Optimized Installations of Air Source Heat Pumps for Single Family Homes

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Executive Summary

Introduction

It is anticipated that installation of air source heat pumps (ASHPs) will increase in coming years. 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. This will be an essential component in meeting Minnesota's energy conservation goal. In recent years, national and local interest in ASHPs has increased significantly. Federal legislation has been passed with a focus on residential decarbonization via tax credits and rebates for ASHP systems. Locally, many Minnesota electric utilities have modified their existing heat pump programs, conducted cold climate ASHP pilots, and have incentivized ASHP installations. There has been considerable progress to raise awareness and transform the market to increase heat pump installations.

This anticipated increase in ASHP installation 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. Without these types of resources to support changes, this potential large-scale deployment of cold climate ASHPs in Minnesota may not deliver their full potential in Minnesota resulting potential failure for quality installations therefore suboptimal performance from a substantial fraction of the current installations, souring the market and creating additional barriers.

This field study has developed and validated design, installation, and operational principles necessary for cold climate ASHPs to achieve high market acceptance and maximum energy savings in Minnesota, addressing the above issues directly. The results from this project will support the ongoing training, program development, and market transformation work happening in Minnesota.

Methodology

This project provides guidance on questions about ASHP design, installation, and operation and determine which considerations are important for ASHPs to meet the goals and deliver their true benefits to customers, utilities, and the climate. Key considerations for the design and installation of ASHPs are highlighted.

Best Practices Development Process

There is a huge range of ASHP system types, design approaches, and goals for installations. Capturing the best practices of every iteration of a heat pump was impractical within the study. Additionally, each manufacturer and many different code enforcement regions have their own specific requirements. However, there are best practices and areas of design, installation, and operation that have importance across a wide variety of heat pump installations.

An initial list of topics and considerations was created during the market assessment phase of this work. These ideas were gathered from past research, stakeholder interviews, literature review, and consultation with manufacturers and their installation guides. These best practices were not all inclusive or step-by-step instructions but rather guiding principles to be considered and evaluated during the installation process.

Principles or ideas for design and install considerations.

1. The ASHP design (product selection, sizing, and install) should align with the customer's circumstances, needs, and goals for heating displacement and/or replacement.
2. The ASHP should be sized by house and by zone based on measured data or detail load calculation and should consider the conditions under with the heat pump will provide the home's space conditioning and when a backup system will be used.
3. How the ASHP will be controlled must be considered, including integration with other heat sources and how an occupant is likely to interact with their system.

After completion of the installation, monitoring, and analysis of this process, these principles and best practices were reviewed and updated based on the results of the work and the experience of their use in the field.

Selected Sites

A total of seven sites were selected for ASHP installation. These sites were chosen based on how well they met the selection criteria and represented electrically heated homes in Minnesota. Table 1 shows the characteristics of the selected sites. A total of four sites were selected for ductless mini-splits, each with two indoor head and one outdoor unit. An additional three sites were selected for centrally ducted systems, with one site having an ASHP paired with a thermal storage unit.

Table 1. Sites selected for ASHP installation

Site #	Baseline	HP
SF_05	ER Radiant	Ductless 2-to-1
SF_08	Hydronic	Ductless 2-to-1
SF_12	ER Base	Ductless 2-to-1

SF_14	Hydronic	Ductless 2-to-1
SF_18	Forced Air	Central ducted
SF_21	Forced Air	Central ducted
SF_27	Forced Air	Central ducted

Results and Recommendations

Overall the focus of this project was to evaluate and highlight the principles all ASHP installations must address to ensure the systems could deliver on their potential. Utilization of the design and installation principles delivered high efficiency performance from the ASHP systems. The monitored system performance curves, COPs and delivered capacity, were in line with expectations for field data. The median ASHP COP at shoulder heating temperatures (30 to 40F) was over 3.5. The ASHPS were two to three times more efficient than the heating system they replaced.

The study highlighted the impact of good design and installation of the heat pumps. The design practices used in this study ensured that the heat pumps were installed and operated to maximize their performance and offset as much auxiliary heating as cost effective and feasible. The energy savings at the sites depended on what fraction of the total heating load the systems could meet. The amount of heating load offset by the heat pump was determined by the design and installation of the heat pump. This project outlined the principles that must be addressed to optimize the displacement fraction for MN homes.

Figure 1 shows the efficiency of each cycle of a centrally ducted heat pump installed for this study (Site 18). The efficiency or coefficient of performance (COP) of each cycle was strongly depended on the outdoor air temperature. But, the COP was also impacted by conditions impacted by the installation such as the percentage of heating delivered by the auxiliary heat in each cycle and the cycling characteristics of the system.

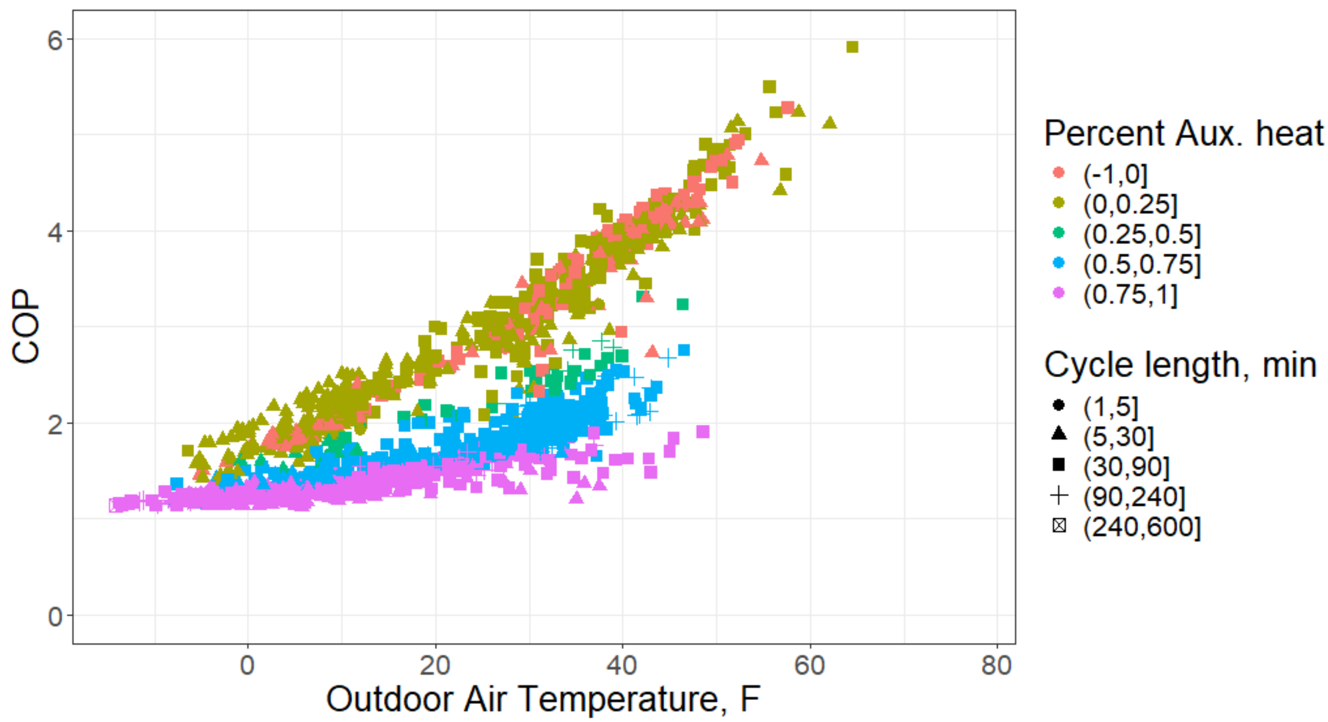


Figure 1. Coefficient of performance of each cycle of a central heat pump installed at Site 18.

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.

Background

Introduction

It is anticipated that installation of ASHPs to increase in coming years. The Minnesota Energy Efficiency Potential Study: 2020–2029 (Nelson et al. 2018) identified cold climate air source heat pumps (ASHPs) as the technology expected to provide approximately 25% of total residential electrical savings in the state in the coming decade. This will be an essential component in meeting Minnesota's energy conservation goal. In recent years, national and local interest in ASHPs has increased significantly. Federal legislation has been passed with a focus on residential decarbonization via tax credits and rebates for ASHP systems. Locally, many Minnesota electric utilities have modified their existing heat pump programs, conducted cold climate ASHP pilots, and have incentivized ASHP installations. Further, the Minnesota ASHP Collaborative was launched to accelerate the transformation of the Minnesota market for residential ASHPS by training contractors on quality installations, developing a qualified contractor list, and increasing awareness among homeowners. There has been considerable progress to raise awareness and transform the market to increase heat pump installations.

This anticipated increase in ASHP installation 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. For example, the Minnesota Technical Resource Manual must provide savings estimates for cold climate ASHP to facilitate accurate accounting in Energy Conservation and Optimization portfolios to encourage program designs that require optimized heating performance. Ongoing improvements have been made to the ASHP TRM measures. However, the ever-increasing complexity 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.

This field study has developed and validated design, installation, and operational principles necessary for cold climate ASHPs to achieve high market acceptance and maximum energy savings in Minnesota, addressing the above issues directly. The results from this project will support the ongoing training, program development, and market transformation work happening in Minnesota.

The focus of this work is Minnesota's single-family homes that are electrically heated, of which there are approximately 153,000 (Nelson et al. 2018). These are located almost exclusively in areas of the state without natural gas service (Figure 2). Electrically heated homes were ideal early opportunities for ASHP research and demonstration. These homes were historically underserved by efficiency programs and lacked sufficient technologies to deliver energy efficiency. Prior to passing Minnesota's Energy Conservation and Optimization (ECO) Act, utility programs could not target applications that changed the primary fuel source, which restricted incentives for ASHP installations to homes with electrical heat.

With the passage of ECO, utility programs can now incorporate some fuel-switching applications. Many of the lessons learned in this project are applicable to homes with any fuel type, including natural gas.

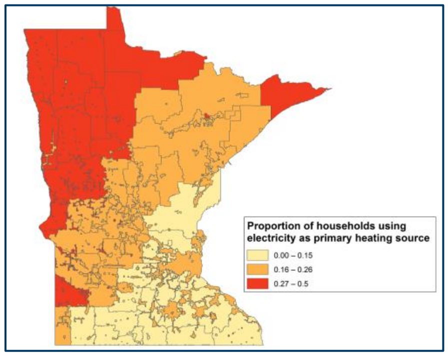


Figure 2. Location of the electrically heating homes in Minnesota

When conducting a CARD study in 2017, CEE verified within two ductless ASHP Minnesota field installations the standard claim of ASHP manufacturers and other ASHP research literature that cold climate ASHPs operated down to -13°F, and saved an average of 55% of the energy used by electric resistance heating systems (Schoenbauer et al. 2017) . That study was limited in that it considered only a single head ductless type of cold climate ASHP system, and only two of the six installations were in homes that had electricity as the primary initial heating source. Since that CARD study in 2017, CEE has verified the performance of cold climate heat pumps at colder temperatures and in centrally ducted systems (Schoenbauer and Haynor 2018; Trojanowski et al. 2023). This project installed a sample of all major types of cold climate ASHP systems in homes that are currently electrically heated with each of the common types of existing systems. It developed interim protocols for system selection, configuration, sizing, control, and integration with backup heat, then implemented, refined, and validated those protocols. It collected and analyzed field data to assess heating performance, comfort, and customer acceptance, and to provide reliable real-world savings data from cold climate ASHPs that have been implemented according to best practices for quality installation (QI). Field testing was used to test and improve interim protocols and calculations were validated in an array of homes in an effort to help support cold climate ASHP installations anticipated through ECO over the next decade are fully optimized.

COVID-19 Project Impacts

This project was funded prior to the COVID-19 pandemic. Field research projects in general, and this project specifically, have long 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. When 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. However, the data collected and the results of this project are still valuable. 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.

Type of Heat Pump Applications

CEE's previous CARD project only examined single-head ductless solutions for electrically heated homes. These systems are limited in the fraction of the heating load they can meet. A typical two-ton ductless cold climate ASHP system is sized for 1,000 square feet of conditioned space and can only condition areas the head's airflow can reach. This project considered these and two additional types of cold climate ASHP systems: multi-head ductless systems and short duct mini-splits as it was anticipated that these additional types will allow the cold climate ASHP to be sized more appropriately and meet a larger fraction of the home's heating load than relying on single-head systems alone.

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.

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. 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.

Best Practice Update Need

Best practice protocols are needed because of the various heat pump types available, and configurations within a home possible to achieve occupant heating and/or cooling needs, desired ASHP performance and actual savings by the customer, utilities, and statewide programs. Best practice protocols need to be developed around configuration of components, system sizing, control methodology, and integration with the backup heating system to achieve ASHP installation benefits. .

Configuration: As the heat pump applications available can be configured in multiple ways due to requirements of the home and comfort needs of occupants to achieve benefits, there needed to be additional work to develop application guidance for the best system choice for a given home as well as the associated quality installation (QI) practices for that system. Guidance will also was developed within this project to address such configuration issues as the number, location, and sizing of heads in mini-split systems.

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 balances 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 (Christie and Dymond 2022, Smith 2022), 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. The two primary control methods currently seen in the field — (1) operation of the backup system when low (but actually 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 include 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 ECO technical reference manual (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 precisely 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 more precisely estimate electricity savings, carbon reductions, and cost-effectiveness of cold climate ASHPs in Minnesota.

Previous Work

ASHPs have been used in Minnesota as supplemental heating systems from many years. By 2015, the technology had advanced to a point at which variable speed or cold climate systems were capable of being installed as the primary heating systems in MN homes. CARD funded research conducted by CEE demonstrated the potential of this technology in MN (Schoenbauer et al. 2017). These systems were shown to deliver on expectations with high efficiency and verified energy savings. Customers were happy with the performance, savings, and levels of comfort. These early installations required a lot of design, installation, and operational input on the ground at each site to make them work effectively in the relatively straightforward centrally ducted full system retrofits completed for that work.

Figure 3 shows the performance of one such system. The coefficient of performance (COP), 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 showed the potential. Since then, application types have expanded, controls options have increased, and the landscape around heat pumps continued to grow.

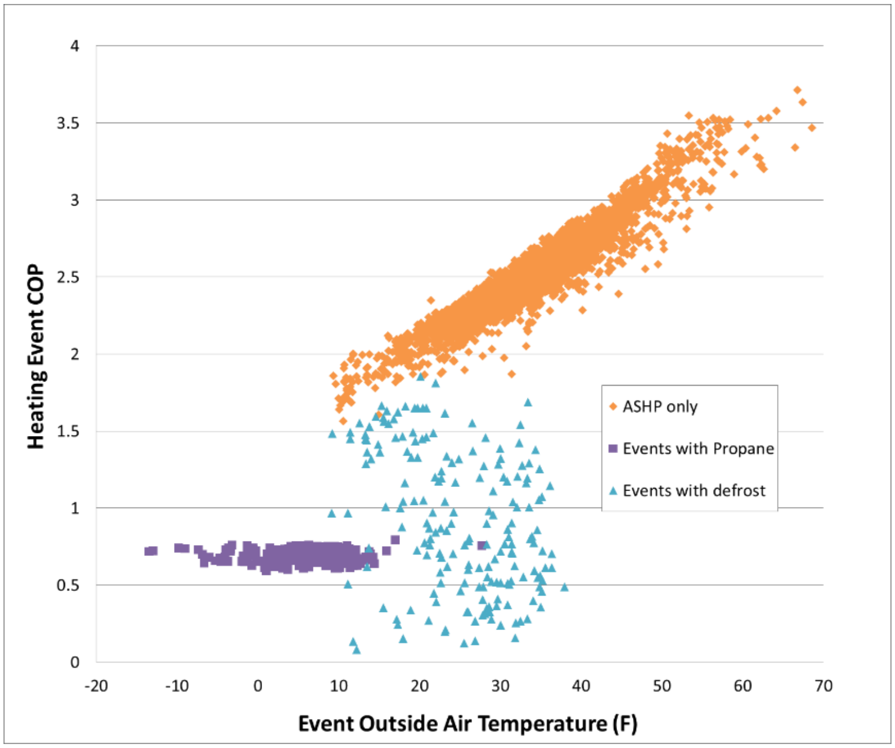


Figure 3. Efficiency of a centrally ducted residential ASHP installed as part of the 2015 CARD study

Relevance to Energy Efficiency Programs

Heating seasonal performance factor (HSPF) — the cold climate ASHP efficiency rating — and the rated capacity do not reflect performance under Minnesota weather conditions. Listed HSPF values reflect an Air-Conditioning, Heating, and Refrigeration Institute (AHRI) region IV climate, while Minnesota is almost completely located within regions V and VI. Rated capacity is listed at 47°F for heat pump systems. Many cold climate ASHP products can maintain their rated capacity down to 0°F, but this is not the case for all equipment. Efficiency and capacity are a function of outdoor air temperature and selecting inappropriate conditions for Minnesota's climate will substantially reduce the accuracy of any calculations. In addition, the proportion of the total annual heating load provided by the cold climate ASHP will vary with system sizing relative to building load and geographic area of the state. These real-world performance characteristics are not currently recognized in Minnesota's TRM calculations, but cold climate ASHP performance maps make it possible to develop calculation procedures that are appropriate. This project developed interim and final versions of these procedures from this and previous field research projects.

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 (ASHPs) when applicable. 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, what type of heating homeowners in their territories use, and if they were 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 widely accepted due to the lack of knowledge around them, lack of rebate opportunities, and skepticism in the technology itself.

