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Air-to-Water Heat Pumps

A Cold Climate Solution for High-Efficiency Cooling, Space Heating, and Water Heating

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Definition of Terms and Acronyms

AHRI – Air-Conditioning, Heating, and Refrigeration Institute

ASHP – Air Source Heat Pump

Auxiliary Heat – Electric or propane heating system serving as backup to the heat pump

AWHP – Air-to-Water Heat Pump

CAC – Central Air Conditioner

ccASHP – Cold climate inverter-driven air-to-air ASHP capable of operating below 17 °F

CEE – Center for Energy and Environment

CEE1 – Consortium for Energy Efficiency

CIP – Conservation Improvement Program

COP – Coefficient of Performance

CT – Current Transformer

DHW – Domestic Hot Water

ECO – Minnesota Energy Conservation Optimization Act

EER – Energy Efficiency Ratio

ER – Electric Resistance

GWP – Global Warming Potential

HOBO – Onset HOBO Air Temperature and Relative Humidity Data Logger

HSPF – Heating Seasonal Performance Factor

HVAC – Heating, Ventilation, and Air Conditioning

IDU – Indoor Unit

IPLV – Integrated Part Load Value

LPG – Liquefied Petroleum Gas

NOAA LCD – National Oceanic and Atmospheric Administration – Local Climatological Data

NPLV – Non-Standard Part Load Value

OAT – Outdoor Air Temperature

ODU – Outdoor Unit

SCOP – Seasonal Coefficient of Performance

SEER – Seasonal Energy Efficiency Ratio

TEC – The Energy Conservatory

TMY-2020 – Typical Meteorological Year weather data published in 2020

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Executive Summary

Introduction

Air-to-water heat pump (AWHP) systems are high-performance space heating systems that offer air source heat pump (ASHP) efficiencies to customers with boilers and hydronic distribution systems. Using water as a distribution medium also enables AWHPs to integrate with domestic hot water (DHW) loads, thermal energy storage, and even traditional furnaces and air handlers using a hydronic coil. AWHP systems are established products with wide ubiquitous application in European and Asian markets. AWHP systems have been commercially available in North America for some time, yet these systems haven't received the same attention as air-to-air ASHPs. However, as interest in and familiarity with ASHPs grow, there is an increasing appetite to understand the role AWHP systems can play in bringing high efficiency to local hydronic-based space heating systems.

Center for Energy and Environment (CEE) studied commercially available AWHP systems in the context of cold climate heating and cooling in Minnesota single-family residential applications. The objectives of this study include identifying opportunities and considerations for AWHP systems in Minnesota homes, a characterization of current AWHP systems and components available for those applications, the installation of AWHP systems in retrofit applications, and the evaluation of associated energy and cost savings. This research was supported by a grant from the Minnesota Department of Commerce, Division of Energy Resources through the Conservation Applied Research and Development (CARD) program. Great River Energy and Steele Waseca Cooperative Electric provided additional support.

Methods

This was a field study on AWHP systems. The project team categorized equipment available in the marketplace and potential applications for Minnesota single-family homes to select equipment for long-term monitoring and evaluation. Four systems from two different manufacturers were installed and monitored for one to two years. Two systems were installed for space heating only, one system for space heating and cooling, and one system for space heating, cooling, and domestic hot water preheating. Over the course of the study, project staff intervened to resolve equipment and control issues and improve the field performance of equipment. Performance maps, consisting of coefficient of performance and capacity measurements as a function of outdoor air temperature were developed. These relationships enable performance forecasting that is largely independent of site-specific variances. These performance maps can be used to estimate representative savings from future installs.

AWHPs Right Now

Despite the lack of familiarity in the Minnesota market, AWHP systems are an established technology. AWHP systems are simply a subset of the broader category of air source heat pumps (ASHPs). The key difference is that instead of exchanging energy between a refrigerant loop and an air stream as in an air-to-air ASHP, AWHP systems exchange energy between a refrigerant loop and a water loop that may serve multiple loads. Dozens of AWHP systems are available from both small and large manufacturers and many of these systems are available from the same manufacturer. While air-to-air ASHP systems can be paired with a traditional furnace or electric plenum heaters for backup or supplementary heating, AWHPs pair with electric or fossil fuel boilers as well as traditional furnaces.

AWHP systems are available in three main configurations including:

- Traditional split systems, which implement most similarly to their air-to-air ASHP counterparts with brand-matched indoor and outdoor units
- Third-party split systems, whereby an indoor AWHP unit is paired with a noncommunicating, conventional central ASHP outdoor unit
- Monobloc systems, where the refrigerant loop and refrigerant to water heat exchanger are contained entirely in the outdoor unit, eliminating the need for onsite refrigeration work

Savings

Although AWHPs can serve space heating, cooling, and domestic hot water loads, they primarily function as space heating systems in Minnesota. Systems installed in this study bring substantial space heating energy savings compared to baseline electric boilers and propane furnaces. The heating savings attributed to the AWHP in this project ranged between 6,300 and 16,600 kWh/yr for the systems field tested in this study. Projected transferrable space heating energy savings are 27% to 50% depending on the system and climate. Seasonal average COPs for the systems in this study ranged from 1.35 to 2.01. For AWHPs installed with hydronic air handlers for space cooling, the hydronic coils were configured to provide space heating as well, displacing nearly the entire propane use of the existing furnace.

Due to their native hydronic distribution, many AWHP systems can also provide domestic hot water service. The unit in this study displaced 30% of the existing electric resistance water load for an overall water heating savings of 40% at one site with approximately double the average hot water use of a typical Minnesota home. Based on these water heating savings, this system may displace over 90% of the load for homes with average hot water use. However, since the installed unit served as a pre-heater, an existing DHW system is still generally required.

Two AWHP systems were installed with hydronic coils to provide space cooling using a conventional propane furnace in place of central air conditioning units. While these systems served space cooling needs, monitoring limitations and only moderate sensible space cooling performance suggest that significant cooling savings are not likely but warrant further study.

Overall, with or without domestic hot water savings and even negligible cooling savings, AWHP systems provide compelling overall energy cost savings for customers with electric or propane boiler baselines, ranging from $453 to $1,450 per year. The projected overall energy cost savings for similar applications ranges from 27% to 53%.

Barriers

While AWHP systems are compatible with all types of radiators, some types of emitters may present challenges. Radiators such as cast iron and older baseboard units designed for high supply temperatures (160°F and up) may struggle to supply sufficient capacity at AWHP supply temperatures of less than 130°F. This finding adds an additional design step; when specifying AWHP systems, detailed load and emitter capacity calculations are required.

As a new technology, AWHPs still face significant market barriers. The four systems in this study were installed by four separate contractors, all of whom were new to AWHP technology. Systems that integrated with forced air systems using hydronic coils, domestic hot water, and existing zoning controls required extensive manufacturer support during installation and commissioning.

AWHP systems do not yet have standard rating methodologies in the U.S. like the HSPF or SEER values of their air-to-air ASHP counterparts. Such standard rating methods may prove more difficult in practice due to the large configurability of AWHP systems. Furthermore, this configuration flexibility of AWHPs poses additional complexity leading to more upfront design work compared to boiler or air-to-air ASHP alternatives.

Opportunities

Despite challenges of high-temperature radiators, AWHPs have current opportunities in retrofit or new construction homes that feature low-temperature emitters, such as radiant slabs. Additional application opportunities will develop alongside familiarity with the technology. AWHPs may be a compelling alternative to other ASHP types. Their configurability is especially suited to bespoke or integrated HVAC and DHW system designs.

Recommendations

AWHPs carry benefits that are similar to or surpass that of other ASHP types. Programs should promote AWHPs as potential customer solutions in any instance where a cold climate air-to-air ASHP is determined to be beneficial but impractical to implement due to the existing hydronic infrastructure.

Overall, AWHPs should be treated as ASHPs and aligned with existing ECO models and programs for air-to-air ASHP systems. Existing strategies for overcoming ASHP market barriers should be replicated for AWHPs. Program and conservation staff should advocate for standardized ratings for AWHP systems and configurations congruent with existing air-to-air ASHPs. In lieu of standard ratings established qualified product listings (QPLs) can be used now to make AWHP systems compatible with existing ASHP programs. Efficiency Vermont has established QPLs for a similar climate that have been adopted by MassSave and Otter Tail Power.

Introduction

Air-to-water heat pump (AWHP) systems are a type of air source heat pump (ASHP) that offer flexible configurations and can extend heat pump efficiency savings to customers with hydronic heating systems and boilers. They also have the potential to integrate with domestic hot water (DHW) loads, air distribution systems, and thermal energy storage. However, with this flexibility comes complexity, which may have thus far limited their appeal compared to simpler ASHP systems in North America. To overcome this new technology burden, this report describes Center for Energy and Environment's (CEE's) study on AWHPs for cold climate heating and cooling. The project team reviewed product literature for available AWHP systems and configurations best suited to residential cold climate heating, hot water, and cooling loads. Then, four AWHP systems relevant to the residential market in Minnesota were retrofitted and monitored in occupied single-family homes to measure energy savings, installation costs, customer acceptance, ability to meet loads, and cost-effectiveness. This work puts AWHPs in context for Minnesota consumers while demonstrating their achievable energy and cost savings. The research was supported by a grant from the Minnesota Department of Commerce, Division of Energy Resources through the Conservation Applied Research and Development (CARD) program. Great River Energy and Steele Waseca Cooperative Electric provided additional support.

Justification

AWHP systems have the potential to play a central role in the future of residential electric heating, which is used in 16% of the homes served by Minnesota's cooperative and municipal utilities (CEE et al. 2018). As with other heat pump technologies, AWHPs have found initial success in mild climates due to very high performance in those conditions and overall flexibility in many configurations. However, there were limited installations and no third-party demonstrations of AWHPs in Minnesota prior to this work. Lack of information remains the largest market barrier to adoption of this energy-saving technology. While one investigation was underway at the start of this study in the northeast (Henderson 2022), complete demonstrations in North America to date are in hot, dry climates. The lack of published field performance figures in cold climates applicable to Minnesota is a major technical gap. Presently, the large number of potential configurations may also present a challenge to early adopters, as research has shown that an overabundance of choices can be a barrier for decision makers (The Decision Lab, n.d.). This report narrows the range of system configurations relevant to Minnesota residences based on the local climate, most common HVAC system configurations, and general building characteristics.

Research Objectives

The objectives of this work include:

1. Identify the opportunities for AWHPs in Minnesota homes.

2. Identify AWHP components and configurations best for cold climate applications.

3. Identify considerations for deploying AWHP systems compared to both baseline systems and other heat pump technologies.

4. Identify the advantages and disadvantages of a combi (HVAC and DHW) approach to heat pump technology.

5. Evaluate heating, cooling, and water heating performance compared to manufacturer expectations.

6. Evaluate total cost of ownership for AWHPs compared to baseline measures.

Background

ASHPs use electricity to transfer energy between heat exchangers located inside and outside of a building that are connected by a refrigerant loop. For air-to-air ASHPs, the inside heat exchanger is typically an A-coil paired with a furnace or air handler. This is like a conventional central air conditioning (CAC) system. The indoor heat exchanger may also be a mini-split head with its own fan and controller for ductless systems. AWHP systems are like air-to-air ASHPs, but they replace the indoor refrigerant-to-air heat exchanger with a refrigerant-to-water heat exchanger such that energy is transferred between the refrigerant and a hydronic loop. The hydronic loop may serve several hydronic emitters or heat exchangers to meet the connected heating or cooling loads. The insertion of a hydronic loop in an ASHP system enables retrofitting hydronic heating systems, the implementation of zoned heat, or integration of space heating with other loads like domestic hot water and heat storage.

