your home in the summer?

   (1=very poor, 10=excellent)

   1 2 3 4 5 6 7 8 9 10

2. On particularly hot days, are there regions in your home that feel hotter than others? If so, where?

3. In general, are you comfortable in your home during the peak of summer when it is particularly hot?

- (1=not comfortable, 10=extremely comfortable)
-
- 1 2 3 4 5 6 7 8 9 10

4. How frequently does your system turn on in one day? How long does it stay on?

5. When the heat pump is on, does the air feel cooler in the space?

6. How do you feel about the noise of your heat pump?

7. How would you rank the noise level of your heat pump?

   (1=loud, 10=do not notice)

-
- 1 2 3 4 5 6 7 8 9 10

Please use the space below if there are any additional comments you wish for the staff to know about your heat pump

Appendix B: System Performance Maps

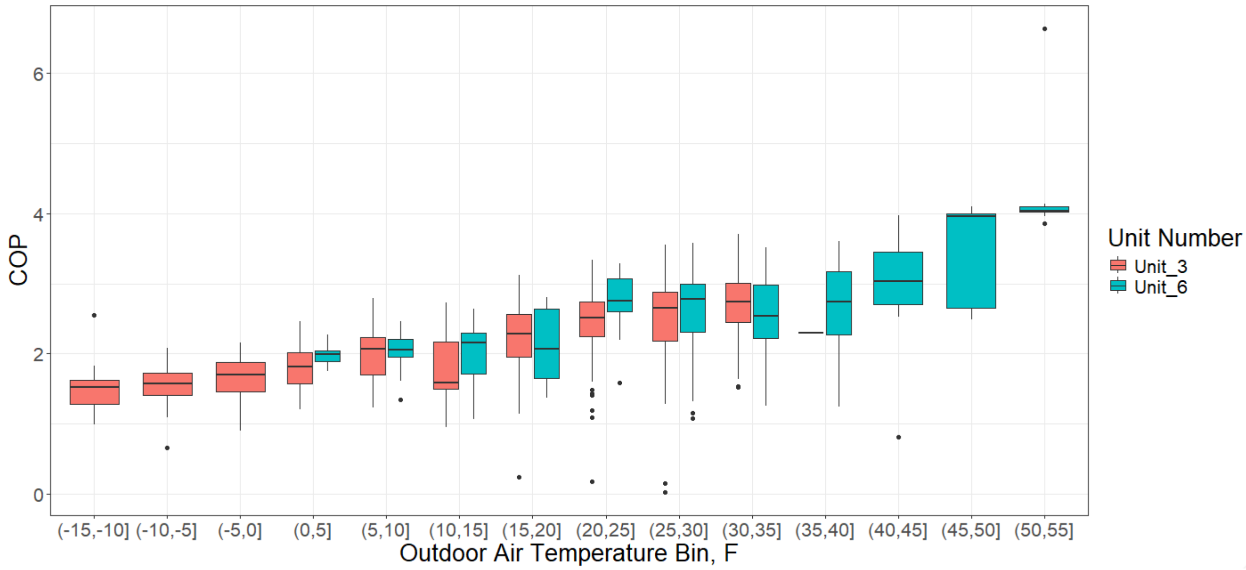

Figure 22. Measured COP of mini-spilt heat pumps installed at MF_1

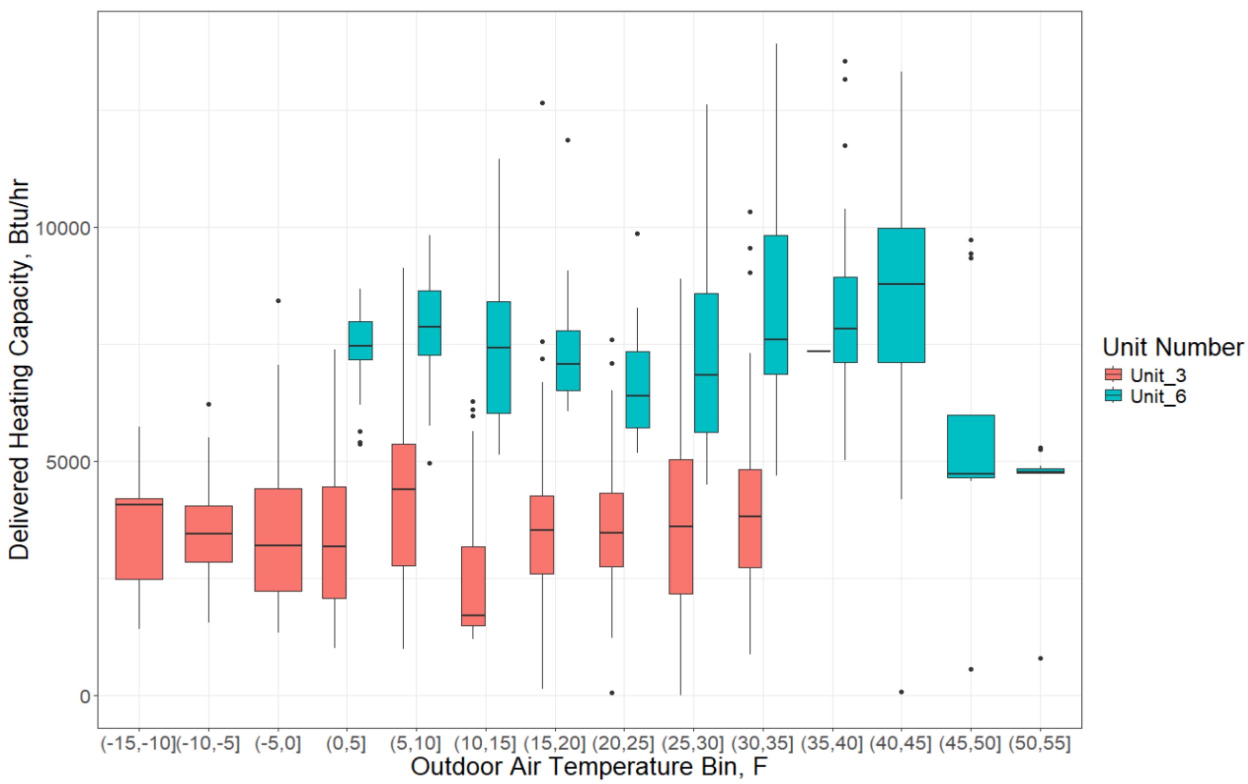