HVAC Contractor Interview Summaries

Some contractors who were interviewed discussed rebates with utilities that they participated in, from which most of their ASHP installations resulted. These rebates usually marketed ASHP 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 agree that the cost is hard to justify when gas heating is available and the most amenable delivered fuel source for residents. For most contractors interviewed, ASHPs accounted for only about 5%–10% of installations. The exceptions were one contractor who installed 20%–25% in 2018 due to a generous new rebate from Dakota Electric and one contractor in the Twin Cities metro who uses ASHPs in 50%–60% of his installations. The majority do recommend ASHPs to their customers, though it usually depends on each customer's fuel mix and the incentives offered by their utilities.

Customers were occasionally aware of ASHP technology and requested them, but this is 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 either because the contractors are authorized dealers or retrofit applications are more practical with certain manufacturers. For example, one contractor preferred Carrier because of the ease of installation and the thermostat. Other common installation preferences were with American Standard or Maytag because customers usually replace their furnace and AC as a package unit and one brand must be used for both systems to qualify for applicable rebates. Many other manufacturers were mentioned in the interview process including Mitsubishi, Fujitsu, Daikin, and Goodman, and 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 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 with some training opportunities, including cold climate ASHPs.

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 to install 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 opt for 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.

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. Over the course of the project utility programs and markets for heat pumps changed significantly. Original interviews were conducted when fuel switching was not allowed within Minnesota ECO 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, propone, as well as electricity. Utility interviews did reveal that ASHP installations in electrically heated homes were seen as good potential, due to the significant potential for increased efficiency of heat pumps compared to standard options. But they were not generally 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 remain heavily involved in the Minnesota Air Source Heat Pump Collaborative at the time of publication of this report, created to tackle barriers to proper ASHP installations in MN.

Customer identification and initial costs were the two biggest barriers for utility programs that targeted electrically heated homes. Generally, utilities were aware of the potential of heat pumps as a possible decarbonization pathway. Initial hurdles around fuel switching programs, customer economics, load impacts for winter peaking utilities, and contractor support were seen as initial barriers by utilities for installation of heat pumps in homes with gas heating.

Cold Climate ASHP Application Scenarios

In the 2000s, the North American ASHP market saw a large amount of technological advancement. During this time, variable speed heat pumps were introduced by most manufacturers and performance metrics like COP and delivered capacities improved. Particularly by introducing variable speed compressors and advancing compressor technology to allow for increased capacity and higher COPs at lower temperatures than previously possible.

In the years since the introduction of variable speed compressors, market innovation has focused on increased application types. Performance data and component-level design will continue to advance (DOE 2022), but there has also been significant manufacturer research and development work around application development, both for ducted and ductless systems. Examples include centrally ducted heat pumps installed as A-coil only systems in which the furnace or air handler do not need to be replaced, ductless heat pumps designed to support multiple heads from a single outdoor unit., and the addition of other types of indoor heads like wall-mounted radiator type units, wall or ceiling mounted indoor units that allow the use of small ducting.

The expansion of ASHP applications and types increases the importance of product selection and design. For retrofit applications, the primary driver in product selection is the existing system type. While changing types is possible, working with the existing distribution and system framework allows for a drastically more cost-effective solution than replacing system components.

Existing Heating System Type

This study focused on homes where electrical heat was the primary heating source. However, the type of heating system and distribution system matter for heat pump selection. Electricity and fuel type were important to operation and cost, but less important to selecting a type of heat pump. Table 2 shows common retrofit applications for heat pumps in electrically heated homes. Each of these installation types was evaluated for this project. In homes where the existing heating type was distributed, i.e., smaller heaters in each zone like electric resistance baseboards, then mini-split systems were the preferred heat pump type. In homes with centrally duct systems, ducted heat pump systems were selected.

Table 2. Heat pump application scenarios for electrically heated homes

Primary existing heat	Secondary existing heat	Recommended application
In-ceiling/floor radiant heat	Electric resistance baseboard	Mini-split heat pump, number of heads depends on number and size of heating zones
Electric boiler	Electric resistance baseboard	Mini-split heat pump, number of heads depends on number and size of heating zones
Electric boiler	Wood/gas stove Electric fireplace	Mini-split heat pump, number of heads depends on number and size of heating zones
Electric resistance baseboard	NA	Mini-split heat pump, number of heads depends on number and size of heating zones
Electric resistance baseboard	Wood/gas stove Electric fireplace	Mini-split heat pump, number of heads depends on number and size of heating zones
Electric resistance baseboard	Infrared space heater	Mini-split heat pump, number of heads depends on number and size of heating zones
Electric furnace	NA	Ducted VSHP, with auxiliary plenum heat. A-coil only based on Furnace age.
Electric furnace	Plenum heater	Ducted VSHP, with auxiliary plenum heat. A-coil only based on Furnace age.
Electric forced air	Thermal storage	A-coil only ducted VSHP

An air-to-water heat pump was another approach considered for an electric boiler system. Air-to-water heat pumps were not considered for installation. At the time, most air-to-water systems were pre-commercial and supply chains and installing networks were not ready to conduct installations, and developing those needs was too much to include for these installations. Further CARD work has been done on the topic (add citation).

Pros and Cons of Each Cold Climate ASHP Approach

Mini-split (or ductless heat pump) for replacement of heat from distributed heaters

Benefits

- Ductless systems do not have ductwork — indoor heads are placed within the heating space minimizing distribution loses.
- Installations are self-contained and only require minimal interactions with the existing systems in homes, ideal for retrofit solutions.
- The advancement of multi-head solutions where more than one indoor unit can be installed with a single outdoor unit, increases the conditioned spaces, and zones a ductless unit can heat and cool while keeping costs lower.
- An ever-increasing array of different types, styles, and forms on indoor heads are aesthetically pleasing to a wider audience and fit better within existing home designs.
- High-performance ductless heat pumps have some of the best performance specifications of all heat pump types. These best-in-class units have some of the best COPs at cold temperatures and were capable of delivering heat in extremely cold conditions.

Drawbacks and Barriers

- Some consumers do not like the aesthetics of indoor units mounted in occupied spaces.
- There are some controls and performance characteristics of multi-head systems that are not fully understood.
- While very efficient and highly capable, these systems do not have enough capacity at extreme temperatures to meet the heating loads of all homes without the need for some backup or auxiliary heating systems. Because ductless units are standalone systems, intelligently controlling those additional heating sources can be difficult.
- Without a centralized distribution system, mini-split systems can’t deliver heat to all areas of a home without an indoor head in each zone or room. This makes replacing exiting systems or whole-home displacement in shoulder seasons difficult without a large number of indoor units, which would be very expensive.

Central variable speed heat pumps in homes with existing ducted forced air systems

Benefits

- Centrally ducted ASHPs are whole-home solutions, capable of supplying heating and cooling to all areas of conditioned space.
- Auxiliary and supplemental heating systems are typically wired and connected to the heat pump system and controlled by the same thermostat. While integration and controls can still be complicated and differing approaches can significantly impact performance of the system, having all the components connected and wired together greatly increases the ability to optimize their performance.
- Installation is nearly identical to central air conditioning systems with which installers are comfortable. No new skills are needed for a ducted ASHP install.

Drawback and Barriers

- Due to their similarity to central AC systems, central ASHPs can be installed as cooling only or minimal heating systems without much attention paid to heating performance.

- Ducted ASHPs rely on existing ductwork to deliver heating and cooling to the home. If the existing ductwork is poor or failed, it can impact heat pump performance
- Zoning can be difficult.

Methodology

Research Questions

There is significant energy savings opportunity in Minnesota through ASHP installations, and ASHP installations are expected to accelerate in Minnesota over the coming years. Significant advancements in the equipment and types of heat pump applications have increased the potential for use of ASHPs for Minnesota's climate. Though, the efficiency of ASHP depends on its design, installation, and operation.

This project aims to answer questions and develop best practices and/or guidance about ASHP design, installation, and operation as well as determine which considerations are important for ASHPs to meet the goals and deliver their true benefits to customers, utilities, and the climate.

Best Practices Development Process

There is a huge range of ASHP system types, design approaches, and goals for installations. Capturing the best practices of every iteration of a heat pump was impractical within the study. Additionally, each manufacturer and many different code enforcement regions have their own specific requirements. However, there are best practices and areas of design, install, and operation that have importance across a wide variety of heat pump installations.

An initial list of topics and considerations was created during the market assessment phase of this work. These ideas were gathered from past research, stakeholder interviews, literature review, and consultation with manufacturers and their installation guides. These best practices were not all inclusive or step-by-step instructions but rather guiding principles to be considered and evaluated during the installation process.

Principles or ideas for design and install considerations, include:

1. The ASHP design (product selection, sizing, and install) should align with the customer's goal for heating displacement and/or replacement.
2. The ASHP should be sized by house and by zone based on measured data or detail load calculation and should consider the conditions under with the heat pump will provide the home's space conditioning and when a backup system will be used.
3. How the ASHP will be controlled must be considered, including integration with other heat sources and how an occupant is likely to interact with their system.

After completion of the installation, monitoring, and analysis of this process, these principles and best practices were reviewed and updated based on the results of the work and the experience of their use in the field.

Site Recruitment and Selection Criteria

Three main considerations were made for household 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 homes 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, homes had to be good fits for the intended heat pump solutions.

Site Selection Criteria

Sites were selected:

- If it was feasible to install monitoring equipment and collect data. This criterion required that the heat pump data collection package was able to be installed. The homes electrical panel had to be accessible and large enough to install sensors. The location of the indoor unit (ductless or central AHU) needed to be accessible for temperature and airflow measurements. Communications through cellular modem or homeowner Wi-Fi had to be possible.
- If the occupant's agreed to participate. The homeowner needed to be a willing and engaged participant in the work, willing to allow access for monitoring and troubleshooting, and open to completing surveys.
- If the location of the home and electric service provider needed to be representative of Minnesota homes. A range of locations were targeted for installation. A specific sampling requirement was not made, but a target of diverse homes to represent a range of interested utility service providers and to capture any differences between rural, metro, and suburban homes.
- If the site satisfied the studies requirements to include at least one of each major type of the existing electrical heating systems needed, which included distributed electric resistance (baseboards), central forced air, and electrical hydronic.
- If the heating load fit study requirements. As heat pump capacity diminishes at colder temperatures, resulting in variations in ASHP sizing, performance, and energy savings with the homes heating load, the participant sites needed to represent a range of loads. Initially, home loads were categorized as small, medium, and large based on existing equipment sizes, house size, the home's insulation level, and presence of any energy updates. Utility bills were used when available to calculate a more accurate household heating and cooling load.

Site Selection Criteria Summary

Over 30 sites were identified for possible inclusion in the project. House and system data were collected at each possible site. Twenty-five sites passed initial review, deeper system data and utility billing data were collected and considered for inclusion in the project. From that pool, thirteen sites were selected for a detailed on-site screening visit prior to final site selection. Table 3 summarizes the primary selection criteria at each site. These sites made up the pool of homes considered for installation and evaluation of heat pump performance. The sites were spread around the state, with slightly more central and metro locations, but widely distributed. Sites had a wide range of primary heating system types. Distributed electric resistance heaters, like baseboards and ceiling panels were the most common. Five different Minnesota electrical utilities were represented and a wide range of heating loads were covered from and estimated load as small as 4,800 kWh per year to a home with an annual heating load of 34,500 kWh.

Table 3. Selection criteria for all screened sites

Site	Selection	Location	Existing Heat Type	Electric Utility	Heating Load
SF_01	No	Central	Electric furnace, ASHP, Gas fireplaces	Dakota Electric	Large
SF_02	No	South	ASHP, Electric resistance plenum	New Ulm Public Utility	4,800 kWh/yr.
SF_03	No	Central	Electric resistance plenum, propane furnace	Dakota Electric	Average
SF_04	No	North	ASHP, Electric boiler	MinnesotaPower	N/A
SF_05	Yes	South	In-ceiling radiant, Electric resistance baseboard	Dakota Electric	17,000 kWh/yr.
SF_06	No	Central	ASHP, Electric resistance plenum	Xcel Energy	13,400 kWh/yr.
SF_07	No	North	Electric boiler, Electric resistance baseboard	Minnesota Power	27,900 kWh/yr.
SF_08	Yes	West	Electric boiler, Electric resistance baseboard	Otter Tail Power	34,500 kWh/yr.
SF_12	Yes	West	In-ceiling radiant, Electric resistance baseboard	Otter Tail Power Co	12,700 kWh/yr.
SF_14	Yes	Metro	Electric boiler, Electric resistance baseboard	Xcel Energy	19,800 kWh/yr.
SF_18	Yes	Metro	ASHP, Electric furnace	Xcel Energy	15,950 kWh/yr.
SF_21	Yes	West	ASHP, Electric furnace	Otter Tail Power Co.	14,800 kWh/yr.

SF_27	Yes	West	ASHP, Thermal storage, Electric furnace	Otter Tail Power Co.	NA

Note: Utility bills provide energy use data from each home. The monthly usage data is correlated to air temperature data. With enough data and an assumed heating efficiency the utility bills can be used to calculate the non-heating energy use and then estimate the homes heating loads at design condition. This calculation could not be completed in some homes because the occupant was not living in the home for enough time, or the system efficiency could not be assumed (heat pumps and/or storage systems). In these cases heating loads could not be estimated from utility bills.

Field Measurements

Instrumentation and Testing Procedures

In the first year of the project, instrumentation packages were deployed for a baseline monitoring period. Packages usually 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.

For the second and third year of the project, heat pumps were installed and monitored for one to two heating season(s). Within the first week of a heat pump being installed, the research team deployed the heat pump instrumentation packages. 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 to the system to operate. Consumption was disaggregated into several system components including the indoor unit, outdoor unit, and the distribution fan. Field measures were also taken to measure the energy output from the system. The delivered energy to the space in the form of heating or cooling. Supply air and return air temperature and system airflow rate 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.

Figure 4 shows the field measurement locations for a centrally ducted air source heat pump system. The diagram pictures normal operation for a heat pump during a heating cycle where the heat from the air outside is pulled through the outdoor unit, transferred to the refrigeration loop, and circulated through the home.

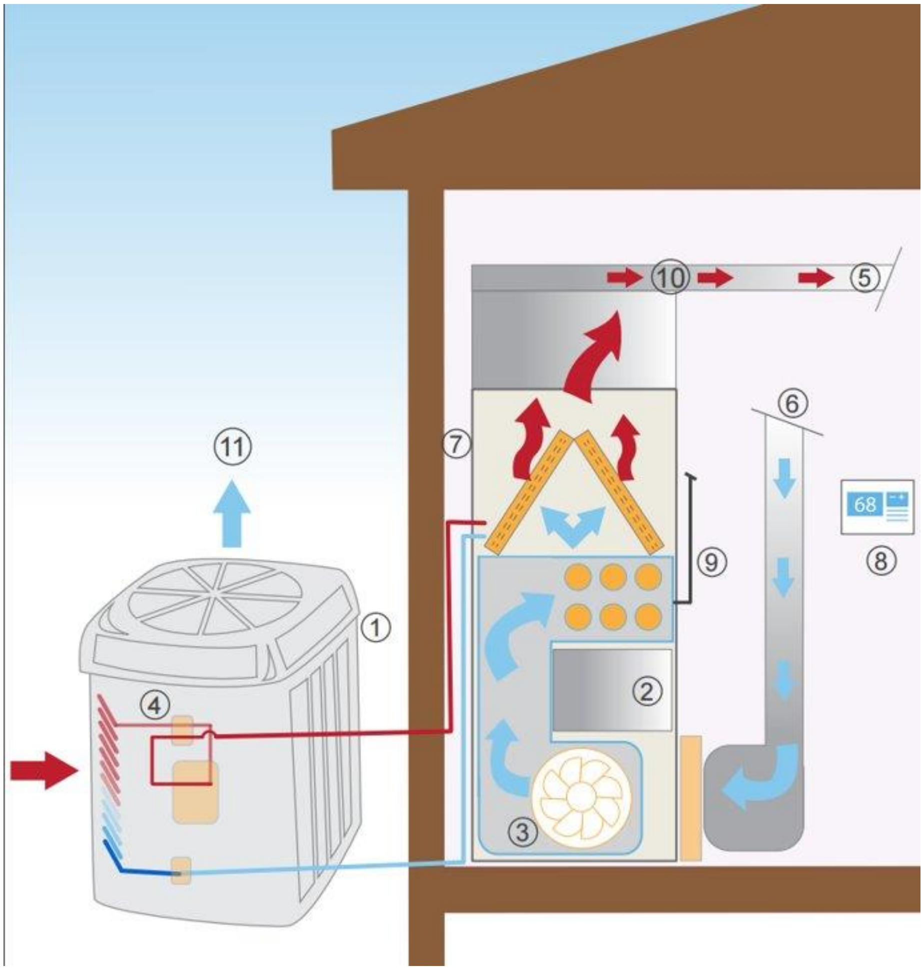


Figure 4. Field measurements made on a centrally ducted ASHP system

Figure 5 shows the Campbell Scientific based monitoring packages that were deployed to collect data used to characterize the energy delivered by the installed ASHP. These loggers were configured to collect data remotely and transit 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 was then correlated to airflow using a Trueflow plate during the installation and confirmed at equipment removal. This process has been used by CEE and others for many years (Ben Schoenbauer et al. 2017 & (Ecotope Inc 2014). 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.