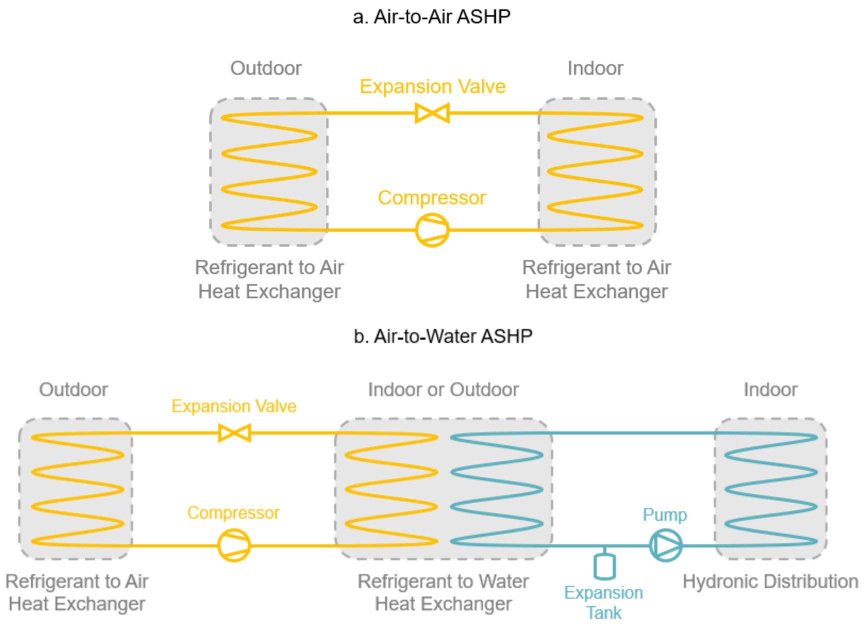

Figure 1: Schematic illustration of the heat exchangers in ASHP technologies including a) air-to-air systems and b) air-to-water systems.

Hydronic distribution presents several theoretical advantages. First, water is a more efficient distribution medium than air. The high heat capacity of water allows it to hold more than 3,500 times as much energy as the same volume of air. Second, modern hydronic systems, particularly radiant floors, use very low distribution temperatures which improve the efficiency of the heat pump cycle. Third, water distribution systems can easily incorporate a variety of heating and cooling equipment simultaneously, including radiant emitters, central hydronic air handlers, mini-split style individual room cassettes, and domestic hot water systems. AWHPs offer a distinct advantage over air-to-air ASHPs because of the seamless integration with inexpensive electric resistance for backup as well as thermal energy storage or buffer tanks for both heat and cold, which can further be leveraged for efficiency gains, additional demand response opportunities, and lowering consumption peaks. This flexibility is a major benefit that allows these systems to address a variety of applications for the cold climate residential HVAC market.

AWHP Equipment Overview

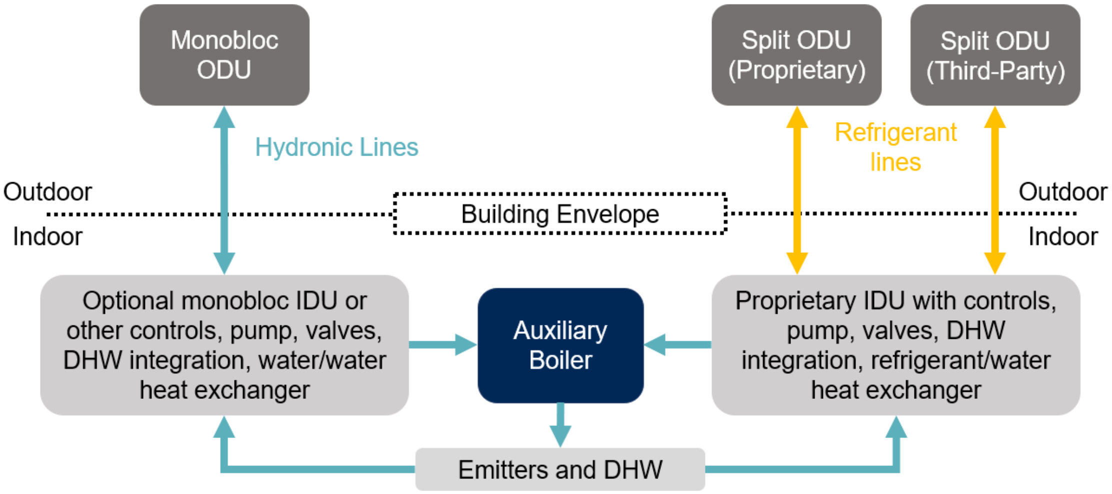

Figure 2: Schematic of major AWHP system approaches

Three sub-types of AWHP systems were identified in the available product literature: the monobloc system, the traditional split system, and the third-party split system. Example illustrations of each AWHP type are presented in Figure 2. All AWHP systems include an outdoor unit (ODU) which contains the compressor and an air-to-refrigerant heat exchanger, the same as any air-to-air ASHP. In monobloc systems, the ODU also contains the refrigerant-to-hydronic heat exchanger. In split systems, the refrigerant-to-hydronic heat exchanger is not located in the ODU but in an indoor unit (IDU) located inside the building. Split systems may be entirely proprietary with manufacturer-matched indoor and outdoor units or they may allow mixed brand matching of the IDU and ODU equipment. Such mix-and-match systems will be referred to as third-party split systems. Their ODUs may be conventional ASHP compressors not necessarily designed specifically for AWHP applications.

Monobloc systems

The defining feature of monobloc systems is that the refrigerant lines never cross the building envelope. Instead, the refrigerant is entirely contained in the ODU and comes pre-charged from the factory, simplifying field installation. Energy exchange with the indoor space occurs via hydronic lines that cross the building envelope. In cold climates, antifreeze must be added to these water-based lines in case of power outages. Propylene glycol is typically added to comprise 25% to 50% of the water mixture to prevent the hydronic lines from freezing in Minnesota's climate. Installers may add similar amounts of glycol to conventionally heated indoor radiant floor loops that do not cross the building envelope as antifreeze protection. Ensuring adequate levels of antifreeze is more critical for monobloc AWHP systems, which expose the hydronic line to the outdoors.

Unfortunately, the antifreeze protection is not without its costs. As the fraction of glycol in the mixture increases, the freezing temperature decreases, but so does the heat capacity while the viscosity increases, too. Compared to a water-only system, a system with a high fraction of glycol has its heat capacity reduced by 10% or more (Zalepa 2020). This impacts the sizing requirements of the distribution equipment. Pump selections are also impacted as the hydronic fluid viscosity can increase by more than 50% over pure water. Finally, hydronic systems with glycol antifreeze require some additional maintenance as glycol can degrade and become acidic over time.

However, keeping the refrigerant loop entirely outdoors has some advantages. More advanced or higher-pressure refrigerants may be more easily accepted in monobloc AWHP designs as they do not need to be charged in the field. The quality controls available to factory refrigerant charging should also improve overall installation outcomes by maintaining the charge closer to manufacturer specifications and reducing refrigerant leaks. Most common refrigerants have very high global warming potential (GWP). For example, refrigerant R410A has a 10-year GWP of 2,256, meaning its impact on global warming is 2,256 times the impact of an equivalent mass of carbon dioxide over 10 years (Smith 2021). Finally, the existing hydronic heating workforce may have less familiarity with refrigerant charging overall, so eliminating this step from the installation may be a major benefit for market acceptance of monobloc AWHP designs.

Split systems

Overall, split configurations resemble traditional air-to-air ASHP systems more than monobloc AWHPs do. Monobloc systems may or may not be paired with an IDU, while split AWHP systems always include an IDU. A monobloc's IDU may include additional controllers, heat exchangers, pumps, and valving designed to simplify connections between the ODU and indoor hydronic distribution system. Split system AWHPs may have any of the previously mentioned optional IDU components in addition to the refrigerant-to-hydronic heat exchanger located inside. Because the hydronics do not necessarily extend beyond the conditioned space, split systems do not always require antifreeze like monoblocs do. Installers and designers may include antifreeze for additional freeze protection anyway, however, or it may be required if any portion of the hydronic circuit is not always in conditioned space.

The ODU and IDU in a split AWHP are usually paired in a proprietary (communicating) bundle, though at least one manufacturer has an IDU designed for non-communicating third-party ODUs. Traditional split systems with manufacturer-matched IDUs and ODUs have a theoretical performance advantage over third-party split systems. Keeping the unit proprietary enables designs in which the IDU and ODU can seamlessly communicate information (temperatures, pressures, etc.) to improve integration and performance when combined with intelligent controls. Third-party split systems sacrifice easily communicating controls to offer flexibility and choice on the compressor (ODU) selection. This may result in more price options for third-party split systems compared to traditional split AWHPs.

Since the ODU of a split system is essentially the same technology as traditional air-to-air ASHP ODU, third-party split AWHPs could theoretically use any air-to-air ASHP compressor unit designed for noncommunicating air-to-air systems. We are not aware of any manufacturers explicitly recommending their air-to-air heat pump compressors for application with third-party split AWHP IDUs as of late 2023. However, a small but growing number of noncommunicating cold climate air-to-air ASHPs are available in the residential market. These variable speed ASHPs are currently advertised to fill the air conditioner replacement gap when homeowners do not want to simultaneously replace their air handler or furnace with their central air conditioner replacement. If the AWHP market sees substantial growth, manufacturers may start to develop ASHP compressors specifically for third-party split AWHPs. Until then, third-party split AWHPs might leverage the growing market of noncommunicating air-to-air ASHPs designed for air conditioner replacements.

Balance of system

The AWHP type (monobloc, traditional split, or third-party split) determines the broadest details of its installation requirements. Monobloc systems are plumbing-only and may resemble traditional boilers in that respect, whereas both split system approaches require field refrigeration work. No matter the AWHP subtype, these systems are broadly compatible with all low-temperature hydronic emitters including hydronic ducted air handlers, cassette-style ductless fan coils, radiant slabs, and indirect domestic hot water tanks. However, manufacturers often explicitly recommend emitter configurations or their own emitter products.

An AWHP system can be as simple as a traditional split-AC/furnace system via an ODU and indoor ducted hydronic coil, or they may be as complex as a multi-zone boiler system with radiant floor loops, auxiliary fan coils, and domestic hot water (DHW) integration. The specific auxiliary heating integration options, domestic hot water (DHW) integration, and other balance of system component choices may vary by manufacturer, AWHP model, or installer. These details are not necessarily defined by an AWHP system’s particular archetype of monobloc vs. split. Part of this project’s work surveyed existing product literature to better understand the features typically available in AWHPs relevant to Minnesota’s cold climate and residential housing stock.