Figure 23. Delivered Heating Capacity of the heat pumps installed at MF_1

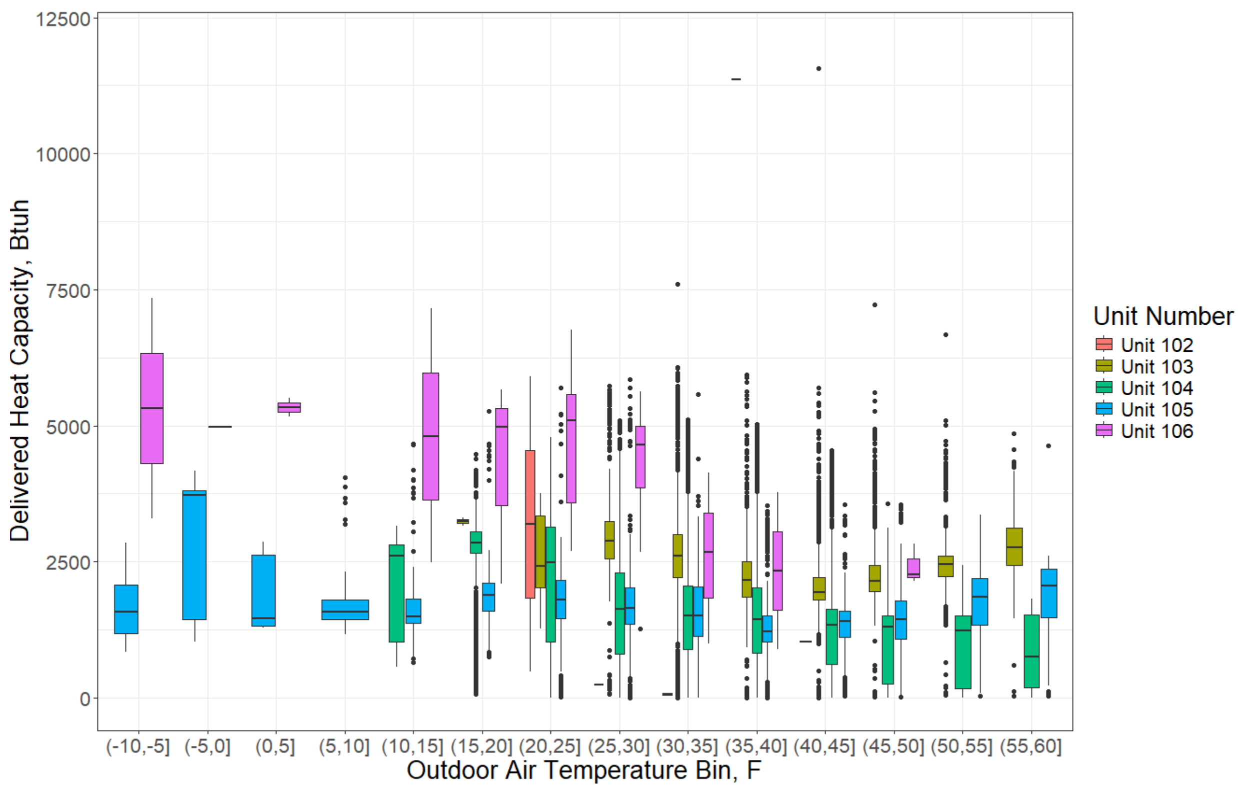

Figure 24. Delivered capacity of the mini-splits at MF_7

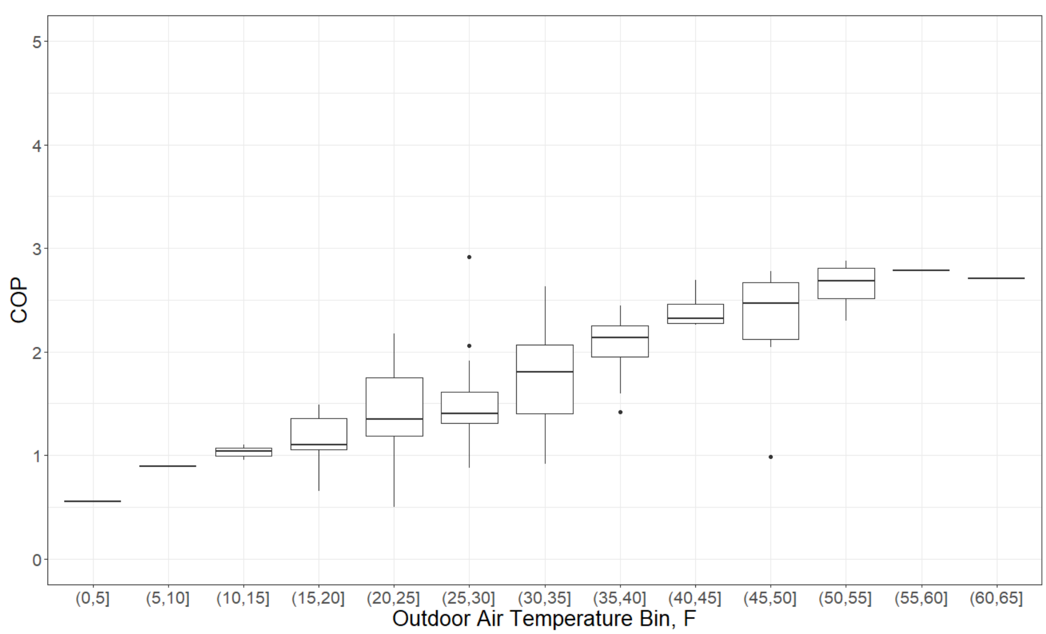

Figure 25. COP of PTHP installed at MF_60

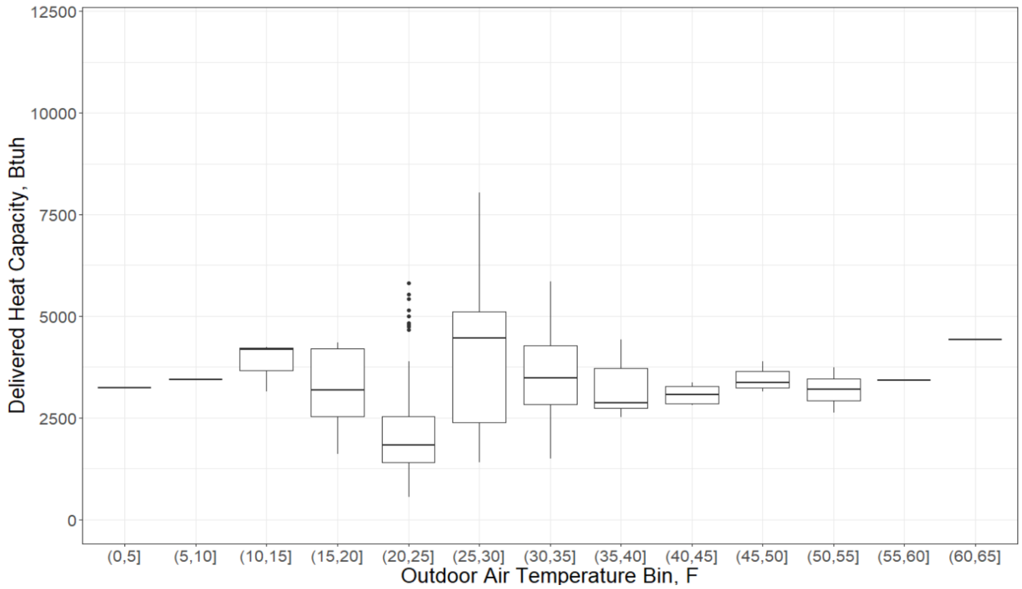

Figure 26. Delivered capacity of the PTHP at MF_60

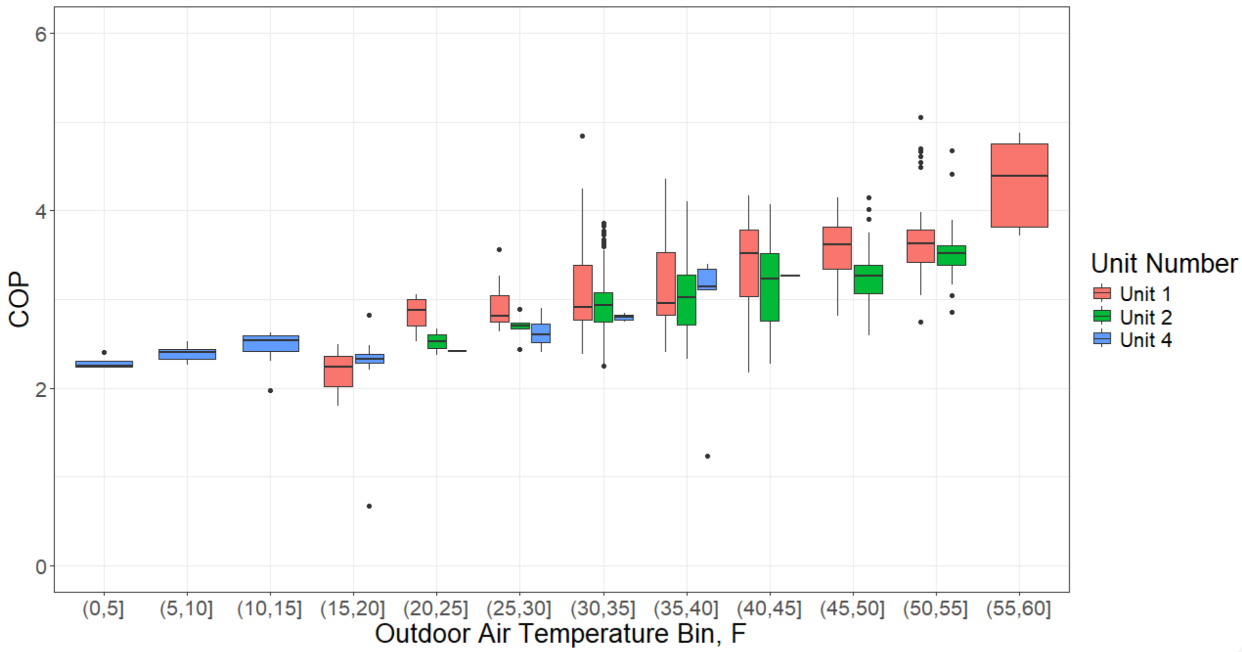

Figure 27. COP of the mini-splits installed at MF_61

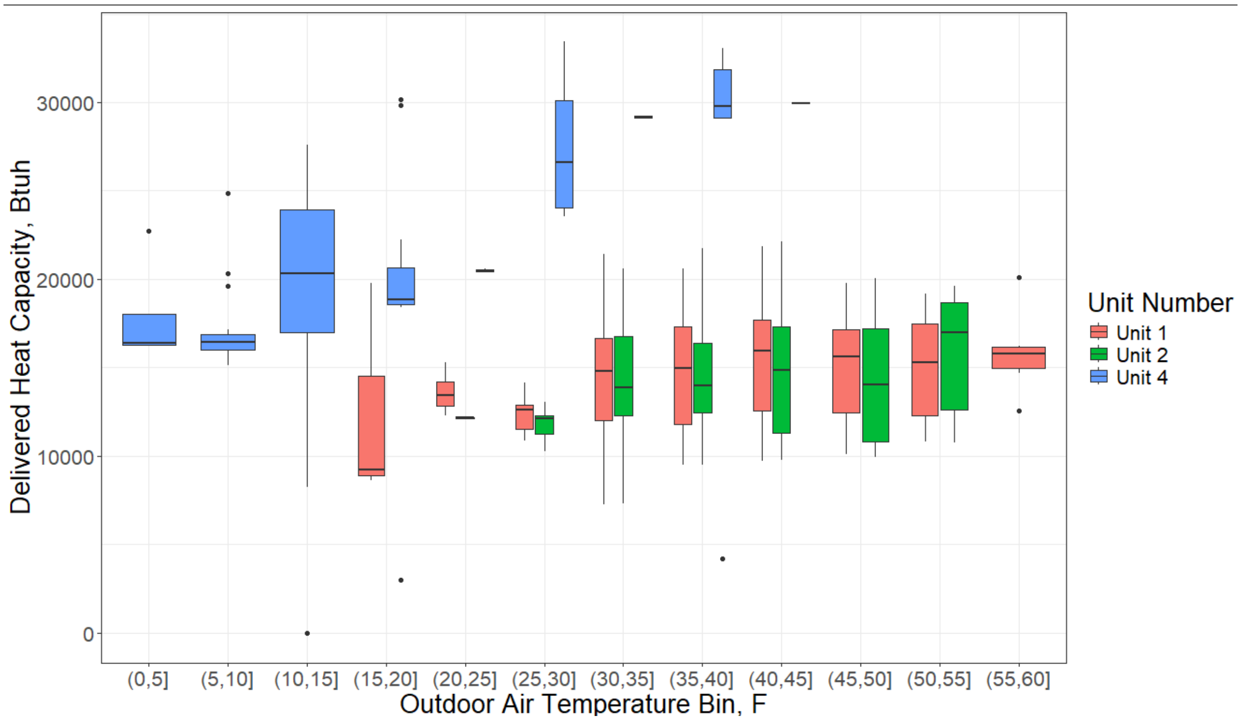

Figure 28. Delivered Capacity of the heat pumps installed at MF_6

Appendix C: Installation Best Practices

The following section was developed for the 2024 CARD report, "Optimized Installations of Air Source Heat Pumps for Single Family Homes." These best practice approaches and ideas should also be applied to multifamily buildings. The results from this research project in multifamily buildings found some additions specifically for multifamily buildings. Those items are included in the Results section of the report.