The energy input data was collected using an E-gauge power meter (Figure 6). The E-gauge was installed in the homes’ electrical panel and directly measured the power of the indoor and outdoor units by measuring the true power consumption of the corresponding circuits in the panel.

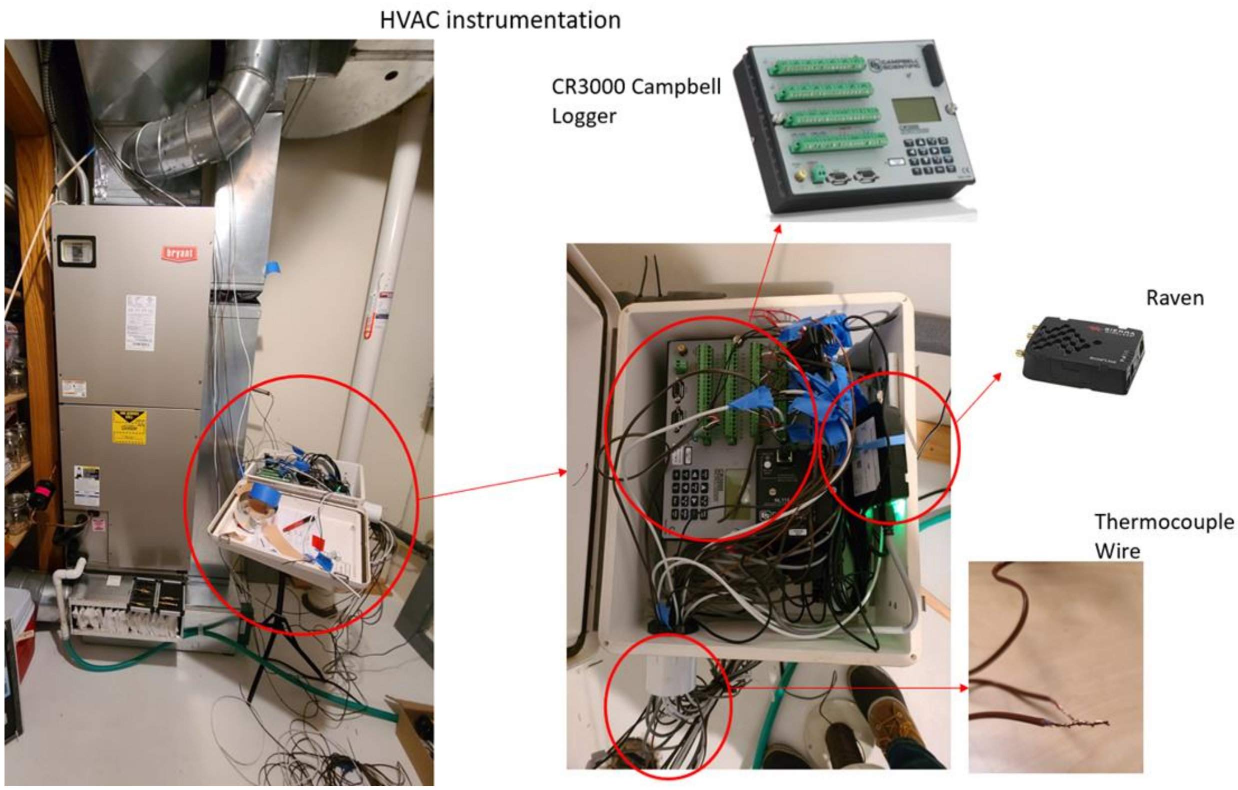


Figure 5. Monitoring package deployed to capture energy delivered by ASHOs

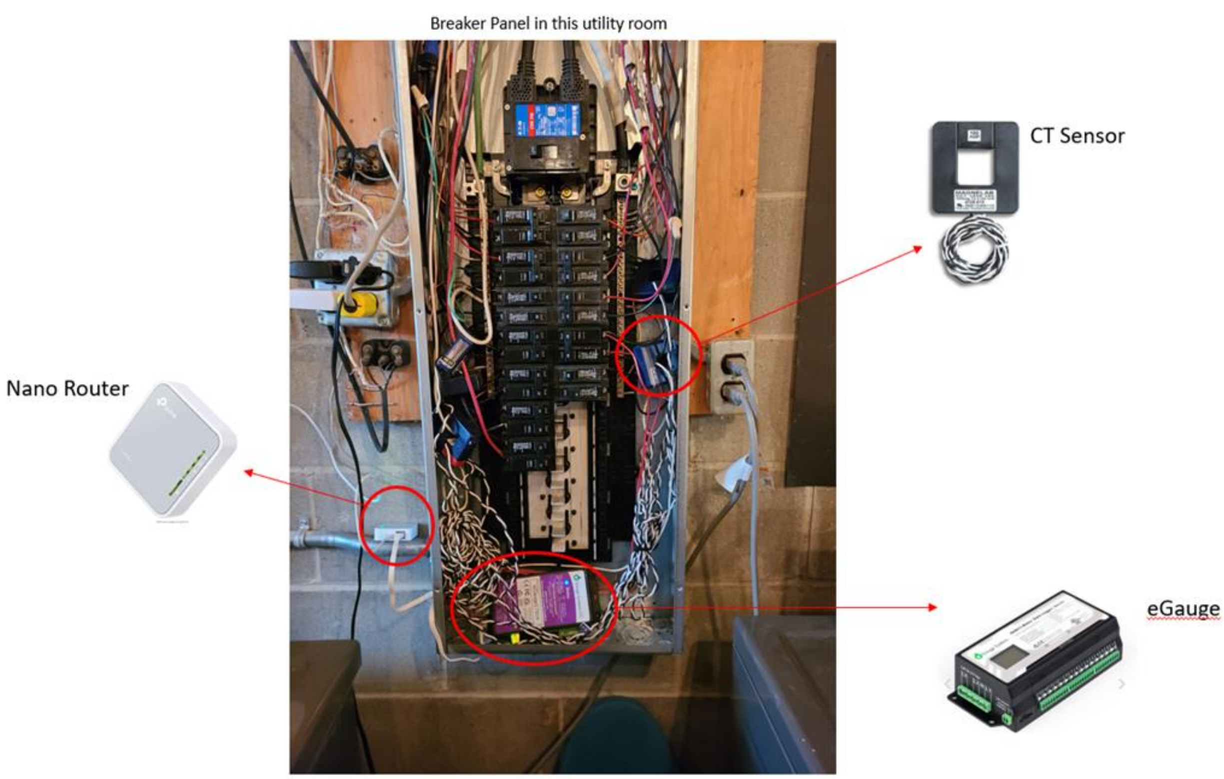


Figure 6. Measurement devices used to measure energy consumption of the heat pump

The baseline measurement package consisted of the same electrical consumption meter used in the ASHP package (Figure 6) and was supplemented with some standalone HOBO temperature loggers within the occupied space. 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.

Occupant Surveys

Occupant surveys were administered in each home 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. Surveys were given to each site at the completion of the baseline monitoring period, a couple of months after completion of the heat pump installation and at the completion of the project. 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.

Data Analysis

Extensive instrumentation packages were deployed days within heat pump installations, and data received from various loggers were run through rigorous quality control (QC) checks for any data discrepancies. Detailed analyses on each heat pump installed during the project confirmed successful quality installation (QI) procedures, helped redefine items on the procedures that were not successful, 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. The team would remotely download data 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 quality check (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 allowed CEE 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 was done to establish accuracy amongst 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 duct of a central HVAC system would read temperature ranges between 50–90°F. If the sensor is out of this range, usually it indicates 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 analysis 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 home uses 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 5 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, cubic feet per minute, in the equation is the air flow speed 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.

Results

Selected Sites

A total of seven sites were selected for ASHP installation. These sites were chosen based on how well they met the selection criteria and represented electrically heated homes in Minnesota. Table 4 shows the characteristics of the selected sites. A total of four sites were selected for ductless mini-splits, each with two indoor head and one outdoor unit. An additional three sites were selected for centrally ducted systems, with one site having an ASHP paired with a thermal storage unit.

Table 4. Sites selected for ASHP installation

Site #	Baseline	HP
SF_05	ER Radiant	Ductless 2-to-1
SF_08	Hydronic	Ductless 2-to-1
SF_12	ER Base	Ductless 2-to-1
SF_14	Hydronic	Ductless 2-to-1
SF_18	Forced Air	Central ducted
SF_21	Forced Air	Central ducted
SF_27	Forced Air	Central ducted

Installation Observations

Each heat pump installation was observed and documented to understand what on-site and installation specific details impacted how the heat pump was to be installed and operated. These included details that were known and incorporated into the design process, but also information that was unknown going into the installation and impacted the install or operation of the heat pump. Information about the existing heating systems and household layout and zoning were both found to be important to delivering high quality installations.

Varied Existing Heating Systems

Market research and past research (NEEP 2020) have shown that it is important to match the selected retrofit ASHP application to the existing site and heating system characteristics. The site selection process highlighted that existing systems were more complicated than might be expected. Most homes had a primary type of heating system, but there were often differences in how heat was distributed to different spaces within the home as well as the presence of auxiliary heating systems. A truly optimized heat pump installation considers the impacts these existing systems have on heat pump operation.

In electrically heated homes visited for this project, the most common type of heating was simple electric resistance heaters. Baseboard-style resistance heaters were most used (Figure 7). While electric baseboards were present in almost all electrically heated homes visited, most had other types of electric resistance heaters as well. Electric ceiling heater (Figure 8), electric wall heaters (Figure 9), and electric space heaters (Figure 10) were other types of electric resistance heat found in homes assessed for heat pump installation.

Figure 7. Example of an electric resistance baseboard heater

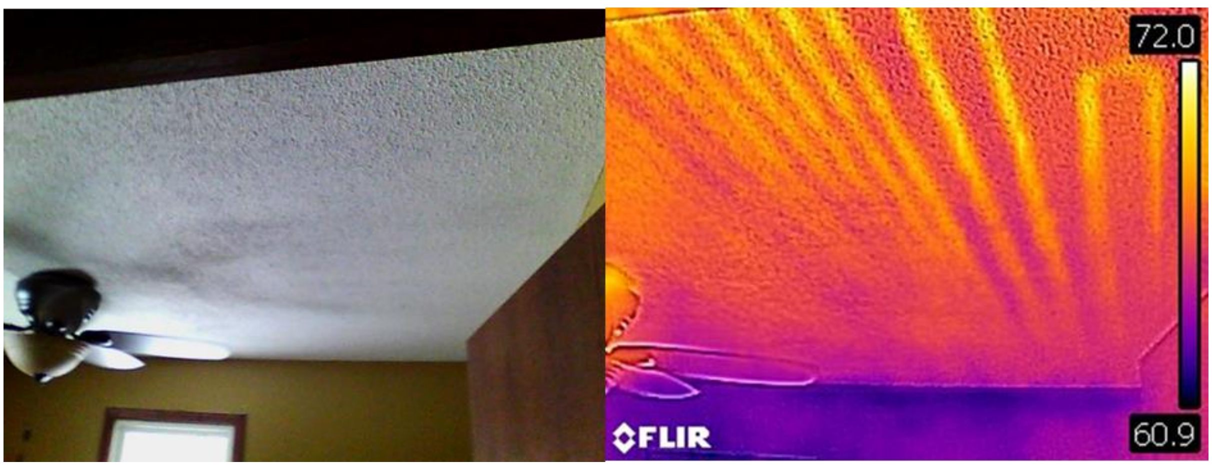


Figure 8. Electric radiant ceiling heat

Figure 9. Electric wall heaters were commonly found in bathrooms

Figure 10. An electric space heater

Homes that are primarily electrically heated were also found to have supplemental fuel types, most commonly via wood-burning fireplaces and furnaces (Figure 11). Wood-fired heating systems were particularly difficult to account for in heat pump planning. Fireplaces and stoves tend to be used for non-heating reasons, cooking, or entertainment, but can deliver a large amount of heat when used. Wood furnaces tend to have a very high capacity. The manual on/off nature of wood appliances also makes their use unpredictable. Installations in homes with a large fraction of heat provided by wood appliances were avoided for this work. It was assumed that the high capacity of wood systems would overwhelm and limit any heat capacity delivered by a heat pump, thus making control and integrated performance difficult.

Figure 11. A central wood burning furnace

Layouts, Zoning, and Heat Pump Placement

For retrofit heat pump installations, the existing heating systems were key to the heat pump system design, but it was also important to consider the location, distribution, and zoning of the existing system. For ductless heat pump installations, the distribution of the heat was limited by the physical location of the indoor unit and the airflow pathways of the unit. Head placement must consider the heating load of the area or zone where it could deliver heat. It must also consider how much existing heat would be delivered to the zone and what steps can be taken to limit or integrate that heating system with the heat pump. One example was site SF_05 (Figure 12), in which heat pump installs were targeted at a zone that consisted of the kitchen and living room area on the first level and a second zone in the master bedroom area on the second level. The heating loads of each of these zones were large enough to justify and indoor head, a one ton system was selected for the master bedroom and a one and a half ton for the living and kitchen zone. Heating loads of each zone were determined for the baseline monitoring mode in this project, but could also be estimated with detailed load calculations like a Manual J.

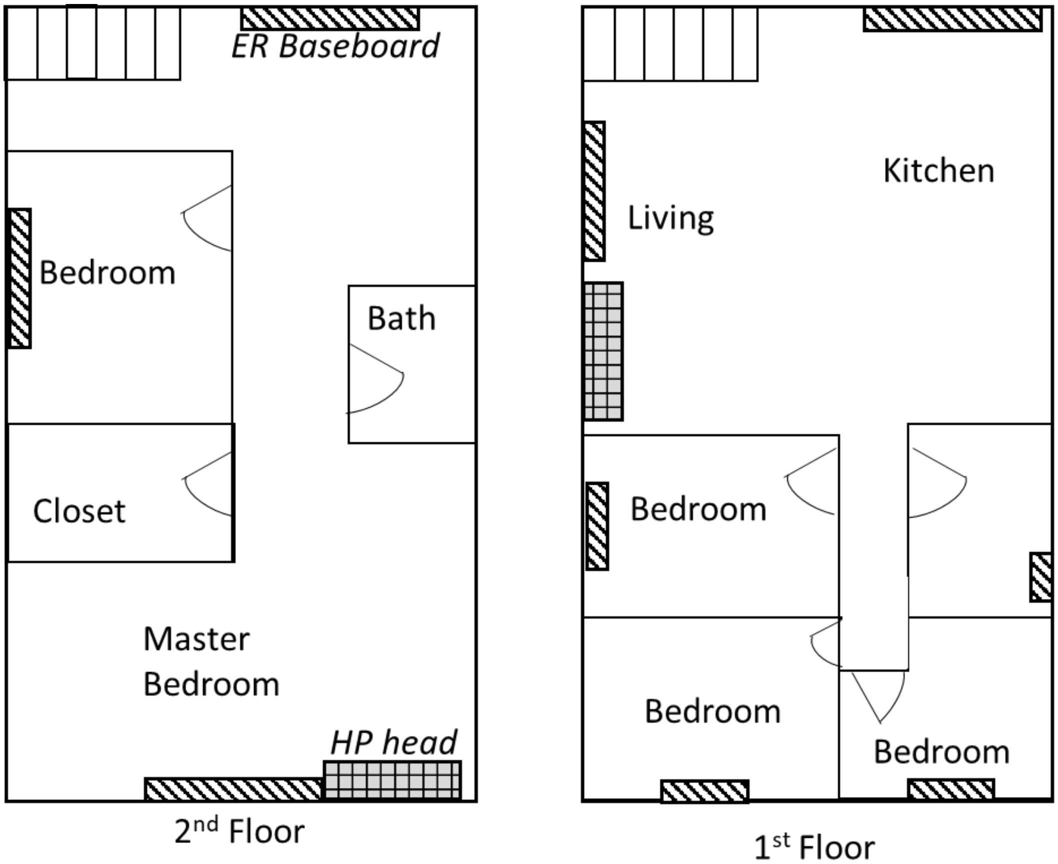


Figure 12. Existing electric heat locations compared to indoor heat pump unit locations at SF_05

Performance of the Ductless Systems

Overall the focus of this project was to evaluate and highlight the principles all ASHP installations must address to ensure the systems could deliver on their potential. Utilization of the design and installation principles delivered high efficiency performance from the ductless mini-split systems. Table 5and Table 6 show the ASHP install characteristics and the heating load met by the systems and season heat pump heating COPs at each site. COPs and capacities were in line with expectations for field data (Schoenbauer et al. 2017; Schoenbauer and Haynor 2018; Baylon, Geraghty, and Bedney, n.d.; Amero et al. 2022). The median ASHP COP at shoulder heating temperatures (30 to 40F) was over 3.5.

The ductless heat pumps performed well at each site with seasonal heating COPs greater than 2.0. However, the fraction of the heating load met varied widely from site to site. Site SF_08 had the highest seasonal COP of the ductless systems measured, but the lowest fraction of the total home heating load. This highlights the differences in ASHP system design and approach, as the zones where the ASHP were installed at SF_08 were a smaller fraction of the total heating load than those installed at the other sites. This limited the fraction of the total load the ASHP could meet, even when optimized.

The ASHPS were two to three times more efficient than the electric heating system they replaced. The energy savings at the sites depended on what fraction of the total heating load the systems could meet. The amount of heating load offset by the heat pump was determined by the design and installation of the heat pump. This project outlined the principles that must be addressed to optimize the displacement fraction for MN homes.