Methodology

This field research project was split into several phases. First, the team used product literature to evaluate the state of the AWHP market and identify specific equipment suitable for retrofitting single-family homes in Minnesota. Subsequently, the team evaluated homes of interested homeowners to select field study installation sites. Once available AWHP equipment was matched with suitable participating homes, local contractors were hired to complete the AWHP retrofits and support the installation of monitoring equipment. Four AWHP installations were completed between November 2021 and April 2022. The study sites were monitored from the time of AWHP installation until August 2023. During the monitoring period, data was regularly compiled and reviewed to identify potential issues. The team used early findings and consultations with equipment manufacturers to make some adjustments during the study aimed at improving performance. At the end of the monitoring period, all data was compiled and analyzed to calculate energy savings and performance. The following sections describe in more detail the methods used to complete each of these project phases.

Equipment Selection

Product information was collected through research into available offerings from national and international manufacturers. This effort, conducted in mid-2021, catalogued 190 outdoor units (ODUs) from 11 manufacturers, plus 8 NorAire IDUs that are compatible with many third-party ODUs (mainly non-communicating ASHP ODUs). As a first step, the listed products included those that explicitly mentioned hydronic applications, non-communicating ASHP ODUs, and products with more ambiguous descriptions that may be compatible with hydronic distribution. Most of these systems belong to large product families from HVAC conglomerates. Sixty-two (31%) are explicitly compatible with AWHP systems and available in the United States, but only 47 of these systems (24%) fall within the target rated heating capacity range of residential equipment (2 to 6 tons). These 47 systems, comprising 14 product lines from 9 manufacturers, represent the systems that were short-listed for this study. Manufacturer-reported specifications were reviewed in terms of heating and cooling capacity, load integration, efficiency, and cold weather performance.

Final equipment selection came down to equipment availability, manufacturer support, suitability for the participant applications, and the project budget. Two system types supporting three different applications were selected. The Electro Industries NorAire system with Bosch BOVA ASHP ODU was selected for heating-only systems with radiant slabs. This is a third-party split AWHP. The Enertech Advantage was selected for participants with heating, cooling, and hot water applications. This is a monobloc AWHP. These systems represented the low and high range of AWHP system cost and capability among the surveyed equipment. Neither the Enertech nor the NorAire heat pumps were expected to meet the space heating load at design conditions; hence, both had integrated electric boilers to supply additional capacity in very cold conditions.

Site Selection

The project initially focused on space heating applications featuring electric boilers and conventional cast iron and baseboard radiators. This combination of equipment proved elusive and only one potential participant was identified. Furthermore, staff found that the emitter capacity in this building would only meet approximately 30–40% of the design load at hydronic supply temperatures of 120°F to 130°F. This finding proved to be a significant barrier to the study of AWHP system capacity and performance in very cold weather. Building upgrades to lower the heating load and replacing emitters were deemed out of scope due to budget and the project refocused on buildings served by existing low temperature emitters, i.e. radiant slabs.

Homeowner recruitment was supported through utility partnerships. Fourteen potential sites were identified across eight electric utilities. Each potential participant was contacted to collect building and HVAC characteristics, utility billing data, and current utility program participation. Several sites from the original list were excluded from consideration at this stage due to low homeowner responsivity or interest causing a lack of timely site information for the team to consider. At the time of site selection, fuel-switching was prohibited under Minnesota statute 216B.241. Consequently, sites that were predominately heated by natural gas or propane were excluded from participation and recruitment focused on participants that used electric boilers as their primary heating source. Of the six remaining sites, four were selected for this project based on a mix of geography and utility. These four sites were predominately heated by electric boilers through radiant slabs. All sites had backup heat to qualify for special interruptible space heating electric rates. Two sites had ducted central air conditioning and propane furnaces as backup heating sources. Of the remaining two sites, one had a propane fireplace and the other one had a wood stove to provide backup heat. The installed AWHP systems were intended to displace the primary electric boiler and most of the space heating load at all sites.

Finding contractors to install systems proved difficult. One site used the participant's preferred contractor, who originally installed the electric boiler and had experience with air source heat pumps. At the remaining three sites, contractors were recruited via their relationships with the AWHP manufacturers through other product lines or the local utility. These connections were invaluable, as project staff were unable to obtain competing bids.

AWHP Installation

Once the study sites were selected, suitable AWHP systems were installed by contractors at each location. The new AWHP systems replaced each site's preexisting electric boiler and central air conditioner (if present) but retained the existing distribution systems. The installations were funded by the project at no cost to the participants. The research team supported the installers as needed in providing information or technical support, but the installers, with manufacturer support, made the final installation decisions. The contractors also installed a power monitor and hydronic flow meter(s) during the AWHP installations. The research team observed most of the installation work onsite and installed the remaining instrumentation for system monitoring. The first field installation occurred in November

2021, followed by installations in December 2021, January 2022, and April 2022. All sites were monitored until September 2023.

The first two sites (site 1 and site 2) were retrofit with the Electro Industries NorAire third-party split AWHP system paired with a Bosch BOVA variable speed ASHP ODU. The Bosch unit was installed due to its familiarity to project staff through prior air-to-air ASHP field work. Its variable capacity compressor offers additional cold weather performance compared to the single speed unit recommended by NorAire. Both sites were installed with 20 kW auxiliary electric resistance boilers in the IDU for backup heat and the existing electric boilers at these sites were removed. The retrofit AWHP systems at sites 1 and 2 provide hydronic in-floor heating only. The homes do not have central air conditioning.

The final two installations featured Enertech Advantage AV060 monobloc IDU and ODU combinations. These 5-ton monobloc systems provide in-floor heating as well as forced-air heating and cooling via hydronic coil at both sites. One site (site 3) also includes DHW preheating functionality by the AWHP system. At this site, DHW preheating is supported as a second-priority load. The system was configured to feed the DHW supply through the AWHP preheater tank before it enters the preexisting DHW heater tank. The water heater operates as normal, but benefits from the inlet water being preheated by the AWHP. Both sites (3 and 4) were installed with integrated 9 kW auxiliary electric resistance boilers in the IDU for backup and auxiliary capacity. They also retained propane furnaces for backup forced-air heating. Enertech provided extensive onsite support during these installations, and continued support throughout the project.

Experimental Design and Data Monitoring

A similar monitoring strategy was implemented at each field site. See Appendix B for complete details on each site's instrumentation package. Broadly, the goal for this field study was to capture overall system performance in terms of energy input and output while capturing transient operational regimes and each system's control logic and behavior as a function of weather. Monitoring included characterization of backup heat operation in addition to the AWHP. Two logging units were used at each site. An eGauge was used to track electrical power consumption in the electric panel while a Campbell Scientific data logger tracked all other sensors including temperatures and fluid flow measurements used to quantify system heat outputs. These loggers were networked such that collected could be downloaded remotely and combined to produce a table of raw data for each site. Data was measured on a per-second basis.

Energy input to the system was measured by tracking the power consumed by the ODU, IDU, auxiliary heating system(s), and distribution system (hydronic pumps and air handler). This included a measurement of line voltage, which was then coupled with component-level current measurements to calculate component-level power consumption in post-processing. Current was measured using split-core current transformers (CTs). These compact sensors were clamped around each component's power circuits to measure current usage by every component. These were typically located in the main electrical breaker box and were connected to the eGauge data logger, which also measures line voltage directly. Some CTs were instead connected to the Campbell logger for components without dedicated breaker circuits, such as the hydronic distribution pumps. Propane consumption at sites 3 and 4 was estimated based on furnace runtime and the manufacturer-specified propane input rate.

Energy outputs were calculated from thermodynamic measurements including temperatures and air and hydronic fluid flow rates. These were collected using a Campbell data logger. Temperature measurements were collected using type-T thermocouple wire and surface thermocouples. Type-T thermocouples were used to measure air flow temperatures in supply and return ducts. The surface thermocouples were adhered to the surface of piping and insulated with segments of pipe insulation to measure hydronic fluid and refrigerant temperatures. Total hydronic flow measurements were collected using a pulse flow meter that was plumbed into the hydronic system during the AWHP installation. Site 3 was outfitted with a second flow meter to measure the hydronic flow in the separate DHW preheating loop. No flow meters were installed on the potable water lines, only the recirculating hydronic loops. Air flow rates in the central air handlers at sites 3 and 4 were measured with a TrueFlow meter once and correlated to the air handler power consumption to continuously estimate the air flow. Output measurements were calculated for each end-use, which can be a combination of forced air heating, hydronic heating, forced air cooling, and domestic hot water, depending on the site configuration.

A few additional measurements were taken to further characterize and optimize system control logic, track heat transfer and losses, identify issues, and compare system operation against local weather. For every site, this includes the use of Onset HOBO air temperature loggers to record the temperature at each thermostat and hourly weather from the nearest weather station to each site downloaded from the National Oceanic and Atmospheric Administration's Local Climatological Database (NOAA LCD). Intermediate current, flow, and temperature measurements were also collected to better understand the workings of the system beyond energy input and output. Site 1 had additional Govee temperature sensors installed to track the use of their woodstove in March 2023. A complete list of measurements, sensors, and data sources for each site is available in Appendix B.

Per-second eGauge and Campbell data were downloaded weekly, along with hourly NOAA LCD weather data for each location and hourly Govee temperature sensor data from site 1. HOBO data were collected manually through periodic site visits. These data were processed in R, with all hourly readings interpolated to a per-second timescale to match the other measurements' frequency. The cleaned data were then used for the analyses detailed in the following section.

Preliminary results informed adjustments to system controls and components. Additional measurements were added to some sites later in the measurement period based on preliminary results as well. The IDU manufacturer for sites 1 and 2 was consulted for control and thermostat interventions midway through the project. Continuous manufacturer involvement at Sites 3 and 4 allowed for periodic updates and interventions to controls and system components based on data collected in this research and measurements output directly from the onboard diagnostics system. These interventions are detailed further in the Results section.

Analysis

Raw data for each site was compiled into monthly data files based on timestamp to ensure data from different loggers or sources were correctly aligned in chronological order without duplicates. The data was range checked to verify that the sensors worked correctly over the monitoring period. If sensors reported erroneously, the data was removed from the dataset. Short periods of missing data, less than 10 seconds long, were replaced with data interpolated across the gap. Energy flow rates were calculated from the per-second raw dataset and then all data was averaged into one-minute increments to reduce the dataset size and increase processing speed of subsequent analyses. Periods of time with a known AWHP malfunction were removed from the dataset, as well as data from any date without a full days' worth of data.

Heating and Cooling Output

The energy output rate from the hydronic systems was calculated as the total hydronic flowrate times the fluid heat capacity and temperature difference measured at the inlet and outlet of the IDU. This is equal to the total system output measured at sites 1 and 2. Since only the total hydronic flowrate was monitored, the total heat delivered to individual radiant floor loops or central hydronic coil could not be quantified separately. For sites 3 and 4, output from the propane furnace was added to the total hydronic output to calculate the total system output. Propane furnace output was calculated as the total air flowrate times the heat capacity of air and the temperature difference measured between the supply and return side of the furnace.