System Design and Equipment Specifications

The heat pump design is as important or more important than the actual selection and installation of the heat pump itself. There are many choices that go into heat pump design.

Determining whether it will function as a primary system with existing heating (displacement) or will be the sole heating source (replacement system) should be a top consideration. In cold climates like Minnesota, a heat pump cannot be the sole source of heat because of the subfreezing temperatures during the winter. Current generations of cold climate heat pumps have diminishing capacity at very cold temperatures, limiting their ability to meet the heating loads on most residential homes without backup; however, it is still important to consider if the heat pump can provide *most* of the heating as a replacement option. Additionally, determining whether a heat pump can provide whole-home or only zoned heating is important. Depending on how large the heating load is, it is not always an efficient or cost-effective option to have a heat pump provide the whole heating load. Finally, both considerations depend on whether the system will be ducted or ductless, which will be discussed later in this document, but an overview of these items as they relate to equipment specifications will be reviewed here.

When choosing an optimal heat pump for a home, the decision process should involve reviewing the layout of a home and considering the main living areas. Questions that should be answered are:

- What areas in the home require heating? Therefore, is whole-home or only zone heating required?
- How much heat is required? Therefore, what would be the appropriate size of the system to heat the space efficiently?
- Will there need to be a ducted or ductless system? Are there cost effectiveness considerations depending on the heating need?
- What are the main living spaces in the home? And do all spaces need to be heated by the heat pump?

Each of these questions may have issues associated with them. For example, when considering to install a ductless mini-split system in a compartmentalized home with no ductwork, for the heat pump to provide whole-home heating, several indoor heads and condensing units may be necessary; however, every room in a house may not need to be heated using a heat pump primarily, such as a guest bedroom. This application scenario addresses some of the most common issues when choosing the appropriate system. The initial issue is whether to have whole-home or zoned heating. Another is determining what would be the appropriate size of the system to heat the space efficiently. A common issue the team found was that many contractors in these cases would bid for mini-split systems that had indoor heads in every room in a home or defaulted to oversizing to meet the heating load; however, installing heat pumps in this manner is not cost-effective, especially if every room in a home is not used regularly. In contrast, if every room is used daily and the home does require many indoor heads, a cost-effective option could be installing ductwork for a ducted system instead of a mini-split system. Though having high-efficiency systems is the goal, it sometimes is necessary to consider cost-effectiveness equally.

In summary, the key components of choosing the appropriate equipment to install in a home are:

1. the home's heating load,
2. the type of heating configuration (displacement vs. replacement OR whole home vs. zoned),
3. the home's layout,
4. if installing a heat pump in a cold climate, the equipment specifications must demonstrate the ability to perform efficiently in sub-zero temperatures, and it is recommended to ensure the heat pump is featured on the NEEP cold climate ASHP catalog,
5. last in some cases, it is important to choose cost-effectiveness for a system over efficiency depending on a home's heating and structural configurations

The next section will discuss specific applications in detail and how to determine the best solution for a home.

Goals and Operating Principles

The flexibility of an ASHP system allows it to deliver many benefits to a homeowner, utility provider, and/or installer. A well-designed system needs to be balanced and optimized to meet the priorities of all parties.

- Homeowner operating costs, ease of installation, and first costs
- Utility load and peak demand impact
- Public benefits: emissions and environmental concerns

Type of Heat Pump Applications

This section will provide guidance on ductless (mini-split) and ducted heat pump applications as well as backup heat integration and control options.

Mini-Split Systems

As the name suggests, ductless heat pumps are systems that do not require ductwork to be installed. These systems are often called mini-split or multi-split systems. In simplistic applications, they consist of one outdoor condensing unit and one indoor unit. More complex systems can have multiple condensing units with numerous indoor units, and in some cases can be integrated with existing systems. Indoor units also come in a variety of models: wall-mounted heads, floor-mounted units, recessed ceiling/floor units, and even mini-duct systems. Mini-split systems are ideal in residential applications where the building does not have existing ductwork, with smaller square footage, in multifamily units, with zoned heating, and where first costs of the installation are a barrier.

Since mini-split systems have an indoor unit used to provide heat to the space, it is important that the location is somewhere that will allow airflow and even heat distribution throughout a larger space. For example, homes with open floor plans are ideal for mini-splits because airflow does not get disrupted by partition walls, allowing the whole space to be heated. Though open floor plans work best, you can still apply multiple indoor units wherever you need to heat. Living spaces and bedrooms are ideal for indoor heads because they are the occupied regularly. Mini-splits are often desirable for providing heat in the primary living spaces while also meeting most of the heating load.

Much like in the guidance for choosing the appropriate equipment type, determining the desired outcome of the heat pump will have different recommendations. Mini-splits can help displace heat or provide zoned heating throughout a space without replacing the existing system. In some homes, they can provide whole-home heating. In cold climates, it is recommended to keep the existing heating system in both cases, provided it is still functional.