Table 5. Site selection characteristics of multi-head ductless systems

Site	Location	Electric Type	Electric Utility	Heating Load before ASHP installed (kWh/year)
SF_05	South	In-ceiling radiant Electric resistance Central AC	Dakota Electric	17,000 kWh/yr.
SF_08	West	Electric boiler w/ radiant heat Electric resistance baseboard	Otter Tail Power Co.	34,500 kWh/yr.
SF_12	West	In-ceiling radiant Electric resistance baseboard	Otter Tail Power Co.	12,700 kWh/yr.
SF_14	Metro	Electric boiler Electric resistance baseboard	Xcel Energy	19,800 kWh/yr.

Table 6. Performance of the multi-head ductless systems

Site	Heating Capacity Delivered by ASHP, at 0°F (-18°C) in Btu/hr.	Total Fraction of the heating load met by ASHP	Total Fraction of heating load met by ASHP if NOT optimized	Percentage Energy Saved over full resistance heat	Annual Heating COP
SF_05	16,215	85%	45%	50%	2.5

SF_08	7,967	10%	5%	9%	2.9
SF_12	7,397	39%	20%	21%	2.3
SF_14	7,342	42%	20%	22%	2.2

Multi-head ductless system performance

Figure 13 shows the performance of a 2 to 1 Mini split system. In addition to good moderate temperature performance, high COPs around 1.75 were maintained to very cold conditions at and below -10F.

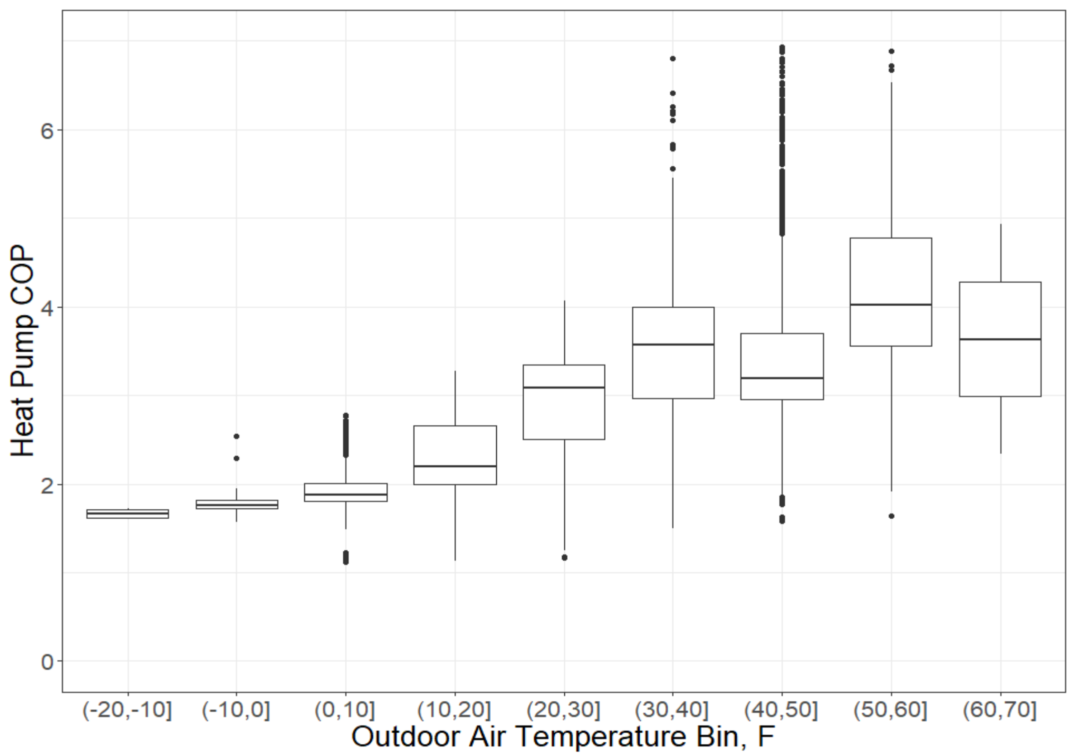


Figure 13. Installed COPs of a multi-head ductless system

Centrally Ducted Heat Pump Systems

The centrally ducted ASHP systems also delivered high seasonal heating efficiencies. Central heat pumps demonstrated that they were capable of delivering high capacity as well as extremely efficient heating over a wide range of temperatures. The central systems installed and operated in these homes were capable of meeting heating loads down to at least 10°F without auxiliary heat and did so at COPs between 1.75 and 2.5. When the ASHPS operated, they were capable of delivering capacity at high efficiency. However, the site to site (and approach to approach) variance in the fraction of heating load met and the overall efficiency was dependent on how the systems are designed and controlled to prioritize the heat pump.

In a given ASHP cycle the COP was greatly impacted by the percentage of the cycles total energy consumed that was used by the auxiliary heater. When the auxiliary heater accounted for less than 25% of the total energy of a cycle (red and gold colored cycles in Figure 14) the system COPs were high, as much as 2.5 at 15°F. When the auxiliary energy consumption increased (blue and pink) they system COPs approached that of the auxiliary heater, 1.0.

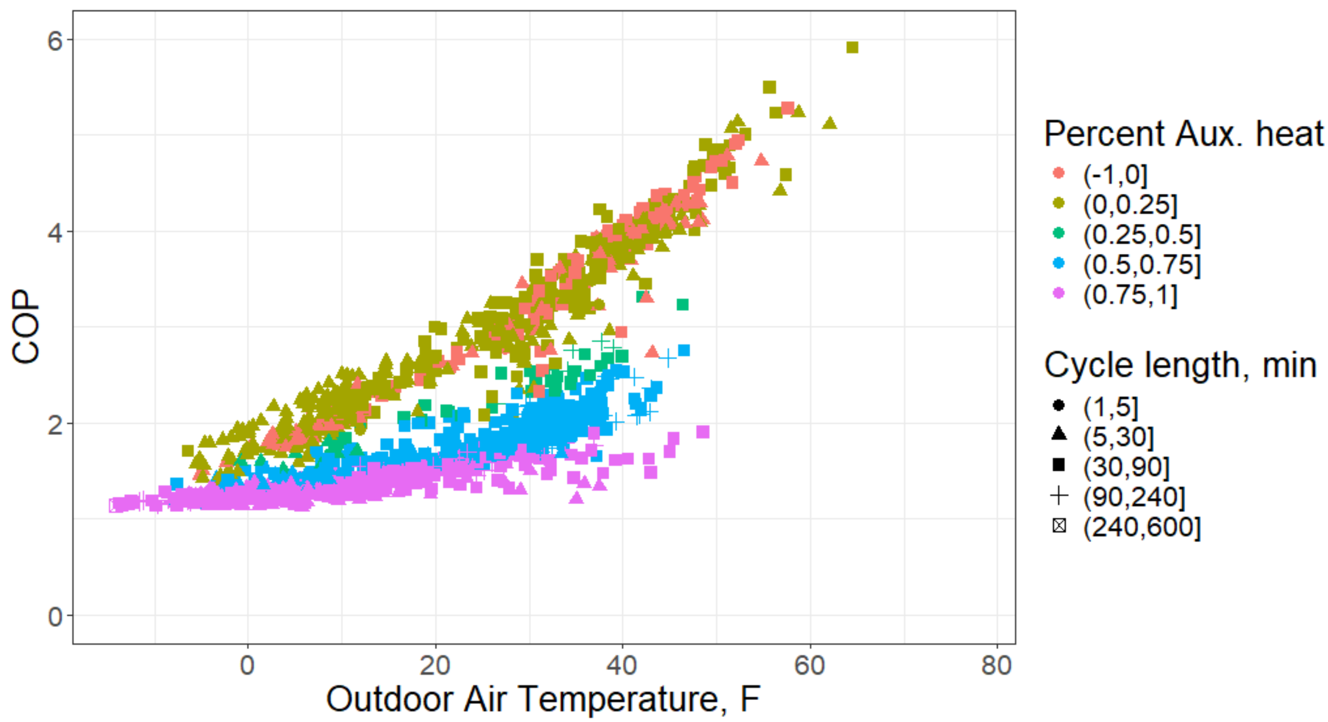


Figure 14. Cycle by cycle efficiency of a central ASHP at Site 18

Table 8 shows the seasonal heating COPs and heating capacity delivered by the heat pumps at the sites with ducted heating systems. The ASHPs with plenum booster heaters had similar performance with annual heating COPs around 2 and total fraction of the heating load met between 35 and 40%. Had the optimization of the auxiliary booster heater not been undertaken, these systems likely would have relied more heavily on the less efficient backup and they would have met about half of the total load the optimized system was capable of meeting.

Table 7. Site selection characteristics of Centrally Ducted Heat Pump System

Site	Location	Electric Type	Electric Utility	Heating Load (kWh/year)

SF_18	Metro	ASHP Electric furnace	Xcel Energy	15,950 kWh/yr.
SF_21	West	ASHP Electric furnace	Otter Tail Power Co.	14,800 kWh/yr.
SF_27	West	ASHP Thermal storage Electric furnace	Otter Tail Power Co.	NA

Table 8. Summary of heat pump system performance at centrally ducted sites

Site	Heating Load Met by ASHP, at 0°F (-18°C) in Btu/hr[1].	Total Fraction of the heating load met by ASHP	Total Fraction of heating load met by ASHP if NOT optimized	Percentage Energy Saved over full resistance heat	Annual Heating COP[1]
SF_18	14,122	67%	36%	56%	2.3
SF_21	7,985	65%	28%	48%	1.9

Note: SF_27 performance is included in Table 9.

Thermal Storage and Centrally Ducted Heat Pumps

One of the sites selected for field evaluation utilized a variable speed cold climate heat pump and an electrical resistance charges thermal storage system. Figure 15 shows the configuration of the storage system and ASHP. This storage system used electric resistance heaters to charge the ceramic bricks to high temperature overnight when utility electric demand and customer rates were low. The storage system varied the amount of energy stored in the brick with the outdoor temperature, such that the system would not over charge in mild temperature. During the call for heat the heat pump refrigerant loop would warm in the indoor a coil, as the return air flowed into the systems the temperate would be increased by the heat pump coil, and then the storage system.

Key benefits of this system were its simple design, the controls were on board the storage system, and it cost less compared to other storage options. The biggest barriers to this system were that it was charged with electric resistance, so it did not take full advantage of the heat pump's higher efficiency and was less dense than other storage mediums.

Figure 15. Diagram of the thermal storage and air source heat pump system

The manufacturer of this storage system had multiple control parameters to balance the storage and heat pump operation. There were several adjustments made to the control methods for this system over the course of the project. There was always a trade-off between the more efficient heat pump heating and the storage-based electric resistance heating at lower electrical rates. The storage charging allowed electric usage overnight when a time of use rate was less expensive. The alternative was to maximize the heat pump runtime, which occurred when the home needed heat, which could be at a higher rate, though heating was delivered much more efficiently.

Figure 16 compared the extreme cases of heat pump only operation (Storage Enabled = FALSE) and default controls for electric storage (Storage Enabled = TRUE). This storage system was originally designed to work with less efficient single speed heat pumps that were not assumed to do a large amount of heating at cold temperatures. During the time of heat pump only operation, the central heat pump maintained the temperature in the home at temperature down to 20°F without backup heating. There was some energy used by the air handling unit to run the supply fan. During the storage period a lot more energy was used at the same outdoor temperature conditions. Almost all the energy was used by the storage system with minimal heat pump operation. The storage system was charged to the point the night prior that there was not much load left for the heat pump the following day.

Table 9 shows the energy performance of the heat pump and storage system at Site SF_27. Prioritizing electric resistance energy use to charge the storage system resulted in much less heat pump operation compared to when the heat pump was prioritized, and backup was only used when needed (as done at ST_18 and SF_21). The heat pump system with storage enabled had an annual heating COP of 1.2 compared to 1.7 when allowed to operate with a more typical backup control. Figure 17 shows the benefit of the storage system. The early morning hours were prioritized for charging the storage system, under all temperature conditions the hours between midnight and 6 AM had the highest usage.

These controls were modified, and the result showed more balance between the systems. The difficulty in optimizing performance for this system design was that it depends on the electrical rate structure and the heat pump efficiency. There for it was difficult to adjust the control settings to truly optimize performance at this site.

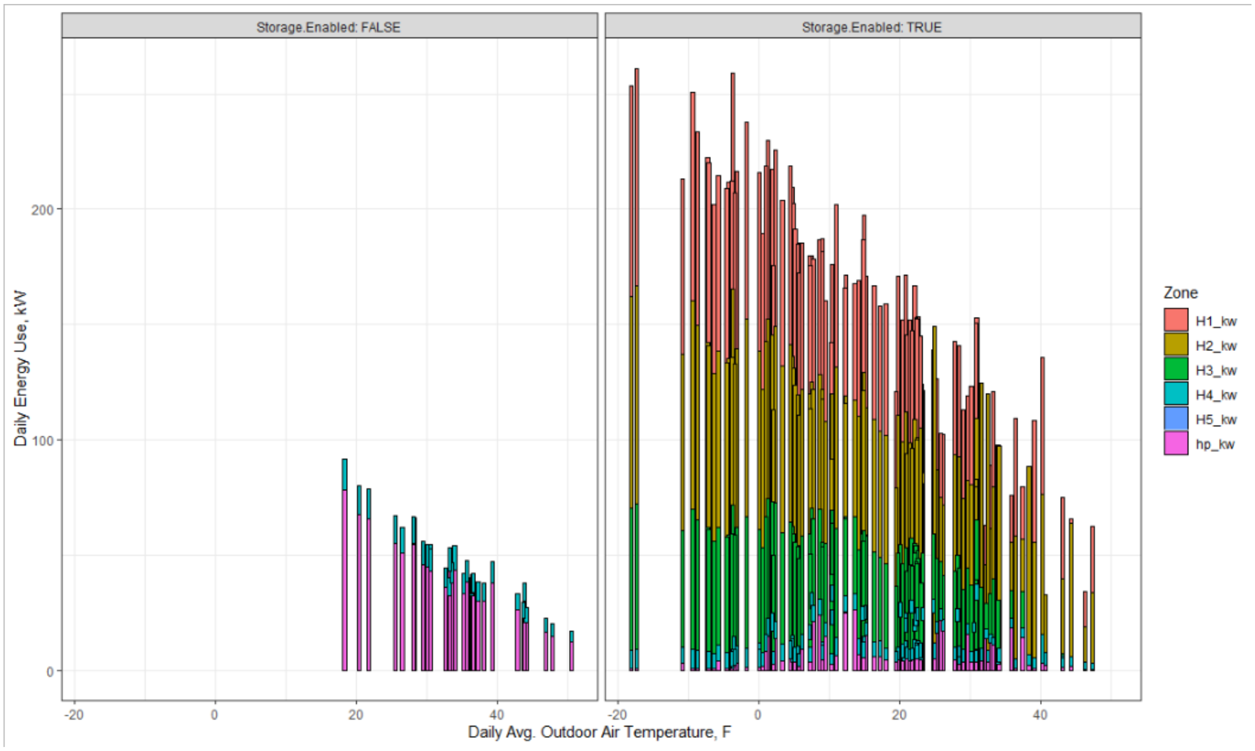


Figure 16. Heating energy consumption during for heat pump only operation compared to heat pump and storage operation.

Table 9. Performance of the heat pump at Site SF_27

Site	Heating Load Met by ASHP, at 0°F (-18°C) in Btu/hr.	Total Fraction of the heating load met by ASHP	Percentage Energy Saved over full resistance heat	Annual Heating COP
SF_27 HP w/ back up*	10,357	74%	41%	1.7
SF_27 w/ Storage	1,175	32%	19%	1.2

*Due to control modes allowed with the storage system, this performance was calculated based on the heat pump only measurements made at SF_27 in moderate temperature conditions and utilization of the performance maps from SF_21 and SF_18 to degrade the COP and delivered capacity. This allowed for an estimated performance if SF_27 was controlled like sites without storage.

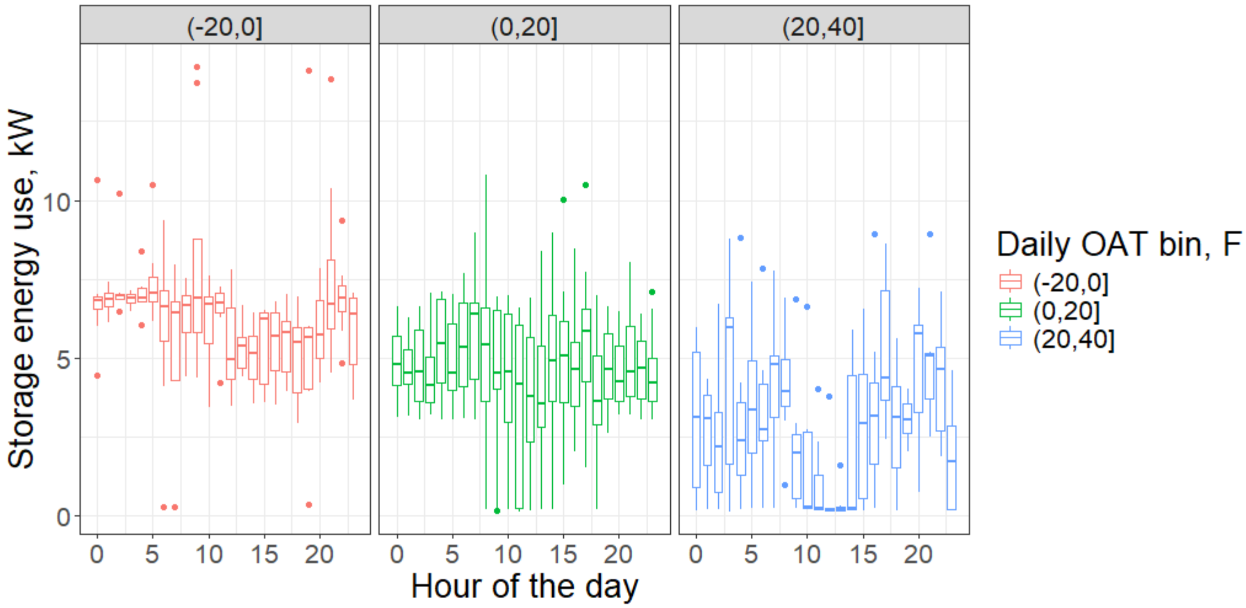


Figure 17. Storage Energy Consumption by time of day at SF_27

Surveys and Customer Acceptance

The project team attempted to conduct three rounds of surveys, the first after completion of the baseline, a second after heat pump installation, and a third at the end of the project. Due to COVID19 impacts which extended length of monitoring as a result of delayed heat pump installation and site participant turnover, these surveys were not able to be collected at all sites. 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.