For all the monitored sites, the power consumption measured from the IDU included power draws due to the internal system controls, pumps, and valving as well as the electric resistance auxiliary boiler that can sometimes run simultaneously with the AWHP. Fortunately, electric resistance boilers draw power in a distinct and identifiable manner that enables identification of different operating modes. The installed boilers all had three or four equally incremented stages of heat inputs and outputs across the total rated boiler capacity. The 9 kW boilers at site 3 and 4 consumed from 3 to 9 kW during boiler operation while the 20 kW boilers at site 1 and 2 consumed from 5 to 20 kW during boiler operation. These are easy to identify as boiler cycles since the power drawn by the other IDU equipment during AWHP-only cycles is less than 1 kW. Whenever the auxiliary boiler operates simultaneously with the AWHP, all power consumed by the IDU was attributed to the boiler operation. The heat output by the boiler at these times was calculated as the total IDU power consumption times the boiler efficiency measured during boiler-only heating cycles. These cycles are when the AWHP or auxiliary propane furnaces did not simultaneously run with the boiler.

Design Load Models

The outputs measured from each heating source was totaled per day and a linear model was calculated as a function of daily average outdoor air temperature. See Figure 5 for these results. These linear models characterize the average amount of energy the central heating or cooling system must deliver to maintain the thermostat setpoint at various daily average outdoor air temperatures. The models were based on the total daily heat output measured at each site from the AWHP, auxiliary boiler, and auxiliary propane furnace if present. During the monitoring period, site 1 often relied heavily on an independent woodstove for heating, the output of which could not be quantified. The model at that site is based solely on data from days during which the woodstove was verified as not in use.

A separate model was calculated for the heating and cooling seasons. Heating season was defined as October through April and cooling season as May through September. Typically, data does not need to be split by heating or cooling season to apply a linear load model. However, a singular model fit poorly at site 4 due to the home's unusually high solar gains that increased the cooling load more than is typical in the summer. The heating design load is calculated as the linear model evaluated at the 99% design temperature. The 99% design temperature is location dependent and equal to the outdoor temperature at which the location stays warmer than for 99% of all hours in the year. For the cooling design temperature, it is the outdoor temperature at which the location stays colder than for 99% of the year. The cooling design temperature is also known as the 1% design temperature because it is only warmer than that temperature for 1% of the annual hours on average. The ENERGY STAR certified homes county-level reference guide was used to determine the design temperatures at each of the project sites (U.S. EPA and U.S. DOE 2019).

COP

System efficiency is calculated as the total energy output divided by the total energy input, or coefficient of performance (COP). For this report, the entire system includes all central space heating and cooling equipment: the auxiliary electric resistance boiler, the auxiliary propane furnace and air handler (if present), the IDU and ODU of the AWHP, and any associated pumps. The total system COP is the ratio of all energy output through any of the various distribution methods for space heating and cooling to the energy consumed by each of these components. The total system COP is generally calculated on a daily increment, meaning the total energy output and inputs for space conditioning are summed for an entire day before calculating the daily COP. Daily system COPs include all heat sources and parasitic power consumption that occurs when the system is not actively supplying space heating or cooling to the building during a given day. On days when both space heating and cooling occur, the daily COPs can be very low since the net heat delivered is reduced by the net cooling.

At site 3, the COP of DHW preheating was calculated separately from the space heating or cooling COP. The system controls deprioritize DHW such that the AWHP never delivered heat to the DHW preheater during space heating or cooling calls. Likewise, the auxiliary boiler was never used for DHW preheating. Time periods when hydronic flow occurs to the DHW preheater tank were identified to filter data to DHW cycles only. The energy flows were calculated over these individual DHW heating cycles to compute the DHW cycle COP as the ratio of total energy delivered to the DHW preheat tank to the total energy consumed by the AWHP (both IDU and ODU) plus any external pumps during that cycle. Standby power or parasitic losses that occur when a DHW cycle is not active are not accounted for in the DHW cycle COP.

Performance Maps

Daily system performance was summarized further with performance maps. These plots organize daily or cycle-level data according to the average outdoor air temperature that occurred in that time. These data are further summarized by grouping the output or COP into 5°F or 10°F temperature bins and taking the average per bin, resulting in an overall average performance as a function of outdoor air temperature. These data may be useful for future modeling work or comparing average performance as a function of weather.

Energy Savings

Annual energy savings depend on the loads served, the AWHP performance, and the baseline system efficiency. At sites 1 and 2, the AWHP is only used for space heating. While the AWHP meets the cooling load at site 3 and site 4 and part of the domestic hot water load at site 3, most energy savings are from space heating loads. One central objective of this project was to create temperature-dependent performance maps of AWHP systems as they meet different loads that can be used to forecast energy savings for different applications. The following describes the process to calculate modeled energy savings from the final performance maps for each AWHP, energy data measured over the course of the study, and typical weather data (TMY-2020) for each site.

The space heating design load is estimated from measured energy data at each site following the design load regression fits. From these design loads, hourly space heating loads are linearly interpolated using the design load and the hourly temperature difference between the outdoor air temperature and a fixed indoor air temperature setpoint of 70°F for all outside temperatures below a fixed balance point temperature of 65°F. The daily average COPs presented in the performance maps are then used to calculate the system efficiency at each of these hourly outdoor air temperatures. Subsequently, the energy necessary to meet the hourly space heating load is determined.

The baseline energy to meet the same load is calculated assuming the same design load and an electric boiler efficiency of 98%. The boiler is also assumed to meet the load below a switchover temperature of either 0°F or -10°F for the NorAire and Enertech systems, respectively. The difference in space heating energy between the AWHP and the baseline boiler is the current achievable space heating energy savings for AWHPs studied in this project. These modeled energy savings differ from the actual energy savings measured at each site over the course of the study. Those savings and the reasons for the deviations are presented in Appendix E.

Additionally, at sites 3 and 4, the baseline space heating load was partially served by a propane furnace. In both installations, the Enertech AWHP was controlled to prioritize the delivery of heat to the hydronic coil over the propane burner. Propane use during the study was estimated according to the furnace input rate and furnace runtime. Propane use prior to the study was estimated by project participants. The estimated change in propane consumption between that measured in the study and that estimated by occupants was included in the overall savings estimates for sites 3 and 4.

Domestic hot water savings at site 3 were calculated in a similar manner as the space heating savings. The total domestic hot water energy was estimated as the sum of the energy input into the existing electric resistance hot water heater and the energy output of the AWHP pre-heater. The energy savings were then calculated from the efficiency difference between the existing hot water heater (UEF of 0.94) and the water heating performance map, which gives efficiency of the AWHP system for the fraction of load served by the AWHP as a function of outdoor air temperature.

Cooling savings from AWHP systems are not presented. Based on data measured in this study, AWHPs in these applications are not likely to lead to substantial, if any, cooling energy savings at this time.

Cost Savings and Payback Period

The total cost savings depend on the energy savings above and the volumetric energy costs. All sites in this study had separately metered heating systems. Whereas standard residential electricity rates range from 0.128 to 0.148 $/kWh, for these project participants, the special electric heating rates range between 0.06 and 0.072 $/kWh. For the benefit of lower cost electricity, these heating systems are remotely interruptible by the utility. In the event of an interruption, each site has a backup heating source. The payback period is calculated using the incremental installed cost of each unit divided by the annual electricity cost savings. The incremental costs are total installed costs less the baseline replacement costs, which are assumed to be $6,000 for an electric boiler and $5,400 for an air conditioning outdoor unit and a-coil package.

Results

AWHP Product Characterization

Traditional air-to-air ASHP offerings are publicly tracked by various data sources including ENERGY STAR product lookups and the NEEP ASHP database. These product lists compile information for tens of thousands of products and matched combinations, tabulating ratings, capacity, efficiency, and capability in one convenient location. As a much newer technology, AWHPs do not have a similar list characterizing available products. The first step in this study was to characterize options available to Minnesota residents, thus to candidates for this field evaluation. Following the example set by ASHP product lists, the project team tracked ratings, capacity, efficiency, and features for a collection of heat pump products that were identified to be potentially compatible with AWHP applications. These products include ODUs, IDUs, and their associated manufacturer-recommended controls.

With a lack of standard ratings and reporting, products from different manufacturers did not always report comparable performance values. The terminology surrounding AWHP applications is also inconsistent across manufacturers and markets, introducing uncertainty as to whether the listed products are in fact capable of operating in a system with hydronic distribution. For example, third-party split IDUs are compatible with a range of traditional ASHP ODUs, though only a few product lines came recommended by the split IDU manufacturer. While the project team made every effort to include all relevant products, the following lists should not be treated as exhaustive. This effort was conducted in 2021 so products that are newer to market are not included. The resulting table included 206 AWHPs, reduced to a shortlist of 47 systems when filtering out those that were not available in the state, were outside residential sizes (smaller than 2 tons or larger than 6 tons), or were ambiguous about their AWHP compatibility. See Appendix A: Equipment Characterization Data for the full list of 47 shortlist products.

Most of the 47 systems short-listed for consideration in this study (55%) are from companies outside the U.S., although there are four domestic companies including one based in Minnesota. Nearly three-quarters of systems (72%) are the monobloc type with the remainder split (11%) and third-party split systems (17%). While all systems are thought to be capable of meeting at least a portion of the domestic hot water (DHW) load, thirty-five units (74% of compatible units) explicitly support this capability. Forty-four units (94%) provided cooling in addition to heating. The remaining three units are heating-only NorAire IDUs. Three-quarters (76%) of systems list either inverter-driven or variable compressors. Just 10% of systems list single speed compressor type, and compressor type was not specified for 17% of systems. Variable speed compressors are a hallmark of cold climate air-to-air ASHPs and should be selected for cold climate AWHPs. Although there is no ENERGY STAR program for AWHPs, several manufacturers make efficiency claims that exceed ENERGY STAR requirements for air-to-air ASHPs. However, ENERGY STAR ratings are performed at the system level (ODU + IDU + emitter), which precludes this designation at the unit level (ODU or IDU). Therefore, it was not possible to classify any one unit as ENERGY STAR capable.

Capacity and Sizing

All the 47 short-listed products reported manufacturer rated heating capacities at 47°F outdoor air temperature. Roughly 90% of units do not report heating capacity at 5°F or 17°F, however, so additional manufacturer data are necessary to evaluate capacity and performance for Minnesota applications. Monobloc and split units are both available across the range of typical residential sizes (2–6 tons), though third-party split systems were not available above 5 tons. The cooling capacity of AWHP units are, on average, 0.6 tons or 7,200 Btu/h lower than their respective heating capacities.

The distribution of minimum operating outdoor air temperatures for all 47 compatible units demonstrated the availability of cold climate-capable products with an average minimum operating temperature of -10.7°F; however, absent data at low temperatures, it remains to be seen what capacity and performance they can provide under these conditions. Notably, the PHNIX Hero Pro monobloc and SpacePak Solstice split system could operate at ambient temperatures as low as -31°F and -20°F, respectively. Overall, the manufacturer-reported operating ranges of AWHP systems are quite similar to those available from residential air-to-air ASHPs but capacity data at low temperatures remains extremely limited for AWHP products.

Indoor Units

The majority of reviewed AWHP products included an IDU option. The IDU packages AWHP system components within the building envelope to interface between the ODU and the distribution loops. These are always connected to the ODU via refrigerant lines in split configurations. The IDU typically contains the refrigerant-to-water heat exchanger (in split systems), controls, expansion tank, circulator pump, and auxiliary heating interface if included. Most split system AWHP manufacturers provide their own proprietary combination of IDU and ODU. Of the five proprietary split ODUs considered, four were produced by LG and 1 by SpacePak. LG produces a range of IDUs intended to be paired with their Therma V Split ODU line. SpacePak also provide a companion IDU to their Solstice Split ODU. As SpacePak IDUs are provided with their ODUs and designed with communication between the two units in mind, it is unlikely that these units are compatible with third-party products, though not explicitly stated.