If applicable, allowing a mini-split system to meet most but not all the heating load in the main living spaces tends to be the most cost-effective and efficient solution because it allows for the efficient system to run in the main areas of a home at a lower energy cost while allowing the backup heat to only kick on when the heat pump no longer can meet the load. Since mini-split systems can have numerous indoor heads and condensing units are costly systems to install, it usually is best to minimize the number of indoor units while ensuring the main living areas are heated. Additionally, the team found that multi-head systems decrease their efficiency when more than one indoor unit is on at a time. Locations such as living areas, bedrooms, and offices are ideal for indoor units to provide heating to the space without removing the existing heating system, though displacing heat from the existing heat system. In this application, a heat pump can provide heat to the primary areas of the home and an existing system will only turn on either when the heat pump no longer can meet the load or additional heat is needed in rooms without indoor units. This is the most common use of mini-split systems and provides the best results, especially when the heat pump is integrated with the backup heat. It is not recommended to install an indoor head in all spaces in the home if they are not occupied frequently because the installation cost will be high while the payoff will be low to none.

One complication with mini-splits is the difficulty to integrate them with a backup system. Since heat pumps cannot meet the load at extremely cold temperatures, it is essential that backup heat remains in the home. Manipulating the balance points and setting lockout temperatures for backup heat will ensure that your heat pump will run independently to what its capacity allows. We recommend the use of a smart thermostat or controller that allows a simple user interface to change different set points on the heat pump and the backup heat; however, this can still be achieved manually. Set the heat pump at the desired temperature in the home and set the backup heating source at least two degrees lower. This will allow the heat pump to heat the home to its lowest temperatures and ensures the backup will only come on when the load is not being met.

Centrally Ducted Systems

Centrally ducted heat pumps are less invasive than mini-split systems because they can be integrated with existing ductwork in a home. Centrally ducted heat pumps are compatible with an array of existing systems, making them practical in many types of applications. They can be integrated with dual fuel systems, gas, or propane furnaces, or they can provide most of the heating load with the addition of an electric resistance booster for extremely cold days. In addition to heating capabilities, many central systems are available with compatibility with existing air handing units and AC units. This also makes integrating a central thermostat or other control options more simplistic. We recommend that the central systems are cross referenced using the NEEP list and integrated control options are utilized.

Centrally ducted systems are usually integrated with the existing heating systems through a central thermostat. Adjusting the setpoints of the two systems is ideal for these types of heat pumps because both heat pump and auxiliary heat are connected through a communicating thermostat. We recommend setting the setpoint for the heat pump to as low a temperature as is rated for the equipment and adjust the auxiliary heat setpoint to not turn on until that setpoint. This will allow the heat pump to run if it is able prior to the auxiliary heat kicking on.

Installation Type

- New installation
- Replacement of existing equipment
- Displacement of existing equipment
    - Dual fuel
    - AC replacement
    - Non-centralized systems

Sizing the Heat Pump

Sizing the appropriate equipment for a home is the most important step in gaining the benefits of cold climate ASHP efficiency. Traditional HVAC sizing practices calculate the home’s heating and cooling load at the design conditions, the worst-case heating and cooling temperatures the home and system are likely to face in a typical year. Properly sizing a heat pump must consider many factors, such as the house’s existing heating and cooling system, the heating load of the building, whether the installation is to provide heating displacement or replacement, and whether it is a whole-home or zoned application. The major result from this work is that there are also performance and energy benefits from additional sizing calculations.

Calculating the heating and cooling loads for a specific zone (e.g., living room or bedroom) load is key for appropriately sizing indoor heads of ductless heat pump systems.

A full house load curve, where the heating and cooling loads are calculated over a range outdoor condition, should also be completed. That house load curve can be matched with the heat pump delivered capacity specifications and the heat pumps designed operation to ensure the system is design to meet the load under the conditions needed to meet the homeowner expectations.

The Minnesota ASHP collaborative (MN ASHP Collaborative 2024) and Northeast Energy Efficiency Partnerships (NEEP 2020; 2024) have all developed good references and tools for sizing and installing ASHP systems. These tools and approaches can be used to implement the practices learned in this work.

Load Calculations

The sizing of the heat pump in cold climates is dependent on the home's heating load, and in some cases, cold climate ASHPs can be integrated with the home's existing heating system that allows it to have more success heating homes efficiently on extremely cold days. Where possible it is preferable to use directly measured data from the home to appropriately size the system either by use of utility bills or logged system performance. This is the best method for accurate sizing, but if real data is unavailable, using Manual J or other sizing manuals is recommended. Using calculations that require energy output per square foot can be done. This method is not recommended for accurate sizing and should only be used if no other option is available.

For field research, CEE collected data using energy monitoring equipment. With collected data and analysis on historic utility bills, a load curve was calculated based on the outdoor air temperature. The heat pump's capacity curves should be compared to the home's heating load to get the best fit (Figure 29). Variable capacity systems allow for systems to be large enough to meet heating loads at colder temperatures, while ramping down to lower capacities and meeting the heating loads in shoulder systems as well as the cooling needs in the summer. A system should never be largely oversized to heat a home, however, as that can lead to short cycling and poor performance in moderate conditions. It is usually more efficient to run a backup system in conjunction with the heat pump at very cold temperatures.