Six of the size sites completed some survey instruments. Five sites responded to the survey regarding the baseline system performance and another five sites responded to surveys about the ASHP installation and performance.

- All the occupants who responded said their comfort was improved or the same with the ASHP.
- All occupants indicated they were generally happy with the ASHP installation and glad to have had the opportunity to participate in this work.

Despite the general happiness with ASHP installations, a few sites mentioned some minor setbacks or inconveniences with the systems.

- One site (SF_14) noted that the kitchen indoor head ran constantly in cold weather and that at times the kitchen and dining room zone was cold. This indicated the indoor head in this zone was undersized or more auxiliary heat could have been added.
- Another site (SF_12) noted cooler temperatures during the winter in a spare bedroom, but this did not appear to be a major concern. These lower temperatures in the spare room were likely due to changes in how zones were controlled when the heat pump was installed. This was one of the areas highlighted for confederation in the recommended best practices.
- Two sites inquired about ice formation around the bottom of their heat pump unit. One site was not concerned about the ice buildup except to understand if it was a maintenance concern. The other site noted that their ice formation approached a walking area, which caused some concern (Figure 18).
- Another site noted that they "had to fiddle with it more than I would like" when asked about controlling the system.

Figure 18. Ice buildup under an ASHP outdoor unit

Operation

Thermostats

The main point of control and operation for a centrally ducted heat pump system is the thermostat. The type of thermostat and the operational setpoint selected significantly impacted heat pump operation. There were two major types of heat pump control, largely dictated by the thermostat used to control the system.

The most common type of control for heat pumps was a switchover based on outdoor temperature. These types of thermostats either directly measure the outdoor air temperature onsite or connect to a local weather station via Wi-Fi or other communications. Figure 19 shows a switchover scheme for a system that did not allow simultaneous operation of the heat pump and the backup/auxiliary heating system. When there was a call for heat, the thermostat reads the outdoor temperature — when the temperature was below the switchover point, typically set in the thermostat, then the auxiliary or backup heating system came on to meet the load. If the temperature was greater than the switchover point, the heat pump ran to meet the load. A modified version of this control can be deployed in cases where the auxiliary and heat pump could run simultaneously. In this case, there is a switchover temperature below which the only auxiliary system would run, and a second switchover temperature above which only the heat pump would run. Between the two switchover temperatures, both systems would run simultaneously.

The second control approach was a staged approach. Under this control when the thermostat called for heat, stage one heat fired initially, which cued the heat pump to run. But after a fixed cycle length (20 minutes was a common default setting), if the thermostat was still calling for heat, stage two would kick on. In this control scheme, stage two was the auxiliary backup heating system. This allowed the heat pump to run at most or all outdoor air temperatures but limited the overall fraction of the load met. This is because most modulating variable speed heat pumps are designed for long runtimes delivering capacity near the load of the home but could not do so when stage two heating came on after a fixed time limit.

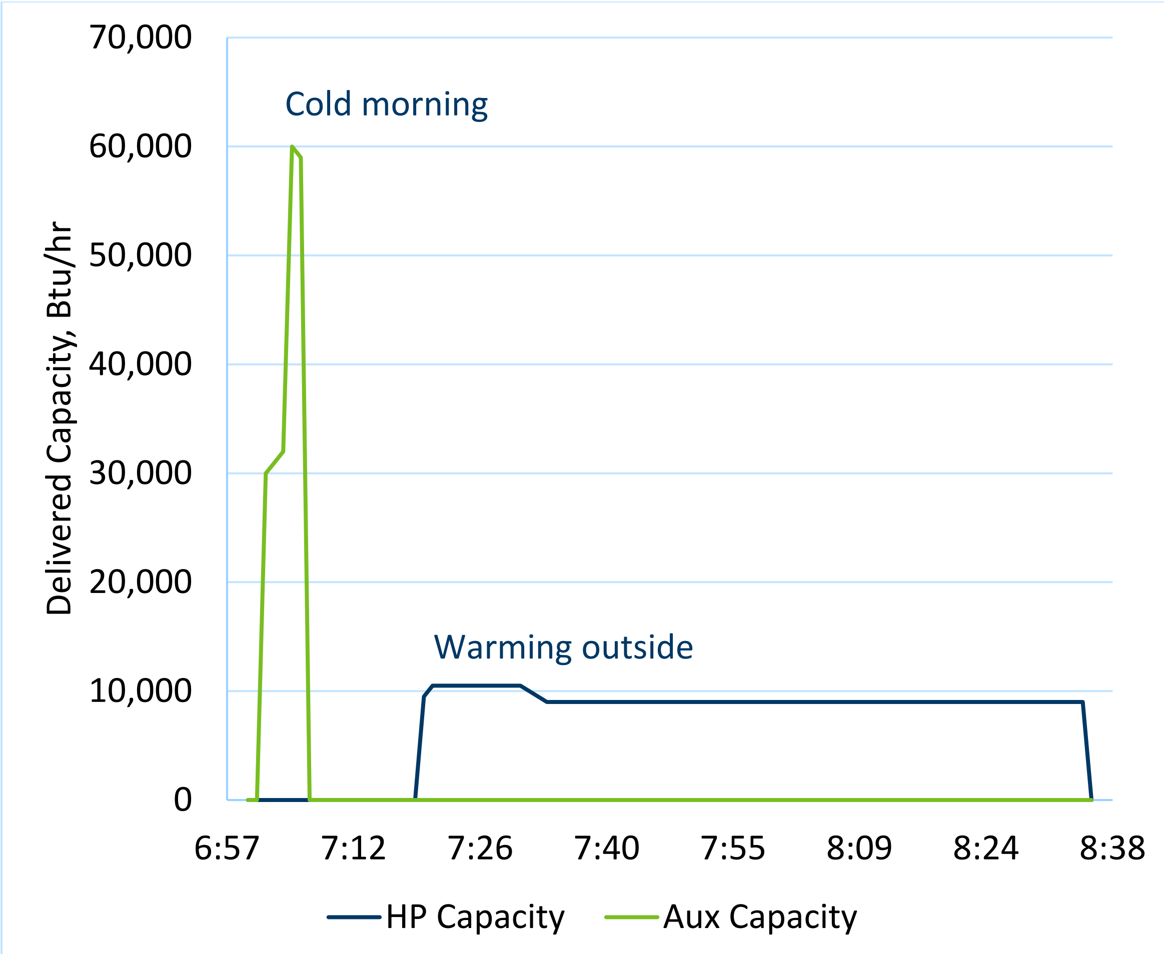


Figure 19. Switchover temperature controls for a heat pump and auxiliary system

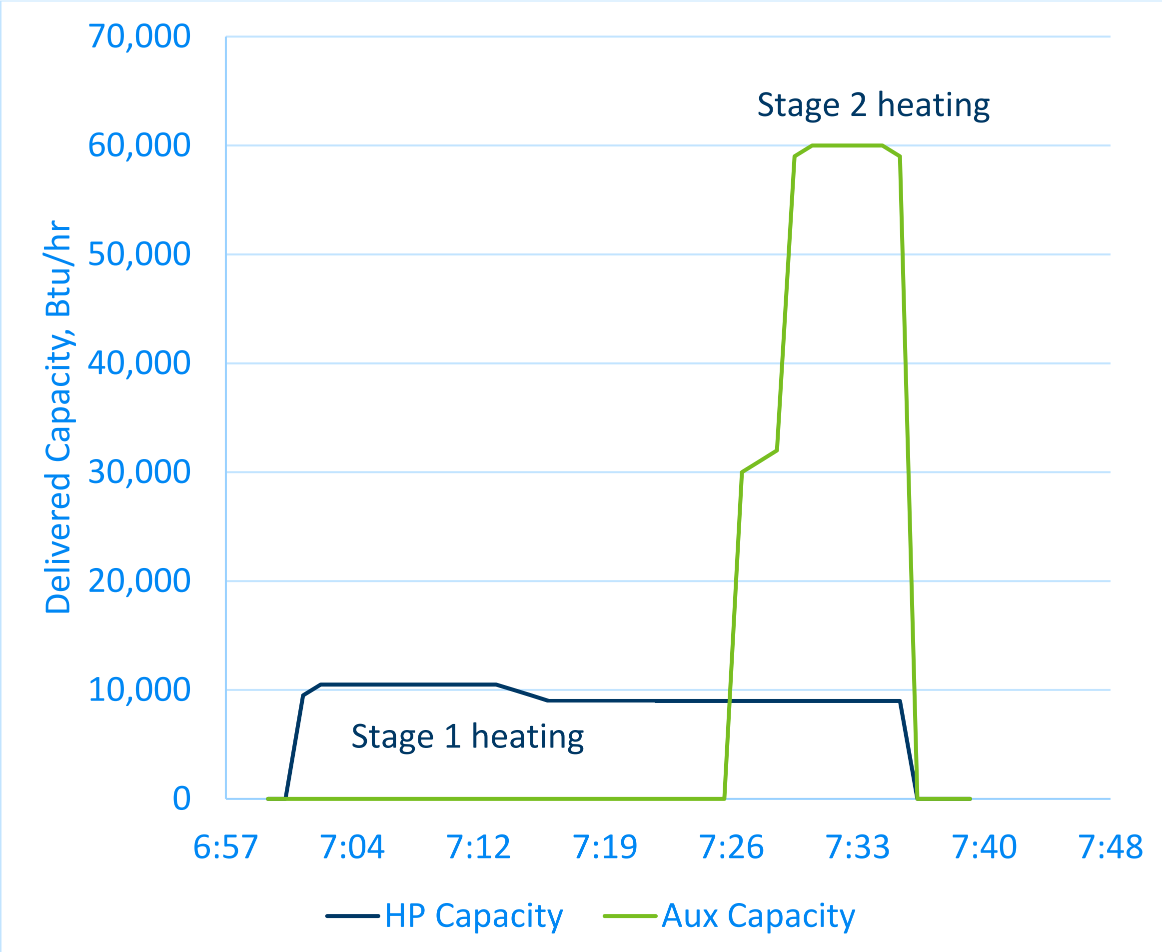


Figure 20. Staged control for a heat pump with auxiliary heating

As a result of the staged control mode, both the heat pump and the auxiliary system could run across all outdoor air temperatures, including the warmer shoulder season temperatures where the heat pump should operate at very high efficiency and have sufficient capacity to meet the load of the home. Figure 21 shows the delivered heat from a central heating system with staged controls. At temperatures above 30°F, the auxiliary heat boosted the heat pump capacity to over 50,000 Btu/hr., which was well above the heating load of the home. Staged control had some benefit in that the heat pump ran at colder temperatures, than it would have under a switchover mode. But that came with considerable backup runtime in warmer temperatures when the heat pump could meet the full load of the home. The heat pump was running at capacities great enough to meet the load of the home. When the temperature was colder, perhaps down to zero, the heat pump had some runtime at capacities needed to meet the home’s load. Because of the 20-minute runtime limit before backup fired, we see considerable runtime where the backup system and the heat pump were both firing, limiting the savings from the heat pump.

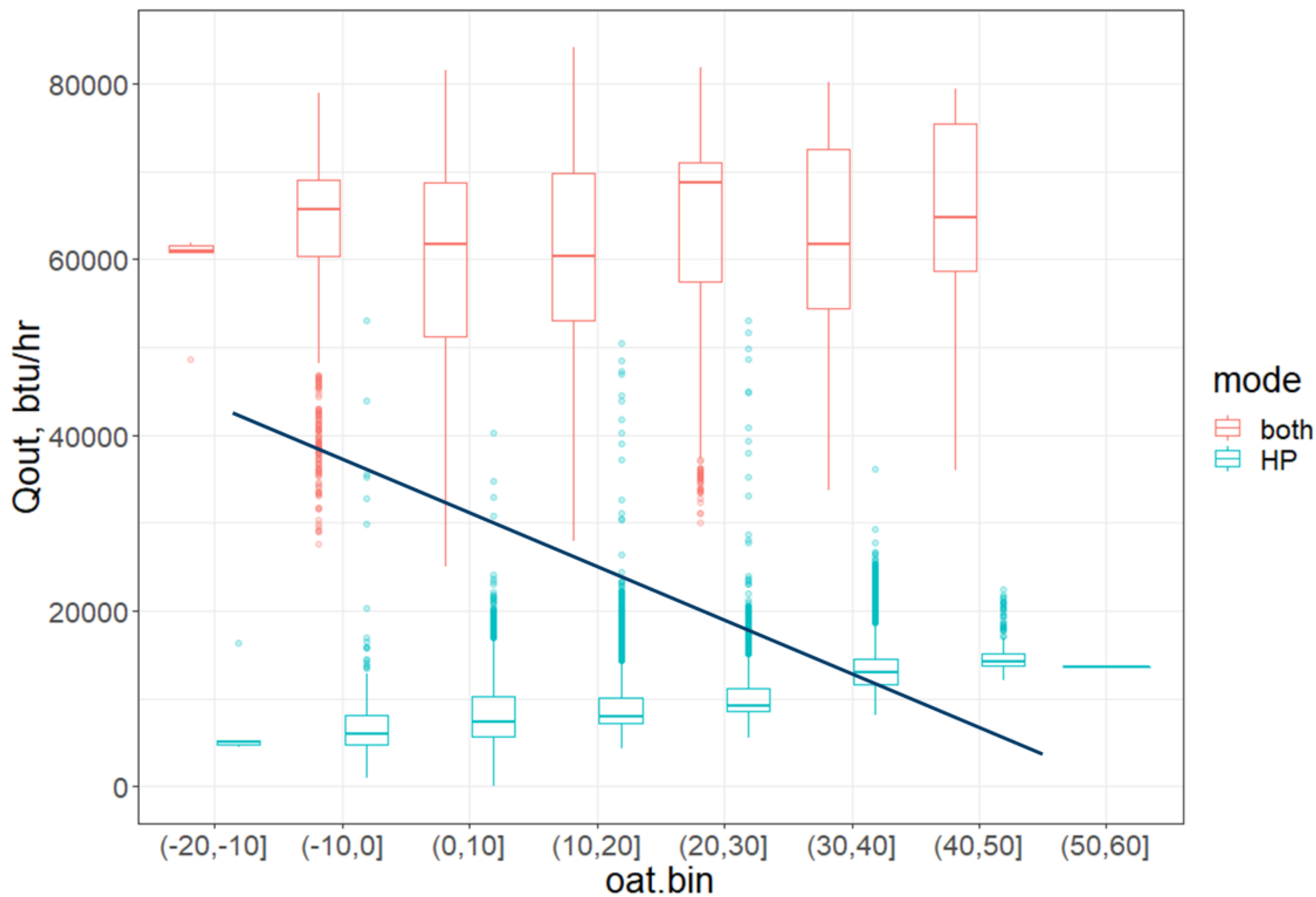


Figure 21. Heat pump and auxiliary heat modes under staged control

Third-party controllers for integrating auxiliary heater

One of the benefits of ductless heat pumps was that the systems were installed independent of other systems in the home. Installations were relatively simple without a lot of site-specific modifications required. A related drawback was that for most ductless heat pumps there was no connection to auxiliary systems, which made it a challenge to control those systems and prioritize the heat pump. Several control strategies were deployed at a site with a multi-head ductless heat pump with electric resistance and an electrical boiler as supplemental heat. Three different control modes were deployed to control the interaction between the systems.

- Mode 1 used separate thermostats for each system. After giving general guidance about how to set thermostats to prioritize the heat pump, the occupants were allowed to run the system as they saw fit.
- In mode 2, research staff adjusted the thermostats for the auxiliary system to have a setpoint 3 degrees lower than that of the heat pump system, thus prioritizing the heat pump over the backup systems.

- Mode 3 tested the use of a third-party control system. This system required re-wiring the backup and auxiliary systems and measured air temperatures in different zones and used those temperatures to control which systems were allowed to heat. The controller prioritized heat pump runtime over auxiliary systems.

Figure 22 shows the impact of the controller over the system runtime. The third-party controller, mode 3, eliminated most of the boiler runtime and the baseboard either off or on depending on occupancy in that zone. The heat pump runtime was increased under the mode 3 controller. For a day with an average temperature of 20°F outside, mode 3 used 15% less energy when compared to mode two and mode one. Unfortunately, this home had some existing electrical issues that limited the monitoring period, and a full seasonal savings was not able to be calculated.