Additionally, some monobloc manufacturers offer IDUs that are designed to accept hydronic lines from the monobloc ODU. They are marketed as control and installation aids as they simplify the system connections. The Enertech Advantage indoor unit is provided with the Advantage line of monobloc ODUs. It contains a pump, expansion tank, and auxiliary heating, with an added control screen built in. Similarly, the PHNIX EasyHydro module includes a pump, pressure regulator, and an electric control cabinet, among other components. IDU units are critically necessary for split system AWHPs but also highly recommended for early adopters of monobloc AWHPs. Because AWHPs remain new to the residential market in Minnesota, any features that can simplify the installation complexity should be strongly considered as routes to improve the technology’s early success in the region.

Controls

Review of product literature shows that AWHP systems are provided with some form of control equipment or software to interface with indoor thermostats. These tend to be proprietary systems that allow a broad range of functions, from basic temperature control to the independent control and scheduling of multiple zoned emitters. User interfaces can also vary broadly from a basic display with a few buttons and indicators, to an elaborate touchscreen interface built into the unit or provided as an external controller. A developing trend includes app-based control, which leverages the home Wi-Fi network to provide wireless connectivity between the AWHP system and the user’s smartphone. Cloud connectivity is also a common feature of modern controllers. This enables them to upload history and share schedules across devices. During the field study, one manufacturer developed a Wi-Fi connected controls package that can be retrofit to their monobloc ODUs to aid the homeowner and contractor with system control and diagnosing potential issues.

Emitters

Some AWHPs specify with which emitter types they are compatible. In most cases, AWHP product literature will mention in-floor heating or low temperature radiative emitters. Hydronic emitters are often sold by the AWHP manufacturer as well. Chiltrix, Aermec, and PHNIX all produce emitters compatible with hydronic distribution systems. Nearly all of these are fan coils or cassettes (similar to mini split cassettes) that are wall mounted, floor standing, or universal. Central hydronic air handlers are also available that allow AWHP systems to serve conventional ducted HVAC systems for both heating and cooling.

The performance of AWHP systems can be greatly influenced by their paired emitters. AWHPs operate with considerably lower supply temperatures compared to traditional boilers. The systems monitored in this study were expected to operate with heating supply temperatures roughly between 110°F and 140°F. Traditional cast iron radiators, for example, are recommended for use with supply temperatures of 160 to 200°F (Caleffi 2016). While lower supply temperatures will reduce heat delivered by any emitter, pairing a low-temperature system with an emitter designed for high supply temperatures can result in insufficient heat delivery, comfort issues, and poor system efficiencies as the AWHP attempts to compensate for these limitations. Lower temperature emitters, such as in-floor radiant heating and fan coils, are more suited to this operating range and are therefore preferred for AWHP installations. Retrofitting high supply temperature systems with AWHPs will therefore need to include an evaluation of the existing emitter types and building heat load. Homes that have undergone deep weatherization retrofits may be able to successfully use high temperature emitters with low supply temperatures, but replacement of high temperature emitters may be required for the average home. This retrofit barrier will be significant for the Minnesota housing market since emitter replacement will increase costs.

Candidates for Field Installations

The complete table of 47 systems was winnowed down to 11 product lines listed in Table 1. This short list comprises products for which AWHP applications were specified in their literature, further filtering down to those products that were available in Minnesota in 2021. The nine manufacturers from this list were contacted for additional performance information specifically in cold climate applications, with several systems ultimately deemed unsuitable for cold climate operation at this step.

Many of these were ultimately ruled out due to lack of availability for this field study. Further discussions with manufacturers helped to select the two products that were most appropriate for this study. Local manufacturer support was a key factor in this decision, which proved useful in obtaining bids from trained installers that were familiar with these specific products. Both manufacturers offered some support in optimizing and troubleshooting these systems through the monitoring period as well. The two systems included in the field portion of this study include the Enertech Advantage Monobloc ODU with its accompanying IDU, and the NorAire EB series third-party split IDU paired with Bosch BOVA variable speed ASHP as the ODU.

Table 1: List of products under consideration for this field study

Manufacturer	Product Line	System Type	Capacity at 47°F [tons]	Min Outdoor Temp [°F]	DHW	Cooling
PHNIX	Hero	Monobloc	2.4 to 11.7	-31 to -13	Yes	Yes
PHNIX	Hero Pro	Monobloc	4.5 to 25.2	-13	Yes	Yes
LG	Therma V	Both	1.6 to 4.5	-13	Yes	Yes
SpacePak	Solstice	Both	3.2 to 6.0	-20 to -4	No	Yes
Viessman	Vitocal	Monobloc	2.9 to 5.9	-4 to 5	Yes	Yes
Aermec	ANK	Monobloc	3.1 to 4.8	-4	Yes	Yes
ArcticHeat	ArcticHeat	Monobloc	2.4 to 5.0	-15	Yes	Yes
Enertech	Advantage	Monobloc	2.6 to 4.6	-13	Yes	Yes
Chiltrix	CX34	Monobloc	3.0	-4	Yes	Yes
NorAire	NC	Third-party split	3 - 5	-5*	No	Yes
NorAire	EB	Third-party split	3 - 5	-25*	Yes	No

*Minimum ODU lockout temperature shown. True value depends on paired third-party ODU.

Product Ratings

There is currently no nationwide standard for rating AWHPs. They are often rated like chillers, with typical seasonal performance expressed as integrated and nonstandard part-load values (IPLV and NPLV). These ratings are unlike other residential heating options that have their performance ratings expressed as a seasonal energy efficiency ratio (SEER2), energy efficiency ratio (EER2), and heating seasonal performance factor (HPSF2). This discrepancy adds to the unfamiliarity of AWHP systems and makes it difficult to compare performance with non-AWHP options in the customer and contractor decision-making process.

SEER2, EER2, and HSPF2 are the basis for the certification of heat pump products by the Air-Conditioning, Heating, and Refrigeration Institute (AHRI) (AHRI 2023). AHRI certification yields an AHRI certified reference number that can be used to look up these ratings on various product databases, also serving as assurance that the certified product will perform comparably to other products with similar ratings. The AHRI certification reference number is also a common requirement for products to qualify for rebate programs. AHRI does not currently certify AWHPs, which impedes the market by restricting access to rebates and incentive programs. There is no clear indication that AHRI intends to add AWHP certifications in the future, although this could be an eventuality as more AWHP products reach the market and the technology gains footing in the sector. AHRI certifications are typically for ODU and IDU pairings, so may be required for each combination of third-party split system.

Competing products can also be ENERGY STAR rated or granted the additional designations of ENERGY STAR Most Efficient and ENERGY STAR Cold Climate (U.S. EPA and U.S. DOE 2022b). This is a familiar U.S. certification seen across the broader landscape of consumer appliances, allowing customers to gauge the relative energy efficiency of one product over another based on whether they are not certified, are ENERGY STAR certified, or are additionally ENERGY STAR Most Efficient or ENERGY STAR Cold Climate products. At present, ENERGY STAR ratings do not exist for AWHPs. The European analog to this rating is the European Union Energy Label (European Commission 2013). Much like ENERGY STAR, the EU energy label applies across consumer appliances, each rated in their own way, but ultimately all sharing a rating format. While ENERGY STAR certifications can be one of four results, the EU label can be as broad as a 10-level letter grade scale from A+++ to G, color coded from green to red. While these differ in granularity, both serve the same purpose in acting as a handy reference for customers to pick out which products are higher efficiency rated without prior knowledge of COPs or ratings like SEER and HSPF. The expansion of ENERGY STAR certifications can bring this convenience to AWHPs, providing another way to compare them to other heating and cooling options on level ground.

The ENERGY STAR Cold Climate designation is required for ASHPs to qualify for federal tax rebates applying to systems installed in the North region defined by the Consortium for Energy Efficiency (CEE1), which includes Minnesota (US EPA and US DOE 2022a). Eligible equipment must also meet or exceed the CEE1 requirements for their highest efficiency tier, not including any “advanced” tier, as defined at the beginning of each year (CEE1 2023). These criteria are specific to each heat pump system type, although tiers for heat pump types are universally defined in terms of SEER2, EER2, COP, and heating capacity ratio. Tiers are defined for packaged, non-ducted, and ducted ASHPs, although it is unclear whether AWHPs would be included should they meet the prerequisites for rated performance.

The latest version of the ENERGY STAR specification for CAC and heat pump equipment (U.S. EPA and U.S. DOE 2022b) mentions the recognition of high-efficiency cold-climate AWHP products as part of the ENERGY STAR Emerging Technologies program. This document expresses the intent to include AWHPs in a future revision of the CAC/HP specification as the product category gains greater traction in the U.S. market. The current ENERGY STAR requirements for ASHPs and CACs are based on SEER2, EER2, and HSPF2 ratings. While it is unclear how AWHP ratings may be handled as an amendment to this specification, this is motivation for ensuring that AWHP ratings align with these existing seasonal rating structures. Given that manufacturer-reported performance for existing products could qualify them for current ENERGY STAR certification based on ASHP specifications, delaying the development of AWHP ratings could be an unnecessary hurdle for customer awareness of this energy efficient solution for homes with hydronic heating. While ENERGY STAR and AHRI certifications can both contribute to accelerating market penetration, they are currently pending further product development.

Although this product class is in its infancy as an option for Minnesotans, it is well established in the European market thanks to the prevalence of hydronic heating in the region. Indeed, several products shortlisted for this study were either directly produced by or sold in partnership with a European manufacturer. This includes the monobloc system monitored at sites 3 and 4, which is a rebadged Swedish design adapted and constructed domestically for the U.S. market. European ratings treat AWHPs equally to other ASHPs and CACs (CEN 2022a; CEN 2022b). In the European rating structure, all these products report SEER and seasonal coefficient of performance (SCOP), COP at specific ambient temperatures, and flow rates. Seasonal performance values and required ambient temperatures are tailored to several climate zones in Europe. AWHP ODUs are rated on their own, allowing for greater parity with other ASHPs and CACs, and additional adjustments are made for split systems that relocate components from the ODU to a paired IDU.

Adoption of a similar rating process for the U.S. market would be optimal from both a customer and manufacturer perspective. Comparable ratings will help customers make informed decisions about AWHPs and evaluate them against alternative system types. Given the strong ties that currently available products have with the European market, some of these systems have likely already been tested for SEER, SCOP, and COP at ambient temperatures under the European rating structure. Bridging the gap between European ratings and U.S. ratings may be a smaller leap for the market than using existing IPLV and NPLV ratings for comparisons.

Field Installations

Site Descriptions

The AWHP systems installed for this work are summarized with their buildings in the table below.