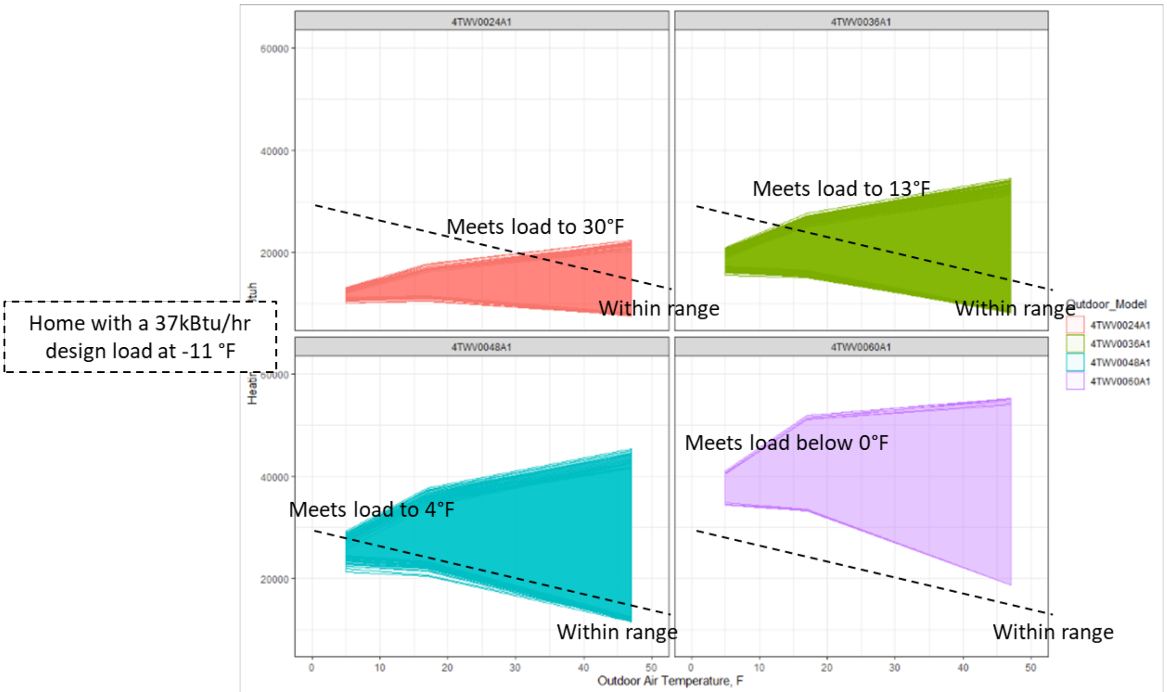

Figure 29. Comparison of the capacity of multiple size heat pumps to a house load curve

Control and Operation

Switch over temperature controls are the most common types of central heat pump controls. If this control method is selected, it is important to be sure the heat pump and thermostat can determine the outdoor temperature and making the switchover. *Figure 30* shows the importance of switch over temperature selection of the fraction of the heating load that an ASHP can meet. The shape of the curve means that it is important to have a heat pump system capable of meeting the load down to around 10F where the curve is steep and small adjustments colder deliver a lot more heating load. As we approach very cold temperatures the total hours are limited so the impact is smaller. This is one reason why an auxiliary heating source to take over the load in extreme conditions is a good practice in MN.