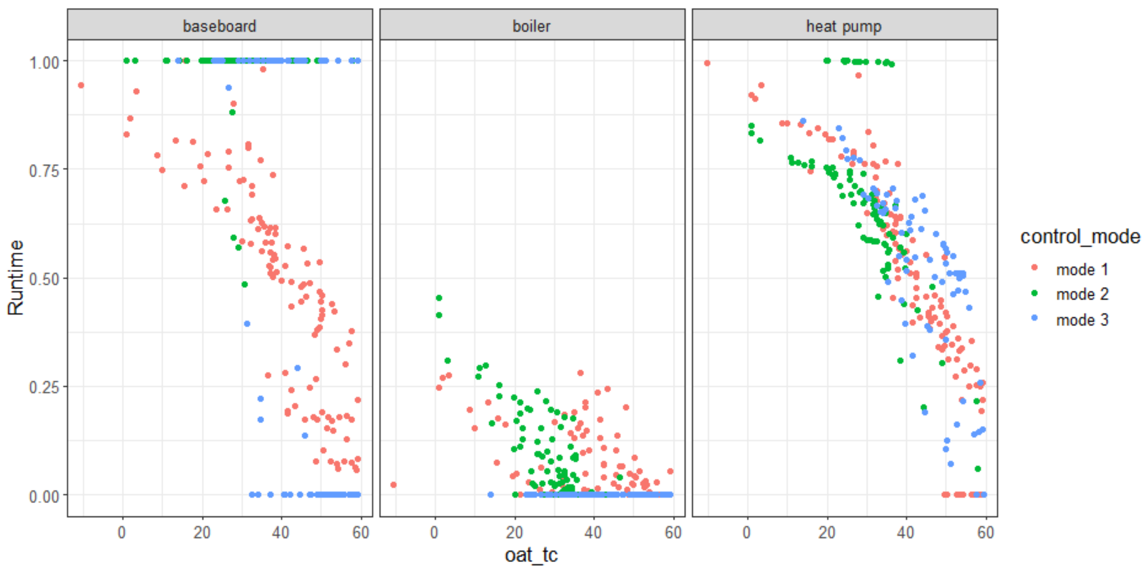


Figure 22. Comparison of control modes and the runtimes of different systems at various heating temperatures

The impact of heat pumps on energy use and load profiles

Climate and energy goals both nationally and locally have increased interest in electrification and decarbonization. As electric heat use increases, so does the importance of understanding winter load peaks and their impact on utilities. Even during very cold temperatures, when winter peaks are at their worst, ASHPs are about twice as efficient as electric resistance heating. That means they contribute half the electrical use to the grid as a traditional resistance heater delivering the same load. Therefore, it is important to minimize the use of electric resistance heating during peak load conditions, whether that resistance use is from electrically heated homes without a heat pump installed or from auxiliary or backup heat in a home with an ASHP.

Choices made in heat pump design, sizing, and installation will impact the electrical use during peak events. The systems can be optimized to reduce this usage. The key to optimizing for peak events is to understand when those events occur and to size the heat pump to meet as much heating load as possible in those events and enable a controller that will prioritize the heat pump operation during peaks.

Figure 23 shows the impact of a heat pump on total energy use in one home. This heat pump was not designed specifically to offset peak load but was intended to displace the majority of heating load in the two largest heating zones with a multi-head system. The heat pump was designed with electric resistance as supplemental in the large zones when the indoor space temperature dropped from insufficient ASHP heat. Resistance heat also remained for use in zones where there was no heat pump head. In cold conditions, the resistance heat was needed to supplement the heat pump use — thus the short-term usage peaks were very similar between the heat pump and the baseline modes, 7.7 kW ASHP plus auxiliary compared to 8.1 kW in baseline. However, the period without heat pump usage had less time with low or no use and a higher average consumption than when the heat pump was installed, 3.7 kW ASHP and auxiliary compared to 5.4 kW in baseline.

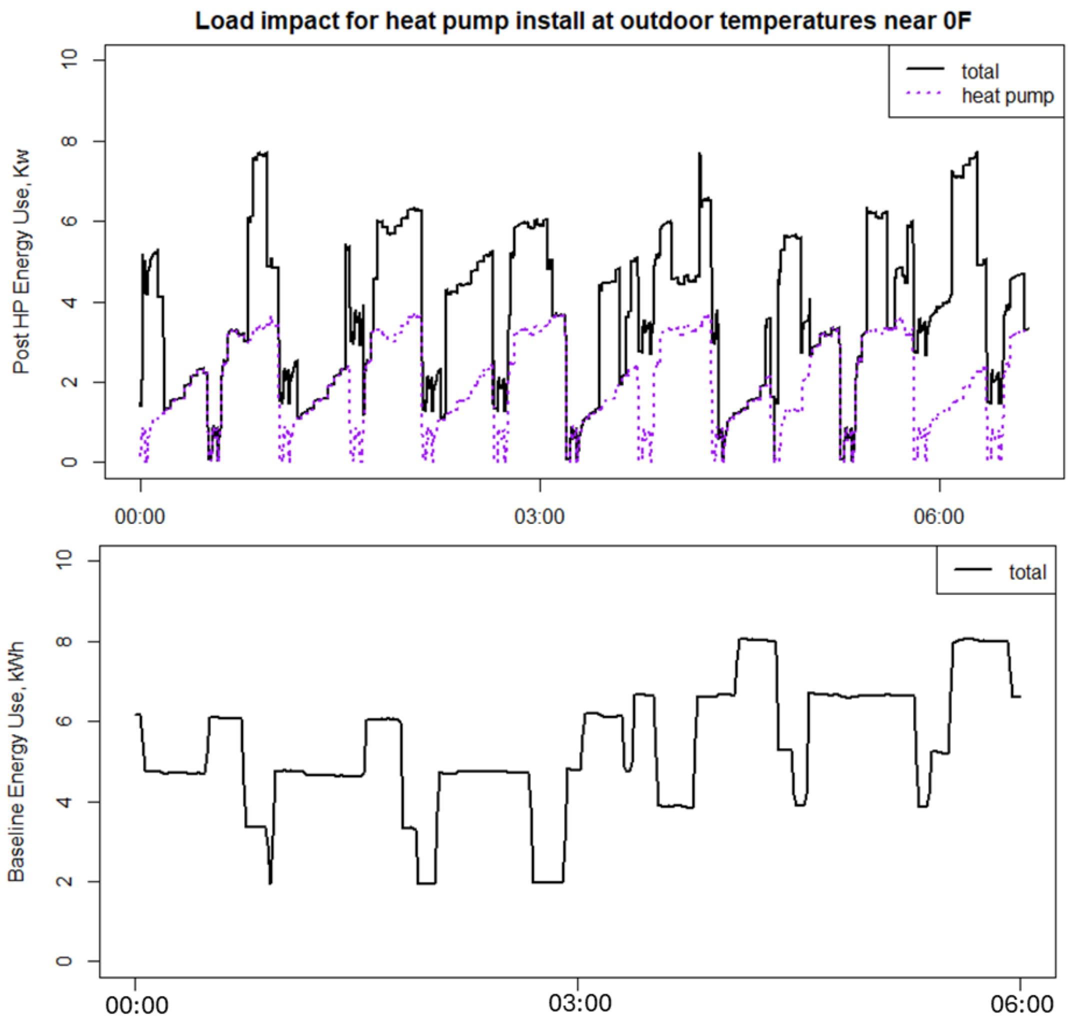
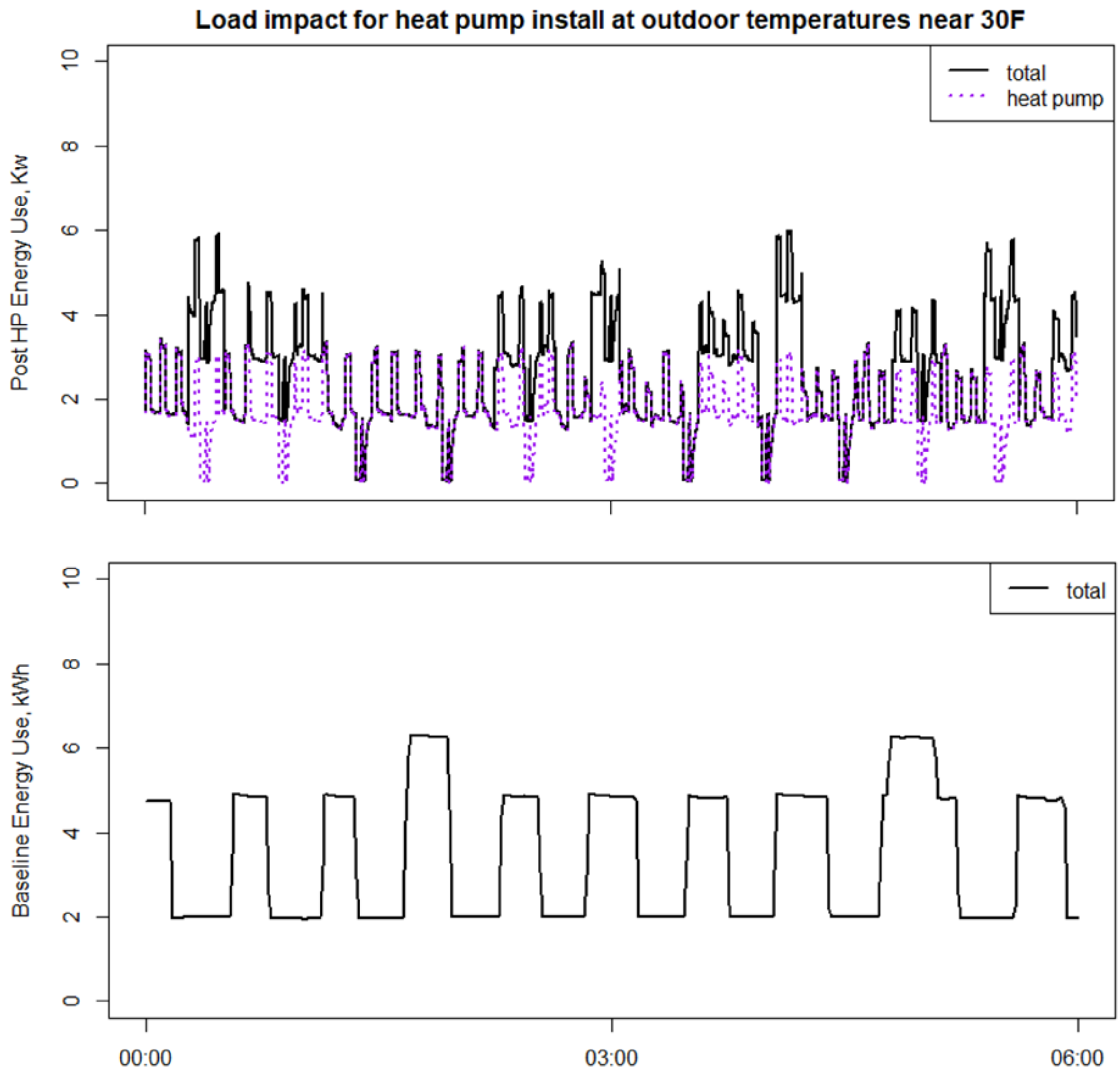


Figure 23. Comparison of total heating energy use at a home before and after the installation of a multi-head HP system over 6 hours around 0 °F outdoors

In operating conditions were the heat pump was designed to meet a larger fraction of the homes load, the system will have a greater impact on peak load use. At this home, at temperatures near 30 °F, the heat pump was designed, installed, and operated in a way that met the majority of the homes load. Figure 24 shows the comparison between the baseline, no heat pump; operation and the energy use after the heat pump was installed. The peak usage was reduced from 6.3 kW to 6.0 kW and the average usage was reduced from 3.5 to 2.5 kWs. Heat pump performance curves have higher efficiencies and equal or greater capacities at mode moderate temperatures. As such they will offset more electric resistance heat (or require less electric resistance auxiliary heat in the case of full decarbonization to an all-electric heating system) in moderate conditions. However, depending on the goals of the installation and the electricity costs and rate structures, it may be beneficial to size a heat pump to optimize for peak load reduction at colder temperatures.


Load impact for heat pump install at outdoor temperatures near 30F
Post HP Energy Use, Kw
total
heat pump
Baseline Energy Use, kWh
total
00:00
03:00
06:00

Discussion of Results

Installation Best Practices

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 24). 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.

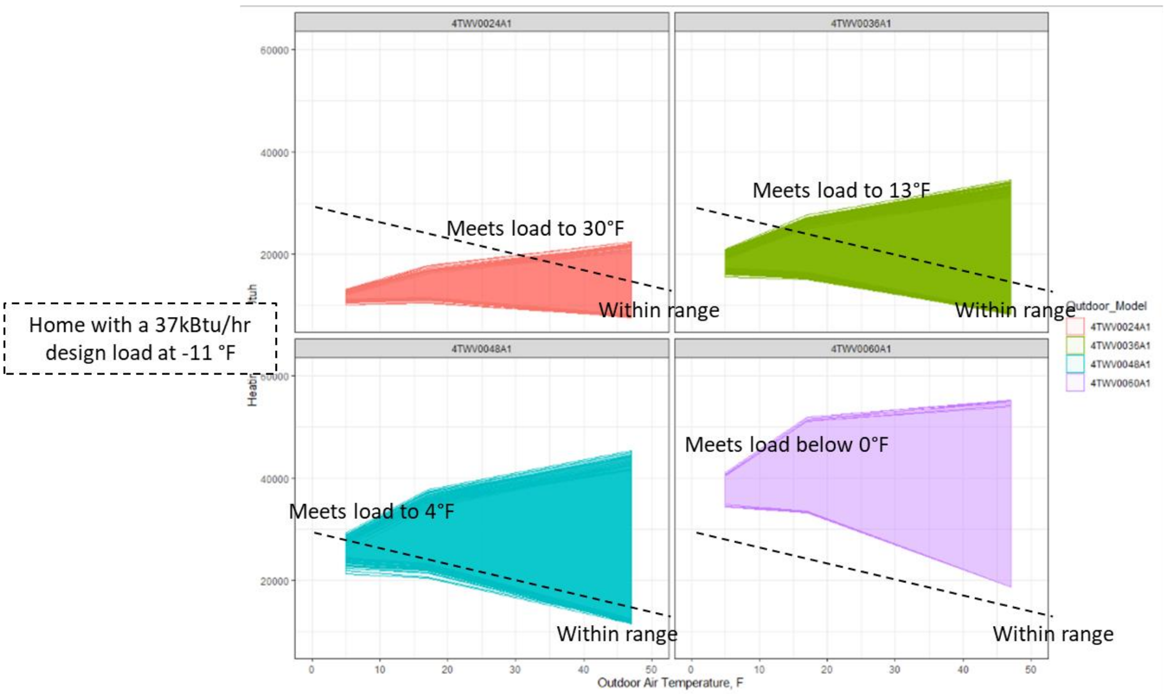


Figure 24. Comparison of the capacity of multiple size heat pumps to a house load curve

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 25* 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 can 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.

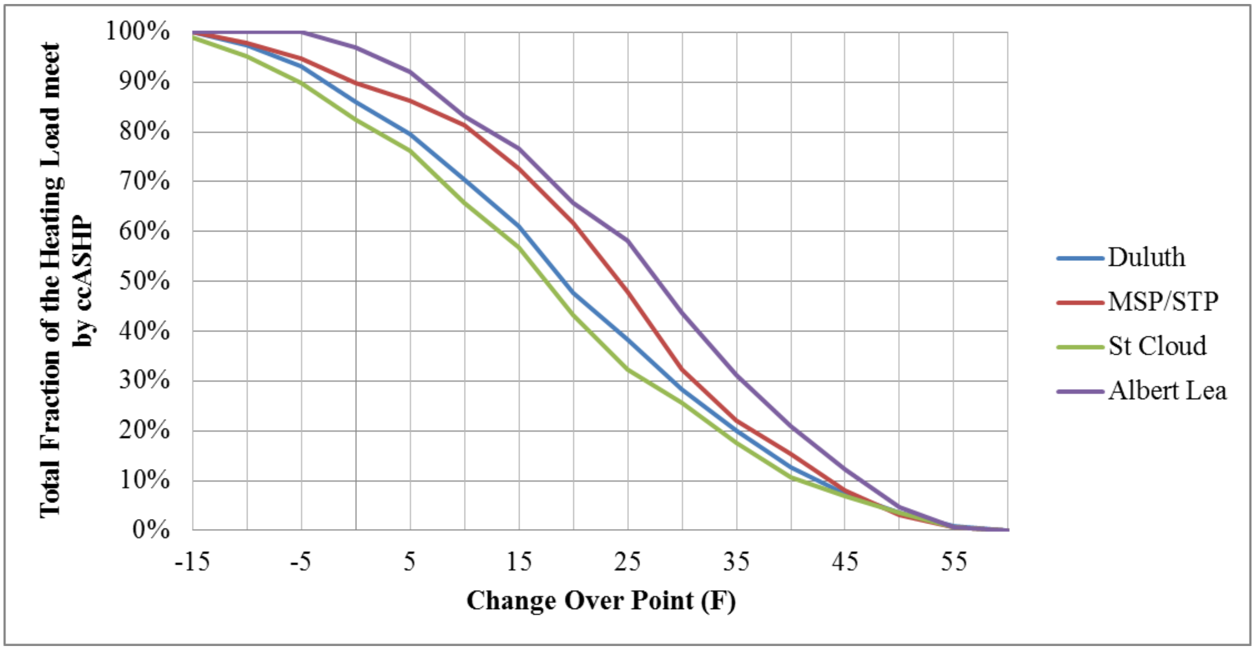


Figure 25. Switch over point impact on heating pump heating fraction

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 10 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 10. 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

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.