Table 2: Summary of field sites and installed systems

Site	City	Home Area (sq. ft.)	Stories	AWHP Model(s)	Emitters	Auxiliary Heat
1	Foley	3,200	1	NorAire EBH-5-020 and 5-ton Bosch BOVA ASHP	In-floor heat	Electric resistance auxiliary boiler, woodstove
2	Garfield	2,600	1	NorAire EBH-5-020 and 5-ton	In-floor heat	Electric resistance auxiliary boiler, propane fireplace

Site	City	Home Area (sq. ft.)	Stories	AWHP Model(s)	Emitters	Auxiliary Heat
				Bosch BOVA ASHP		
3	Faribault	2,600	1	Enertech Advantage EAV060 with IDU and Turbomax indirect water heater	Lower level: In-floor heat Upper level: central forced AH with hydronic coil DHW: AWHP fed preheater	Electric resistance auxiliary boiler, propane furnace
4	Garfield	4,000	1	Enertech Advantage EAV060 with IDU	Lower level: In-floor heat Upper level: central forced air with hydronic coil	Electric resistance auxiliary boiler, propane furnace, two propane fireplaces

Third-party Split AWHP Sites

Site 1 is a single-family home built in 2007 totaling 3,200 square feet of conditioned space. The home is a single story, slab-on-grade home with hydronic loops embedded throughout the floor, serving two zones inside the home. The attached garage is generally unheated but has hydronic loops and could be heated based on homeowner preference. Their preexisting heating system was a Hydroshark 29 kW electric resistance boiler supplemented by a woodstove if needed. This site was recruited for this project through their utility, which the homeowner contacted due to high heating bills. Prior to this project, the homeowner had obtained a quote for an AWHP but found it too expensive to pursue by themselves. We proceeded with their existing quote for this project. While their woodstove was retained, the boiler was replaced with a NorAire EBH-020 heat-only split IDU with 20 kW of auxiliary electric resistance heat and a 5-ton Bosch BOVA ASHP ODU. This site does not have central cooling. The AWHP system was installed in November 2021. The IDU and hydronic manifold is in the rarely conditioned attached garage space.

Site 2 is a slab-on-grade single-family home built in 2009, with roughly 2,600 square feet of conditioned space. The home is primarily laid out over a single story, with the addition of a single room above the attached garage with ER baseboard. Hydronic loops supply in-floor heat through all but the garage, where hydronic loops exist but were disconnected due to insufficient insulation in the garage slab. In-floor heating serves the home as a single zone. A propane fireplace is located in the central living space of the home but is not a primary heat source. This site does not have central cooling. Site 2 was recruited through their electric utility, as the homeowners had previously reached out to them over cost concerns. Like Site 1, site 2 is a heating-only installation with in-floor heat as its sole emitter for a third-party split AWHP. Their existing 27 kW Thermolec B-27U electric boiler was replaced by a NorAire EBH-020 20 kW heat-only split IDU with a 5-ton Bosch BOVA ASHP ODU, mirroring Site 1. Installation occurred in December 2021. The IDU and hydronic manifold is located in the unconditioned attached garage space.

Monobloc AWHP Sites

Site 3 is a one story single-family home with walkout basement with approximately 2,600 square feet of conditioned living space plus an attached and heated four-stall garage with a workspace. The upper level is served by a centrally ducted forced air system. The lower home level is a partially finished walk-out basement heated with in-floor hydronic circuits. The two living levels are connected by a narrow open stairway. The attached garage and workspace addition are heated using in-floor hydronic circuits but do not have ductwork for cooling. The system is split into three zones, each with its own thermostat: the upstairs forced air heating and cooling zone, the downstairs in-floor heating zone, and the in-floor heating zone serving the garage and workspace. The homeowners typically keep the garage and workspace just warm enough to avoid freezing the domestic water supply lines in the workspace. The garage increases the heat load in peak winter conditions despite its low setpoint because of its large size. The home previously relied on an 18 kW Electro Industries TS Series Electro-Boiler for their in-floor heating needs, supplemented by a Trane XR90 forced air central propane furnace and a central air conditioner (CAC) primarily serving the upper level of the home. The air handler system includes Broan HRV90H heat recovery ventilator. Site 3 was retrofit with an Enertech Advantage AV060 monobloc IDU and ODU combination with a Turbomax indirect water heater. The Enertech IDU includes a 9 kW auxiliary electric resistance boiler. The preexisting boiler and CAC were replaced by the new AWHP but the propane furnace was retained as an auxiliary backup heat source and air handler for the AWHP's centrally ducted hydronic coil. The preexisting electric resistance water heater (Rheem Marathon) was also retained to serve the remaining water heating load. The AWHP can serve heating, cooling, and partial DHW loads at site 3 and was installed in January 2022. The IDU and balance of system is in a conditioned utility room in the basement.

Site 4 is a 2,240 square foot single story home built in 2002. It has a finished basement relying on in-floor hydronic circuits to heat the living space. The HVAC room is in the conditioned lower level. The upper level has forced air heating and cooling, a second fireplace, and large west-facing windows in the primary living area. The two levels are connected via a large open stairwell beneath the westward windows. An Enertech Advantage AV060 monobloc AWHP system with IDU and 9 kW auxiliary electric resistance boiler was installed at this site in April 2022. The AWHP displaced an Electro EB-R-13 13.5 kW boiler supplying in-floor radiant heat to the lower level. Much like Site 3, the Enertech AWHP at site 4 supplies forced air heating and cooling via a hydronic coil installed above the furnace, displacing the CAC at this site. To retain a backup forced air heating system, the preexisting end-of-life Carrier WeatherMaker 9200 furnace was replaced with a new Armstrong A951E unit at the time of the AWHP installation. The existing Carrier HRVCCSVU ducted heat recovery ventilator and Thermolec ACU-5 humidifier were retained. The attached garage has a Sterling LPG ceiling-mounted heater but does not interface with the home's heating system in any way. Site 4's AWHP can serve heating and cooling loads through the central air handler or radiant floor loops, similar to site 3. However, site 4's AWHP does not serve DHW loads.

Split system installations

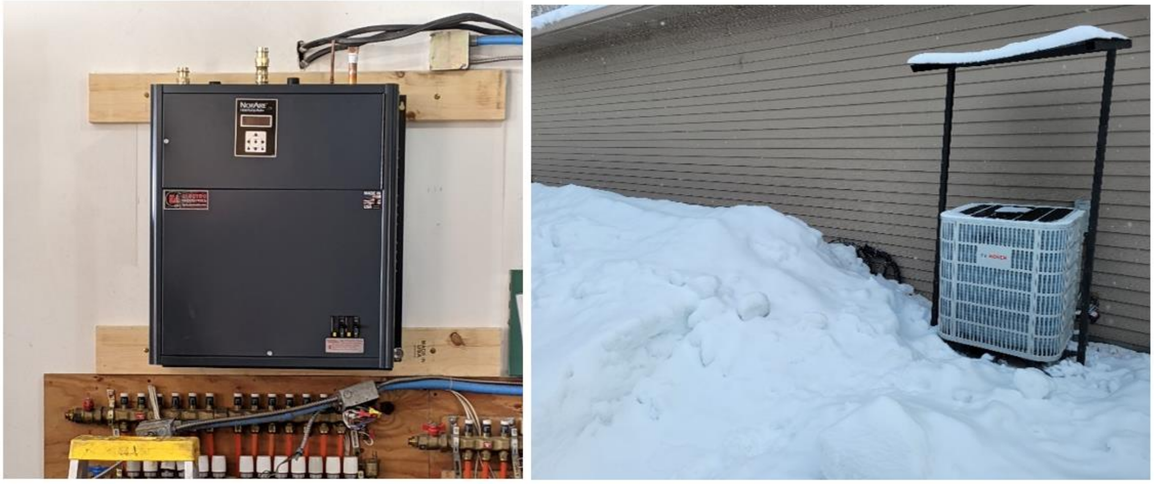

Figure 3: The NorAire third-party split system IDU (left) and Bosch BOVA ODU (right) as installed at site 1

Split AWHPS are installed like a traditional ASHP or air conditioner, where refrigerant lines cross the envelope and connect the ODU to the IDU. Mechanical and HVAC contractors are generally familiar with the ODU of a split system. At sites 1 and 2, the ODU is an existing central ASHP product from an established manufacturer that is typically installed as a centrally ducted ASHP or air conditioner. In terms of installation, connecting the third-party ODU to the AWHP IDU was relatively simple and comparable to a conventional air handler connection. Once the ODU and IDU were connected by refrigerant lines, the IDU interfaced through a single inlet/outlet pair to the home's hydronic distribution system. In the case of our test sites, these simply included a hydronic radiant floor manifold that was straightforward to pipe a connection.

The IDU manufacturer for the split systems studied here is an established electric boiler manufacturer who is also relatively familiar to local hydronic installers. Their IDU system connection with the hydronic distribution is very comparable to any electric boiler unit they otherwise manufacture. Although the hydronic lines were contained within the building envelope, both split systems installed for this project had their HVAC equipment located in attached garages that were either unconditioned (site 2) or were not held consistently above freezing (site 1). Both sites therefore required the addition of glycol to the hydronic lines as a means of freeze and burst protection in the unconditioned portions of the home. The resulting mixture was 25% glycol at site 1 and 50% glycol at site 2, determined by homeowner and contractor preference.

Calls for heat from one or more of site 1's three radiant heating zones are passed through a zone valve controller that interfaces with the AWHP IDU. The AWHP system acts as a simple replacement for the existing electric boiler, interfacing with the home's thermostats in much the same way as the preexisting heating system. Site 2 is simpler still, as its single radiant heating zone does not require any external zone control equipment. At low ambient temperatures, the electric boiler in these systems is set to run simultaneously with the AWHP to deliver the total heat required. The electric heating element controls are split into four stages, each with their own lockout temperature. Each stage increments the boiler capacity by 5 kW, ranging from 5 kW to 20 kW in total. The stage lockout temperatures limit the use of backup electric resistance in milder weather. These settings were left at the default values, where 5 kW can be used at any time, 10 kW can be used below 40°F, and the 15 and 20 kW stages share a lockout of 20°F. The system relies entirely on the 20 kW backup boiler below the Bosch ODU minimum lockout of -4°F.

Monobloc system installations

Figure 4: The Enertech Advantage AV060 IDU (left) and ODU (right) as installed at site 3

Since the monobloc ODU contains more components than a standard ASHP, they tend to be larger in physical size, approximately 1.5 to 3 times the volume of a residential air conditioner or ASHP. The monobloc ODU installed in sites 3 and 4 is significantly larger than a typical ASHP or CAC unit and was more challenging to transport and position onsite. The size and weight of monoblocs may require more footing and foundation work before installation compared to traditional condenser units, which can sometimes be mounted to a buildings' exterior wall via brackets. The hydronic lines crossing the building envelope also require an additional consideration of freeze and burst protection. Glycol was added to the hydronic loops in mixtures of 25% and 30% at sites 3 and 4, respectively.

Overall, the monobloc system design was less familiar to local installers and required additional manufacturer support during installation. However, the monobloc uses hydronic lines to connect to the IDU, avoiding the need for refrigerant work during installation. Refrigeration work is specialized and requires an experienced HVAC contractor while hydronic lines can be installed by an experienced plumber. Theoretically, a monobloc system could be a simpler installation than a split AWHP system if it is helpful to reduce the number of installer specialties required. If the installation is completed by a plumber, they do need experience in hydronic heating systems and an understanding of the weather-dependent performance of heat pumps.

While the connection between the IDU and ODU in the monobloc system was a simple hydronic line, connecting the IDU to the balance of system was more complicated due to its greater flexibility in application. The installation of the IDU and other indoor components was very unfamiliar for the contractor, and significant manufacturer support was needed when designing the system to interface with in-floor hydronic loops, a forced air hydronic coil, and domestic hot water. Extra time was required to lay out the plumbing to tie these systems together, and this was partly exacerbated by the project's need to install monitoring equipment on the hydronic distribution loop for this field study.