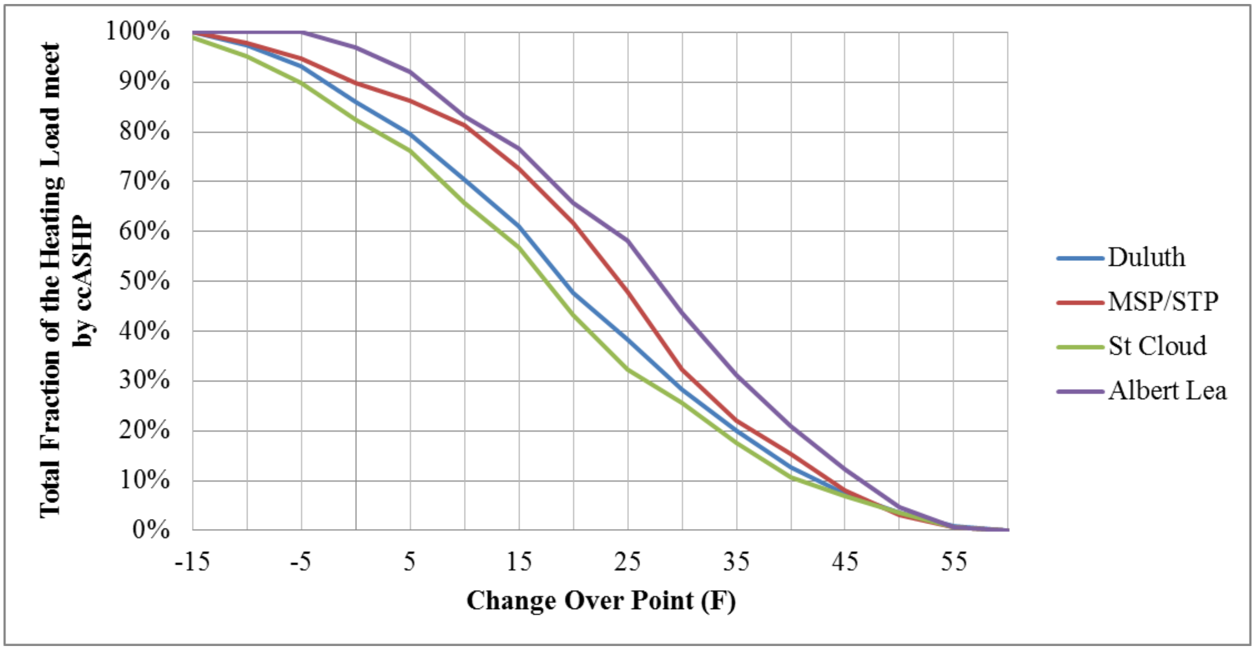

Figure 30. Switch over point impact on heating pump heating fraction

Integrated controls and advanced thermostat settings

Using integrated control options either by using smart thermostats or controllers is one of best ways to achieve efficiency potentials with cold climate ASHPs. Integrated controls not only allow for simplistic operational use for the homeowner, they also allow for significant energy efficiency outcomes. There are a few ways to integrate the backup systems with the heat pump whether it is ductless or ducted; however, integrating a backup system with a ductless heat pump can prove challenging in some applications due to the technology being underdeveloped at this time. In general, ductless systems are not integrated with the backup heat for this reason, but methods for optimization are still present.

There are two types of control options available: smart or central thermostats and smart controllers. Smart thermostats generally are wall mounted and are more familiar to individuals as they resemble traditional thermostats. They are easier to integrate existing central systems such as furnaces with ducted heat pumps, though in some cases, can be used with ductless systems as well. Smart and central thermostats allow the user to change balance and setpoints of the two integrated systems (heat pump and auxiliary heat), which helps fully optimize a heat pump's runtimes. Most of them also provide a scheduling feature, which can be as simple as a seven-day heating/cooling schedule or as complex as having at home, away, and even vacation modes. Smart controllers on the other hand, usually are independent controllers that reside somewhere close to a mini-split indoor unit or a central smart thermostat. They act as a bridge between the heat pump's manufactured controller, the auxiliary heat's controller, and the user. Smart controllers provide the same type of benefits as a smart thermostat such as scheduling and changing setpoints, but the main difference is that controllers usually are application based and controlled from an individual's smartphone as opposed to a wall-mounted user interface.

There is an array of smart thermostats available on the market, but many of them can only be installed with centrally ducted systems . Many of the smart thermostats are also limited to the type of backup central system they are installed with, such as furnaces or electric resistance boosters. Though limited in some cases, smart thermostats provide significant energy efficiency potential and savings when applied during a heat pump installation and are recommended whenever applicable. Installing a smart thermostat will allow a user or contractor to easily change the system's setpoints in a way that provides optimal efficiency. The auxiliary heat should always be set about 2°F lower than the heat pump to ensure the heat pump meets most of the load.

Below is a summary of various control options that can be applied based on simple existing heat systems. Further explanation for each type of option and their features can be found in our supplemental Controls Table.

Integrating existing heating systems, specifically electric resistance baseboard heaters, with a ductless heat pump is challenging. The simplest way to optimize the ductless install is to ensure the auxiliary heat is set about 2°F lower than the heat pump, but the use of smart controllers is recommended as it eliminates the need to manually switchover, which usually has higher efficiency outcomes. Smart controllers have simple user interfaces and ways that allow an individual to access all their controls via smartphone on an application. They can be integrated with existing systems including electric baseboard heaters; however, the technology is still new and limited when integrating ductless systems to existing systems.

Table 9 lists thermostat and control options available in today's market that can be integrated with either ducted or ductless heat pumps and existing systems.

Table 9. Control options

Thermostat Controller	Heat Pump Application	Existing System Compatibility	Notes
Mysa Smart Thermostat	Ductless	Electric resistance baseboard In-floor electric resistance	Central thermostat and app interface
Z-wave thermostats	Ductless	Electric resistance baseboard	Can be integrated with smart controllers

Honeywell REDLink thermostat	Ductless Ducted	Furnaces Boilers Electric resistance baseboard	
Google Flair Puck controller Google Flair Puck Pro controller	Ductless Ducted	Boiler Furnace	In some cases, can be integrated with electric resistance baseboard
Mitsubishi Kumo Station controller	Ductless Ducted	Boiler Furnace	Only compatible with Mitsubishi systems
Tado controller	Ductless	Boiler	
Google Nest thermostat	Ducted	Furnace	
Ecobee controller	Ductless Ducted	Furnace	
Cielo Breeze controller	Ductless Ducted	Furnace	
Sensibo Air controller	Ductless Ducted	Furnace	In some cases, can be integrated with electric resistance baseboard