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.

Recommendations and Conclusions for SF ASHPs

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.

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).

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 Survey

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

For CEE staff Only:
Please use the space below to provide additional comments/follow up questions on participant survey.

Appendix B: Site Screen Summaries

SF_05

Homeowner was initially contacted via phone to confirm home met initial criteria for the project.

Initial site visit: 12/11/2019

Home Characteristics

- Built in 1975
- Two stories
- 2000 square feet
- No existing ductwork

Ease of Monitoring

- Breaker panel behind the hot water heater makes access slightly difficult but not impossible.
- Mechanical and other areas of the home required for monitoring are accessible and do not present additional monitoring challenges.

Heating Characteristics

- In-ceiling radiant in the upstairs living space
- Electric resistance baseboard heat throughout the home
- Wood burning stove in basement/master bedroom

Cooling Characteristics

- Window AC unit

Thermostat

- Non-programmable thermostat that controls baseboard heat throughout the home

Planned ASHP Approach

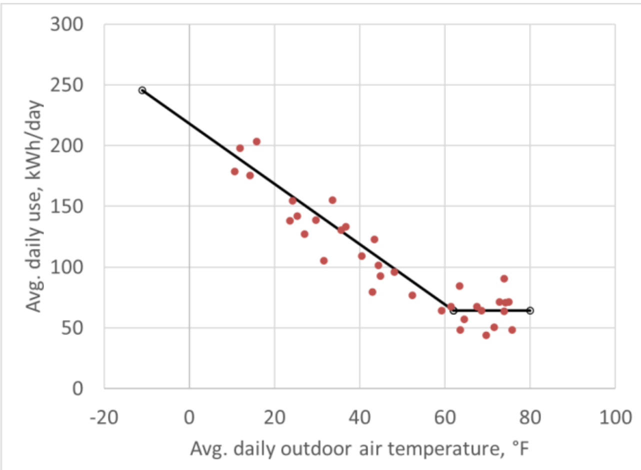
- Ductless mini-split with one to two heads in main living spaces.
- Need to confirm via sizing and like savings potential but likely installing in living room and master bedroom in the basement.

Screening Summary

- Homeowner demonstrated willingness to participate in the project. Their main motivation for participation is to lower significant energy bills.
- The home itself seems to be a good fit for the project. There is moderate insulation throughout the house and good envelope. The floor plan is relatively open, especially in the basement/master bedroom making it ideal for ASHP application. Adding ductwork is an option

because the downstairs area is unfinished, but a ductless ASHP would also be viable due to the open floor plan.
- There is a wood burning stove in the basement that is used as supplemental heating on particularly cold days; however, homeowner said they would be willing to not use it for the duration of the study to assist with monitoring.

Billing Analysis



Bill Analysis Results	SF_5
Change point	62 °F
Heating use at design temp (-11°F)	25,838 Btu/hr
Annual heating use	18,276 kWhr/year

Appendix C: performance maps of COP and capacity versus outdoor air temperature

Ductless

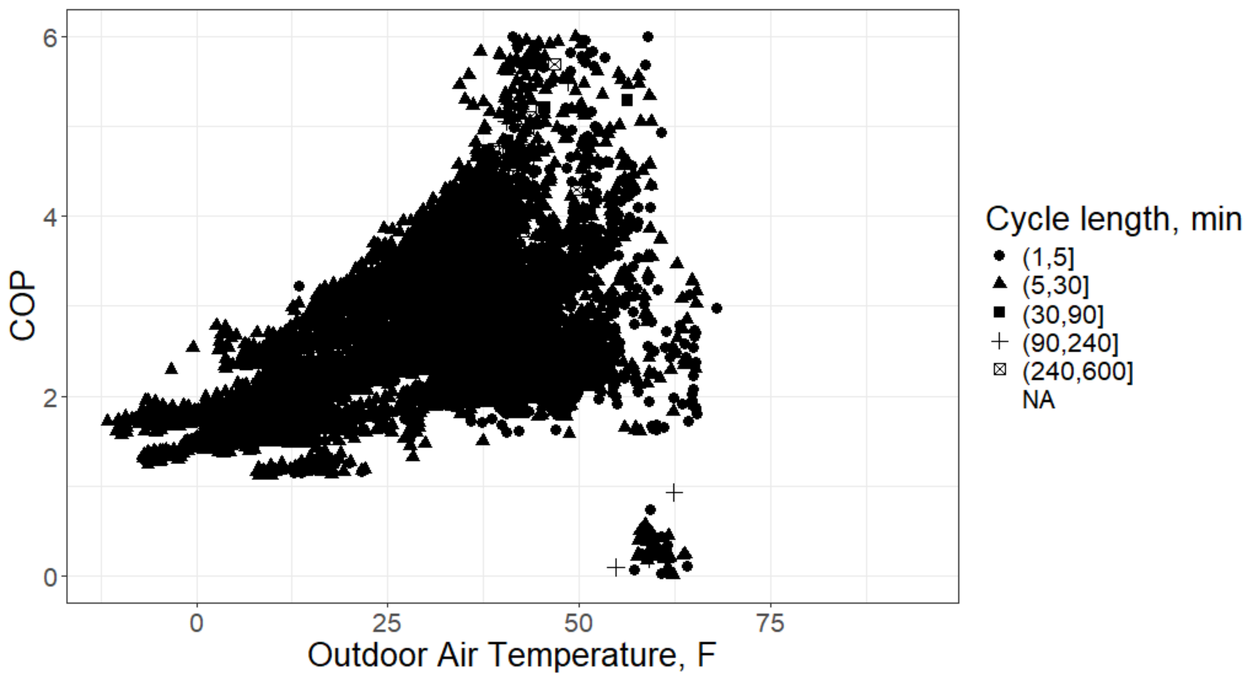


Figure 26. Heating Efficiency of ductless HP at SF_5

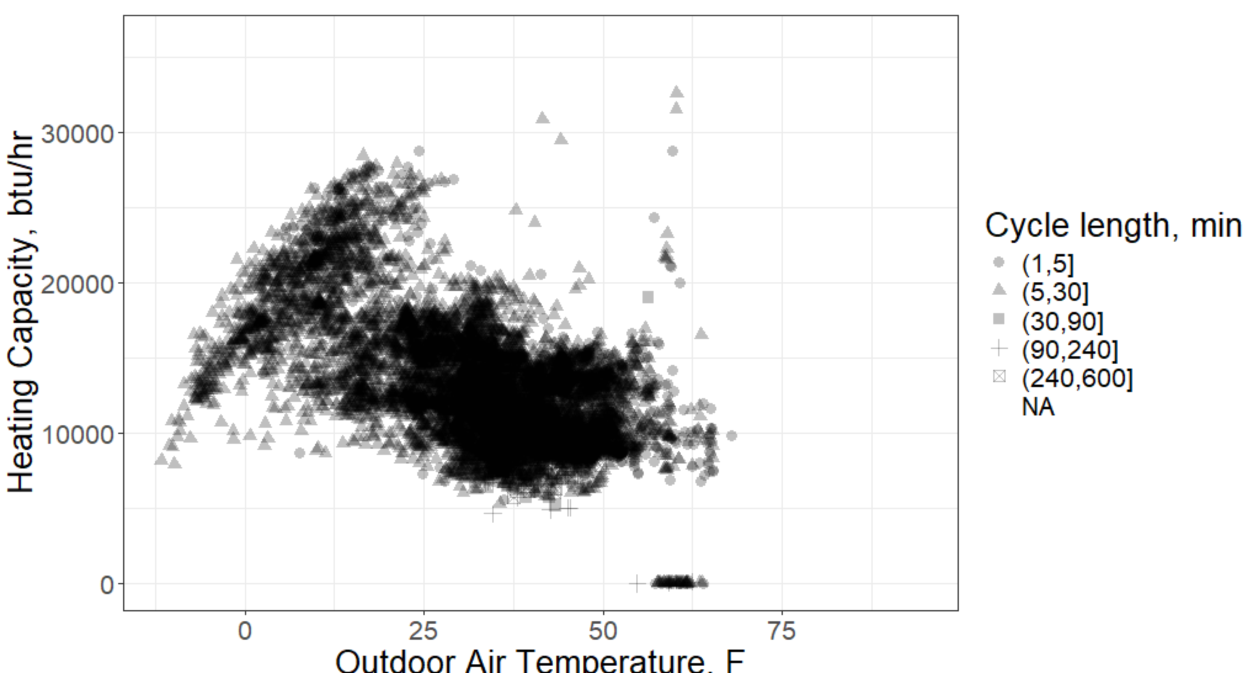


Figure 27. Heating capacity of each cycle of the ductless heat pump at SF_5

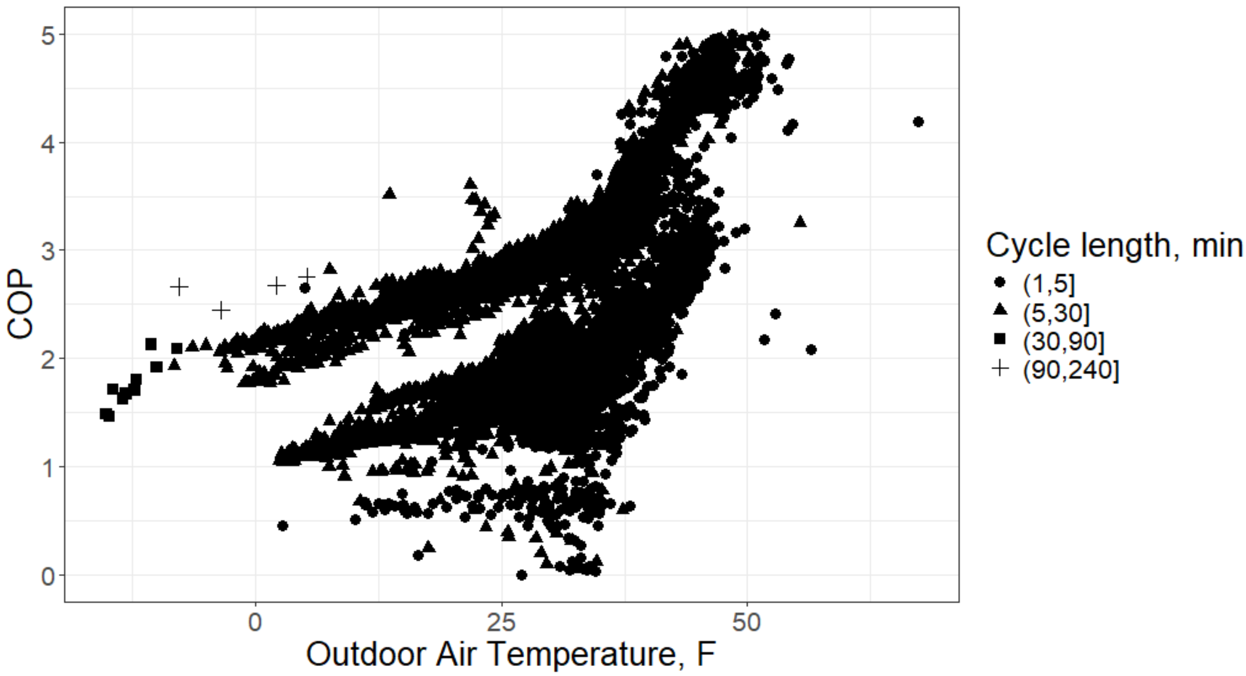


Figure 28. Efficiency of ASHP cycles at SF_14

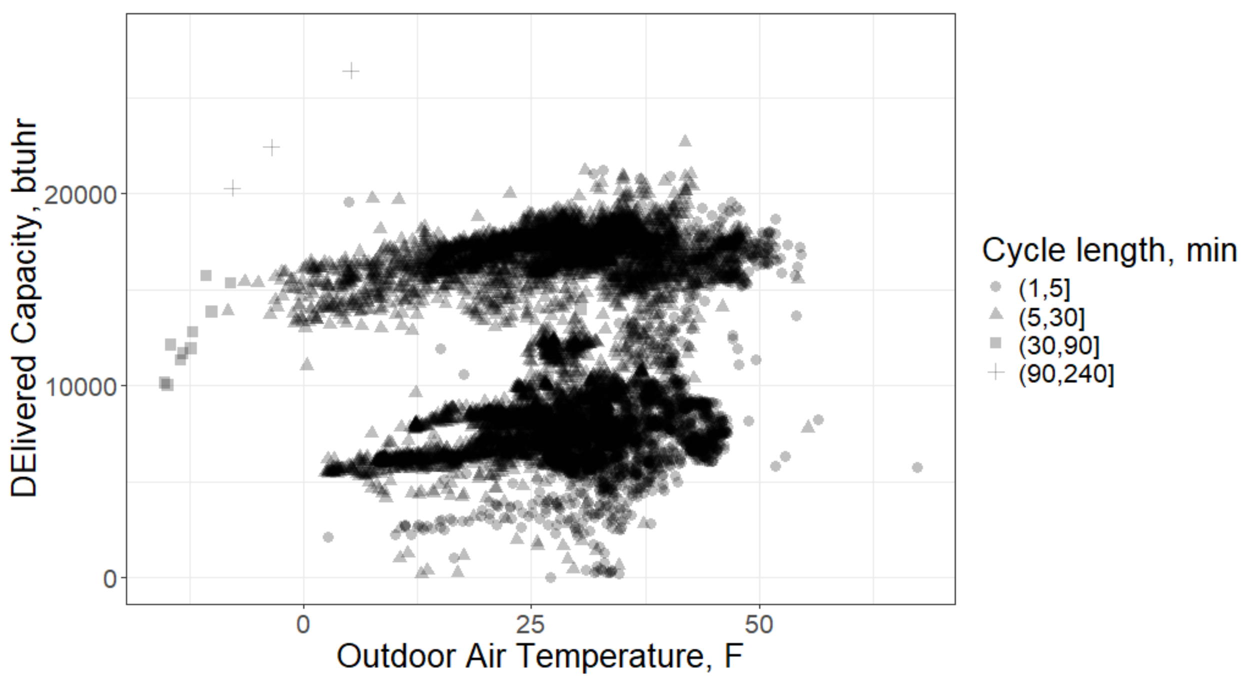


Figure 29. Delivered capacity of the ductless heat pump at SF_14

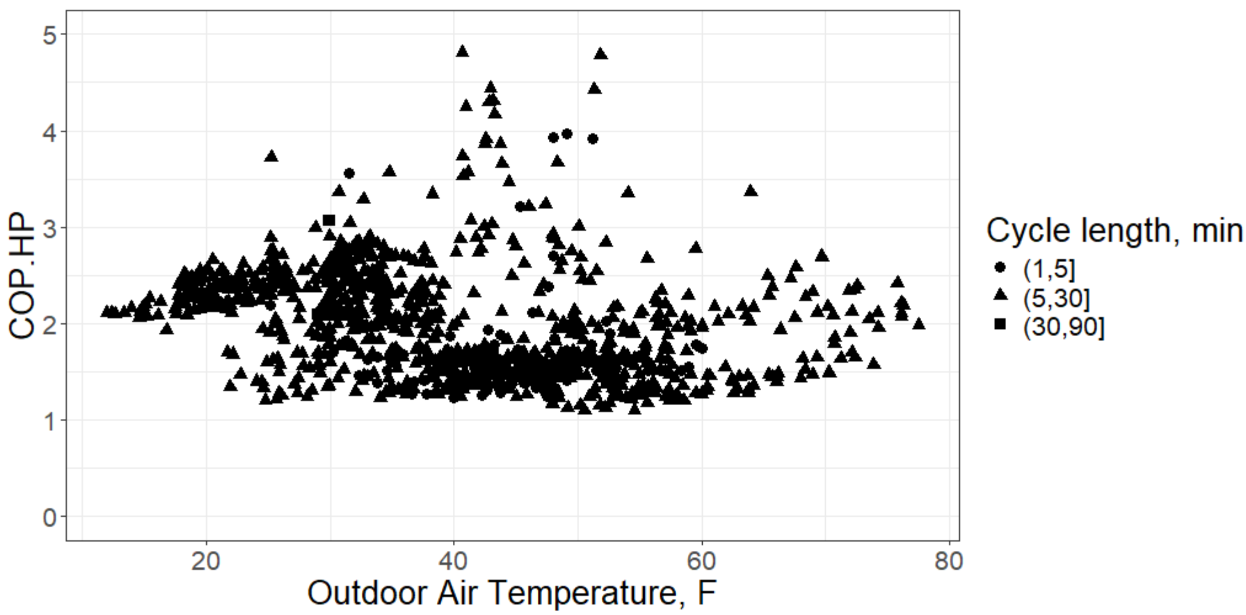


Figure 30. Heat pump cycle efficiency at SF_12

SF_12 cycled in a different way than other multi-head systems. For about half of the events one of the indoor heads did not turn on while the other head ran for the full cycle. These events with partial operation had lower efficiency and capacity than events with both heads in operation. The difference in these two modes can be seen in the performance curves with bimodal fits, unlike at other ductless installs.