Setting up the required controls presented an additional hurdle. The monobloc system was a newer product at the time of installation and proved a learning experience for the manufacturer and contractor alike. Neither party had prior experience to rely on in these specific configurations. These factors contributed to installation times significantly longer for the monobloc (2–3 days) compared to the split systems (1–2 days). The more complex installations introduced additional issues soon after commissioning. Site visits were needed within a few weeks of installation to correct incorrect valve settings and to refine control inputs based on initial operational data.

Site 4 included multiple radiant hydronic zones plus an additional loop for the hydronic coil that provided forced-air heating and cooling to the upper level. To accommodate these in-floor zones, the system includes several preexisting zone valves responding to each thermostat's call for heat. The zone controller informs the IDU of the radiant heat demand via a low-voltage signal input. Calls for the hydronic coil are handled similarly, with two low-voltage inputs dedicated to air handler heating and cooling demand. The system supplies forced air heat much like any other zone, though there is a separate outlet temperature control setting for the hydronic coil supply. The AWHP can supply heating to in-floor and forced air zones concurrently but is unable to supply heating and cooling at the same time. This limitation did lead to a homeowner comfort concern as they were used to operating their central AC to cool the upper level while heating their lower level with an electric boiler. In the event of a new call requiring a transition to a different mode, the system will complete the current call before energizing or de-energizing the reversing valve.

Site 3 added DHW service from their AWHP in addition to forced air and radiant emitters. The IDU accepts a low-voltage connection to the thermistor that is pre-installed in the AWHP-fed preheating DHW tank. In this case, the controls were set to prioritize all space conditioning calls before providing heat to the DHW pre-heating tank. Heat is only supplied from the IDU to the DHW tank when there are no active calls for heating or cooling. Supplying DHW will de-energize the reversing valve and transition the system to heating mode if it is currently in cooling mode. This transition can result in a system cooling efficiency penalty when the system provides DHW heating between cooling calls. The DHW preheat tank is not the sole hot water supply, however. The preexisting hot water tank was left in place. This heater operates normally, but with inlet water preheated from the AWHP preheat tank. Aside from water heating, the AWHP at site 3 functions identically to site 4 when servicing the two radiant heating zones and the single forced-air heating and cooling zone.

The auxiliary boiler can run concurrently with the AWHP to provide extra capacity as needed at all sites. For the monobloc sites, the ODU locks out at -13°F, below which the radiant heating load relies entirely upon the 9 kW electric resistance heating element within the IDU. The monobloc sites include propane furnaces serving as forced-air heating backups. They function much like traditional dual fuel air-to-air ASHP configurations, where the propane furnace functions as second stage heat. The propane furnaces can run concurrently with the AWHP except when the AWHP is supplying heating or cooling via the hydronic coil.

General installation observations

Contractor and product selection

Regardless of whether the desired system is a split or monobloc configuration, the installing contractor must be experienced with boiler/hydronic heating systems. The knowledge required for the plumbing and hydronic work needed on these installations was significantly greater than the complexity of refrigerant work needed for the split systems. It is recommended to select a contractor for AWHP installations who is experienced in the nuances of hydronic heating. Finding appropriate contractors was challenging for this project and only one bid was received per site as a result.

Product selection for AWHP systems was also a challenge. Unlike other ASHPs and traditional heating products, AWHPs do not have a nationwide standard process or rating system that can compare AWHP options to other system types. Therefore, using whatever performance rating are available requires a greater understanding of the system's design to determine the appropriate setup. Also, opaque and/or counterintuitive onboard control logic can make it difficult to predict performance based on ratings, adding an additional layer of complexity to this process.

Retrofitting considerations

Retrofit installations can pose significant challenges compared to new build installations. For AWHP systems displacing old boilers, the location of the boiler and distribution systems within the home could pose a unique challenge. Homes with hydronic heating may not be generally conducive to heating systems that require an ODU because they do not necessarily have their existing boiler and hydronic manifold located near an external wall. This is most likely an issue in homes that have not been designed with air conditioning in mind. The retrofit AWHP may therefore require lengthy line sets between the ODU and IDU. For example, site 3's HVAC equipment was installed in an underground corner of a walkout basement dug into a hillside. The fluid lines had to span almost the entire width of the lower level to the opposite end of the home to reach the nearest suitable position for the sizeable monobloc ODU.

Initial data collected at the two third-party split AWHP sites (sites 1 and 2) encouraged the installation of new hydronic thermostats with slab temperature sensors. Although slab sensors may be recommended by most hydronic system designers, they do not necessarily get installed and retrofitting them can be risky. The contractors for these sites were concerned that drilling the well for the slab sensor would risk rupturing an in-floor hydronic line. The existing maps of these hydronic circuits were not drawn to the precision required to ensure this would not occur, and the contractors were not confident in the tubing depth. The project team consulted with the AWHP manufacturer to provide options to the contractors. The least risky solution was determined to be drilling beneath the bottom plate within the wall where the thermostat is mounted. The work could be conducted through an opening that will be hidden by an 8”x14” return air grille, or behind the baseboard if enough space was available. Homeowners may prefer the behind the baseboard method in lieu of the return grille approach for aesthetic purposes.

Distribution system design

This project retrofit AWHPs to existing homes, and as a result had minimal control over the design of the hydronic distribution system. This can impact AWHP performance, however. Notably, the monitored AWHP systems displayed issues with load balancing, particularly with small in-floor distribution loops like those at site 4. Some of the in-floor zones in this home were as small as a single bedroom. The monobloc unit in this study is not currently capable of modulating low enough to efficiently support so-called micro zones. The manufacturer did not provide guidance on minimum loop sizing at the time of installation but updated their current recommendation for individual zones to be 12 kBtu/hr of heating load or larger, based on system performance in the first heating season of this study. The manufacturer reports a software update is in development that will allow the capacity to be turned down to service smaller zones. Hydronic distribution systems that need high turndown ratios can face significant short-cycling and decreased efficiency from AWHPs if emitter sizing is not appropriately accounted for in their design.

The equipment manufacturers in this study provided minimal guidance on the need for a buffer tank at the time of installation. The third-party split AWHP manufacturer suggested that buffer tanks were not required at the study sites with only high-mass floor emitters. The two monobloc sites (sites 3 and 4) also included forced air distribution for both heating and cooling, paired with high-mass in-floor heating, but that manufacturer did not recommend buffer tanks for these homes, either. The indirect water preheating tank at site 3 is not functionally a buffer tank for the space heating system. While not in this project’s scope, buffer tanks might improve an AWHP’s responsivity to simultaneous calls for heat from a fast-responding forced-air zone and a high-mass in-floor heating loop. Careful addition of a buffer tank to these sites might have allow the AWHP to more frequently maintain optimal operation, minimizing short cycling events, or it may integrate poorly with the existing controls. These hypotheses were not in the scope of this project.

Furthermore, AWHP systems providing forced-air cooling may also need more thoughtful coil sizing when installed in cold climates. The project team was partially involved in the process of sizing the hydronic coil for the systems installed with cooling capabilities. Given the 5-ton units that were installed, it was suggested that the coil be sized smaller to better match the cooling load expected in these homes. Despite these suggestions, 4-ton and 5-ton hydronic coils were ultimately installed. Oversized coils are generally associated with shorter cooling cycles and poor dehumidification. Variable speed ODUs can electronically limit the system to a lower capacity in cooling season but may not always be able to reach turndown ratios needed to serve small cooling loads in Minnesota’s heating dominated climate.

Supply chain

Finally, it is notable that the equipment installations for this project experienced major equipment failures at every participating site. See the Callbacks & System Issues section for descriptions of each site for more details. Some failures were related to cold climate design flaws, such as the fan failure in the third-party condensers that have since been addressed, but a systemic cause for the other failures cannot be clearly determined beyond the fact that the technology remains new and has had less time to be perfected in the field. Supply chain challenges further exacerbated part failure issues and slowed the speed at which issues were addressed. As the AWHP market matures, fewer equipment failures than were observed in this field study should be expected.

Field Performance

Design Loads

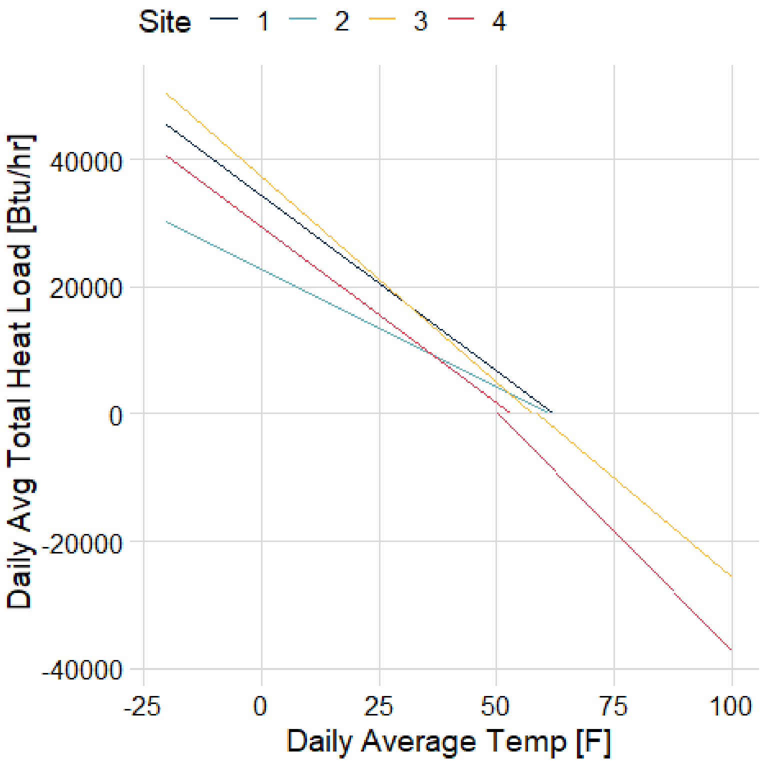

Figure 5: Daily heating and cooling loads measured at each field site

The measured daily heat rate supplied by the heating and cooling systems at each site allowed us to estimate the total home heating loads as described previously. These linear models are plotted in Figure 5 and tabulated in Table 3**Error! Not a valid bookmark self-reference.**. The data accounts for any heat delivered by AWHP, auxiliary boiler, or auxiliary propane furnace, if present. All cooling loads were supplied solely by the AWHP. Sites 1 and 2 with their third-party split, heating-only systems do not have central air conditioning, so cooling load data is not available for those two systems. The monobloc AWHPs at sites 3 and 4 supplied cooling through a hydronic coil on their central air handlers without any backup cooling source. Site 4 notably has a relatively large cooling load due to atypically high solar heat gains in the summer months. Cooling loads are plotted as negative heat loads in this plot since cooling is equivalent to removing heat rather than adding it. The field study sites ranged in design loads from about 28 kBtu/hr to as much as 43 kBtu/hr. These are comparable to median home heating loads in the state of Minnesota.