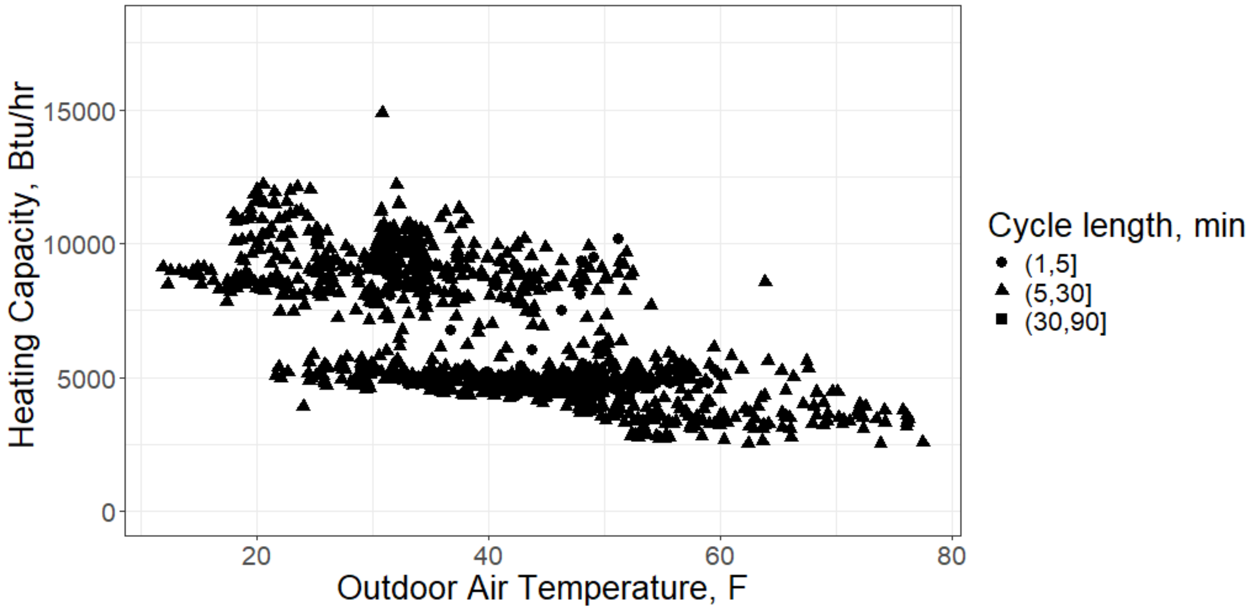


Figure 31. Delivered capacity of each cycle at SF_12

Ducted Systems

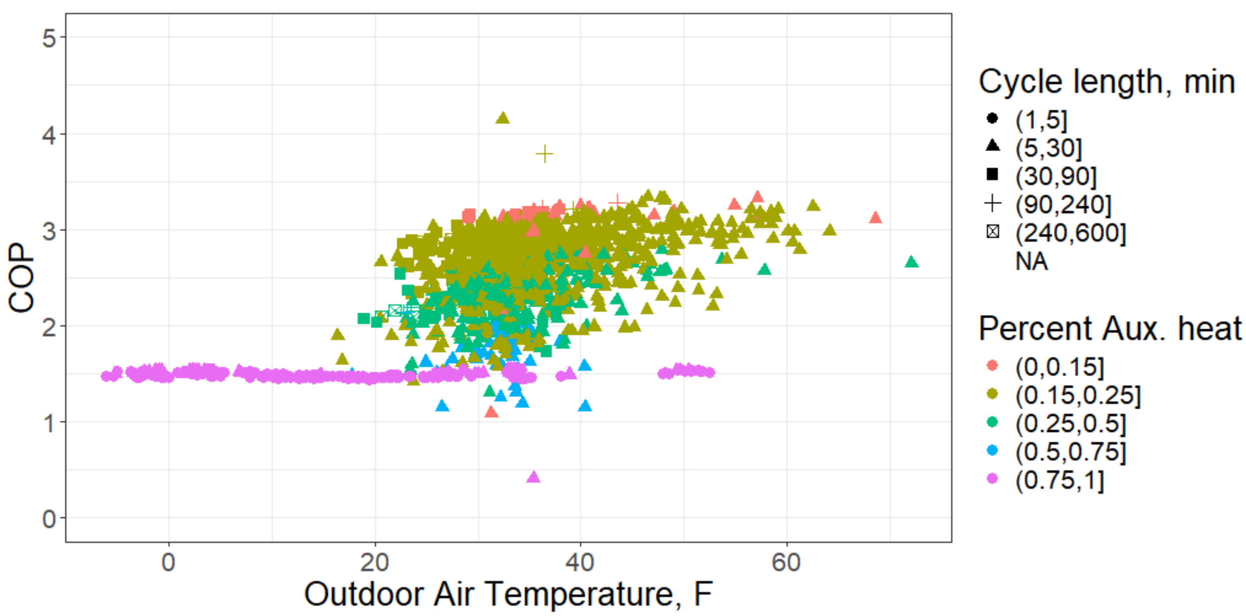


Figure 32. Efficiency of the heat pump cycles at SF_21

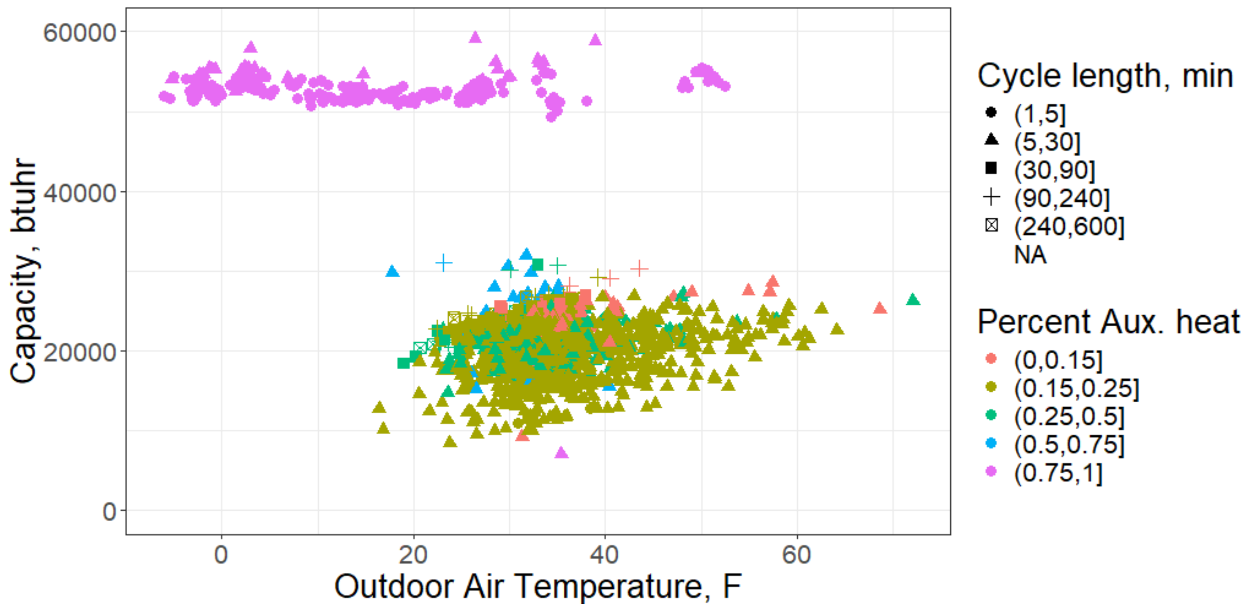


Figure 33. Delivered heating capacity from the centrally ducted ASHP at SF_21

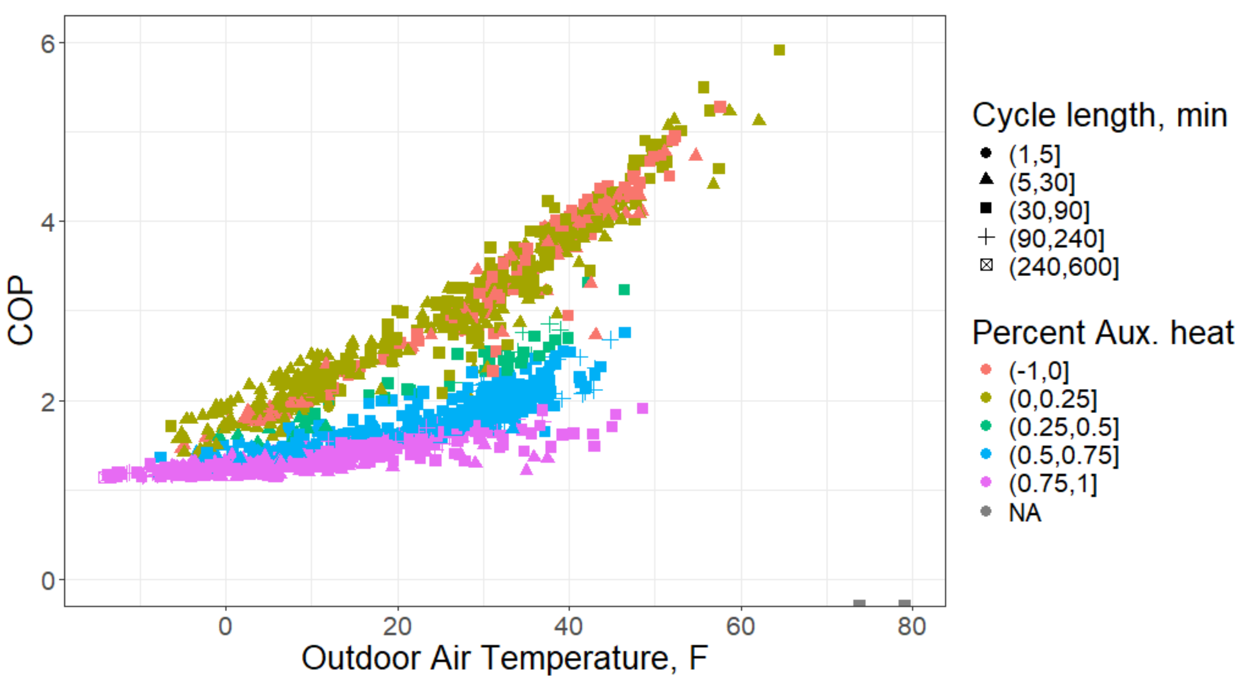


Figure 34. Heating cycle efficiency at SF_18

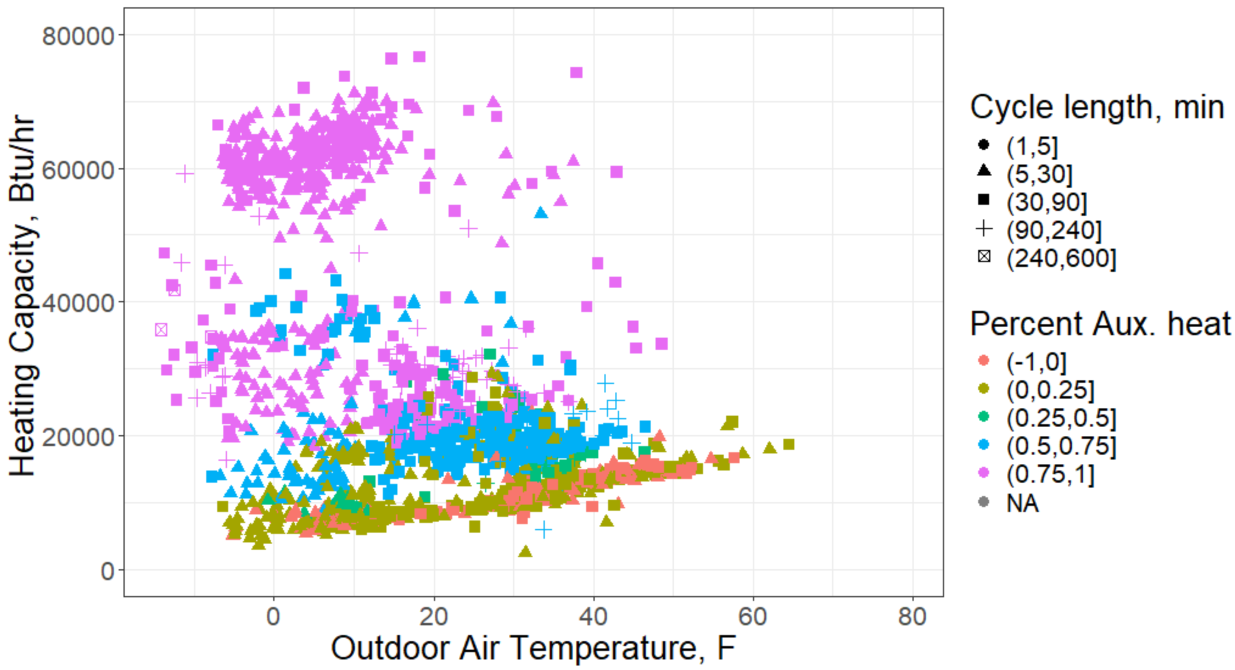


Figure 35. Heating cycle delivered capacity at SF_18

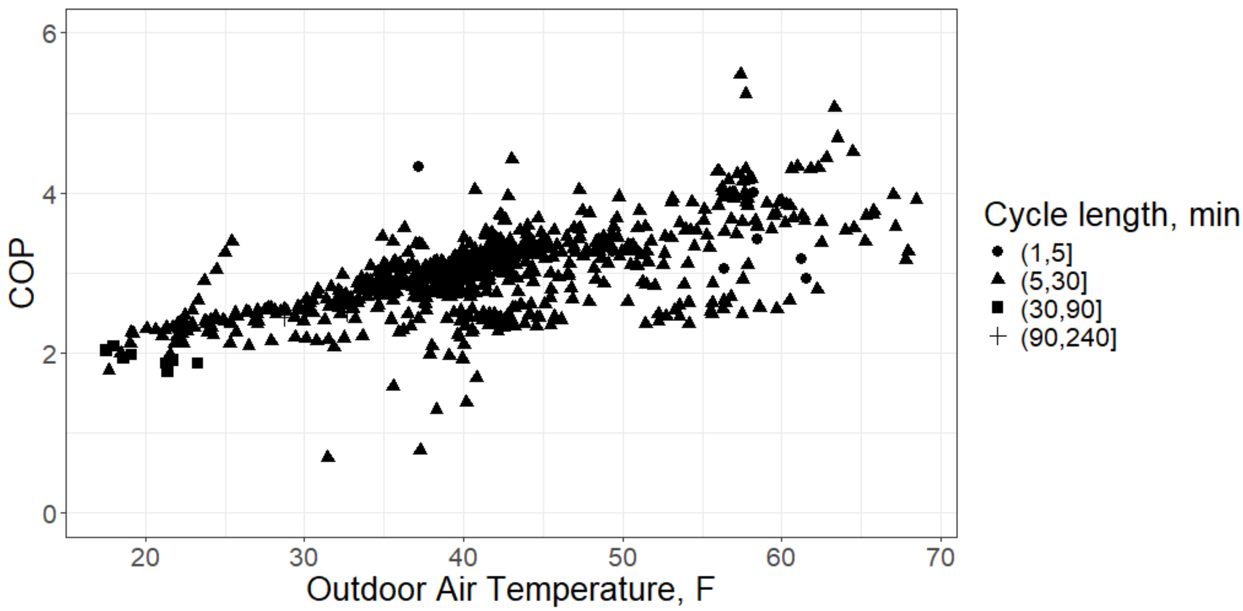


Figure 36. Heat pump only efficiency at site SF_27

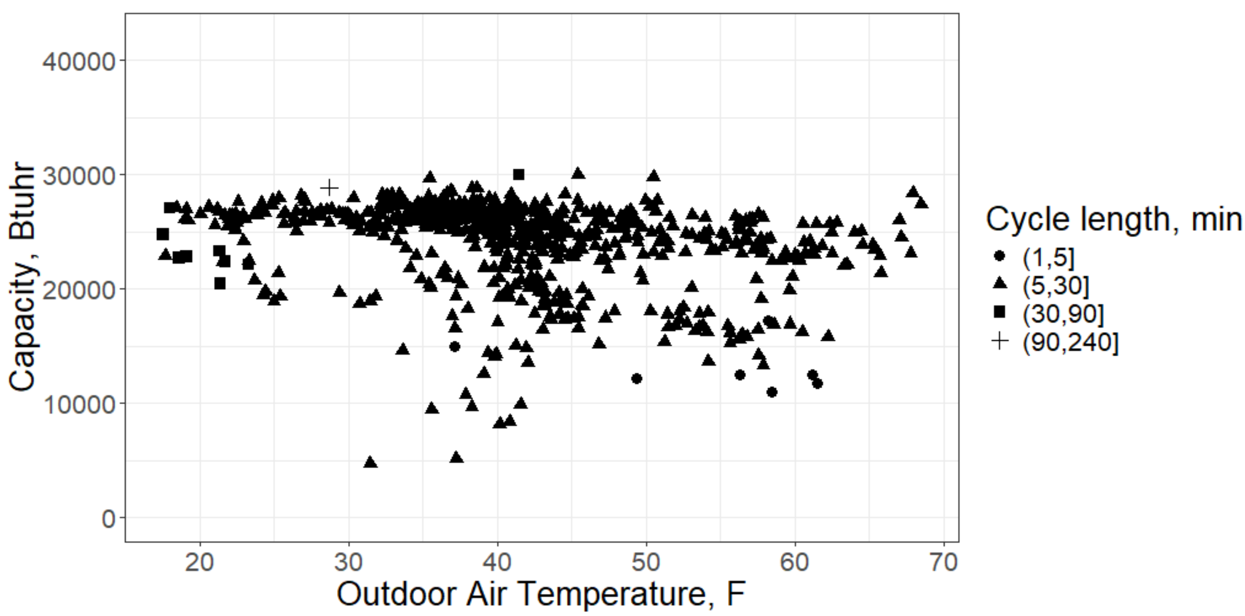


Figure 37. Delivered heating capacity of the ASHP system at SF_27