Table 3: Tabulated load data for each field site

Site	Design Heating / Cooling Temperature, °F	Balance Point, °F	Design Heating Load, Btu/hr	Design Cooling Load, Btu/hr
1	-13 / 87	62	42,000	-
2	-14 / 86	61	28,000	-
3	-9 / 87	58	43,000	18,000
4	-14 / 86	51	37,000	27,000

AWHPs and Auxiliary Heat: Heat Delivered Daily by Source

Overall, the field data from this project show that both third-party split and monobloc AWHPs can deliver most of the energy necessary for space heating of typical single-family homes in Minnesota. AWHPs can also operate in cold temperatures like other field-tested air-to-air ASHPs. Similarly, AWHPs can integrate with fossil fuel and electric resistance auxiliary heat sources to seamlessly cover any remaining capacity gaps. In fact, the active heating source can be difficult or impossible to discern by occupants in the building. As a result, controls settings or ODU failures that result in excess auxiliary heat use may go unnoticed for quite some time and never cause a loss of comfort. In the systems studied here, the controls to engage auxiliary boiler heat were set via the IDU while auxiliary propane heat could be called via thermostat with typical staged heat settings. Occupants interfaced only with their thermostats, not the IDU controller, however, so AWHP controls set at the time of installation can significantly impact overall savings. Generally, controls settings should be set to prioritize AWHP heating whenever possible and limit less efficient and more costly auxiliary heat sources. Specific settings vary by AWHP model and their optimization may vary depending on the paired emitters.

Third-Party Split Daily Heat Delivered

Both sites 1 and 2 with third-party split AWHPs had integrated auxiliary boilers and were hydronic heating systems only. Heat could be delivered by the AWHP, the auxiliary boiler, or by both at the same time. The average daily heat rate delivered by each source is plotted in Figure 6 for each site. This data includes only days where the AWHP was functional (i.e., the system was not in boiler-only mode). A surprising variation in the amount of heat delivered by the auxilliary boiler is observed for daily outdoor air temperatures between approximately 10°F and 40°F. In these mild temperatures, the AWHP is expected to be capable of meeting the full heat load. To investigate the behavior, the boiler datapoints are further coded to identify which year the data was collected and thereby what controls settings were used. Solid red circles show the daily average rate of heat delivery from the auxilliary boiler in the second year of the study, after some controls adjustments were made, while the hollow red circles show the same data during the first year of the study, when manufacturer default controls were used.

The main control settings modified at site 1 and 2 were called “boost” settings by the manufacturer. They determined the control logic for engaging the auxiliary boiler. In the default settings, the boiler was turned on whenever the temperature difference between the IDU supply and return lines fell below 10°F and the heat call had been on for at least thirty minutes. For the second winter of monitoring, these settings we adjusted so the auxiliary boiler could not engage unless the temperature difference from the IDU supply and return lines fell below 6°F and the heat call had been on for 199 minutes (the maximum allowable setting). This controls change reduced the tendency of the boiler to run in mild weather when the AWHP had enough capacity to meet the load. It also led to longer heating cycle runtimes.

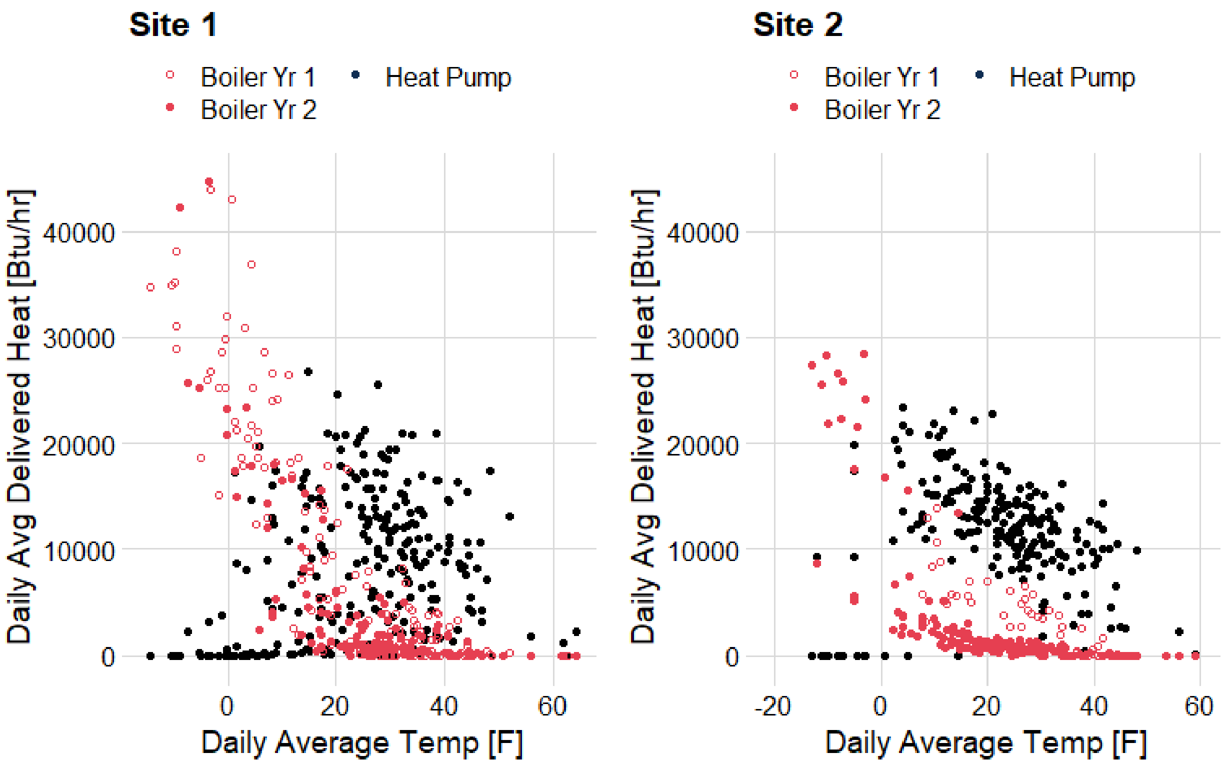

Figure 6: Daily average heat delivered by the AHWP (black) and the auxiliary boiler (red). Hollow red circles indicate daily average heat delivered by the boiler in the first year of the study, before IDU controls settings were adjusted to reduce boiler use.

The optimization of these or similar AWHP settings will depend on the home heat load compared to the AWHP capacity as well as the emitter type. Especially for systems with high thermal mass emitters like the radiant floor systems at site 1 and 2, controls strategies that prioritize system responsivity may inadvertently result in lower overall efficiency from an overreliance on the auxilliary heat with little to no perceptible benefit to comfort. Variable speed AWHPs tend to be most efficient when they are allowed to operate in very long cycles, perfectly matching their heat output to the heat losses of the building. There is not necessarily an advantage to cutting heat cycles shorter by overshooting the thermostat setpoint quickly in high mass AWHP systems. High mass emitters are also slow to cool off, limiting risks to comfort for slower responding heat sources. Systems with other types of emitters may benefit more from fast heat recovery compared to the radiant floor emitters studied here.

The third-party ODU at sites 1 and 2 has a self-imposed lockout temperature of -4°F. If outdoor air temperature is below this lockout temperature at the start of a heat call, the compressor will not turn on, though it will finish a heat call if the temperature falls below this threshold while the compressor is already running. This is reflected in Figure 6 data where the heat output rate on days with a daily average temperature of 0°F and below is generally very low or near zero while the boiler supplies the majority of the heat load. In addition to the ODU-imposed lockout temperature, the third-party split IDU has setting options to select a lockout temperature for the ODU independently. The lockout setting in the IDU was set to 10°F at site 1 for the first heating season by the installer and was later adjusted to 0°F by the homeowner in the second heating season. The lockout was set to -25°F at site 2, which is why the AWHP tends to supply more heat at colder temperatures at site 2 compared to site 1. When the IDU and ODU lockout settings do not match, the system will ultimately abide by the highest lockout setting.

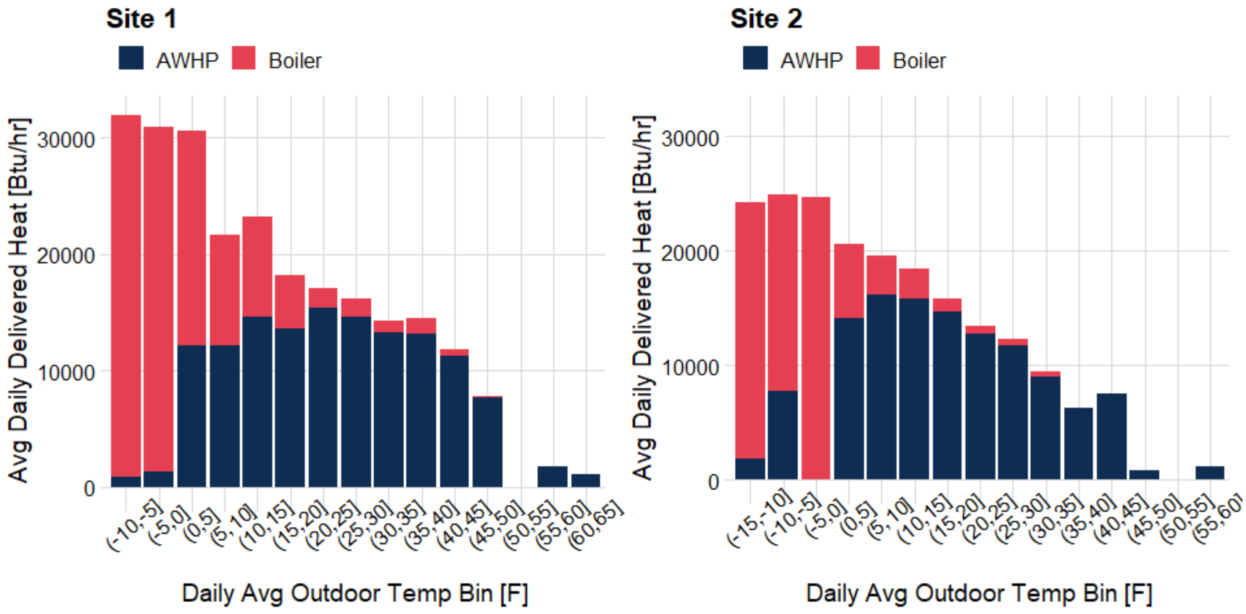

Figure 7: Average daily rate of heat delivered by source during the second winter of the study, averaged into 5°F temperature bins

To summarize the results in Figure 6, Figure 7 shows the average performance grouped into 5°F daily average temperature bins. The data in Figure 7 includes only data from after the IDU control settings were modified in late 2022. This represents the best seasonal performance we measured at sites 1 and 2 and may be suitable for future modeling work. For the average performance over the entire study period or the first winters’ performance, see Appendix D. Figure 7 shows that most of the heating load was displaced at site 1 down to average daily temperatures of 0°F to 5°F and -5°F to 0°F at site 2. The average daily heat delivery rate from the AWHP at both sites exceeded as much as approximately 15,000 Btu/hr for 5°F to 10°F daily average temperatures. Note that these data are daily averages. Heating cycle output rates were observed from the AWHPs at sites 1 and 2, which were congruent with manufacturer specifications of the ODU in air-to-air applications, from approximately 30,000 Btu/hr at 5°F to 60,000 Btu/hr at 50°F. See Appendix D for more details. The daily average AWHP output measured at these field sites is more a function of the home heating load than the AWHP’s output capacity.

Monobloc Daily Heat Delivered

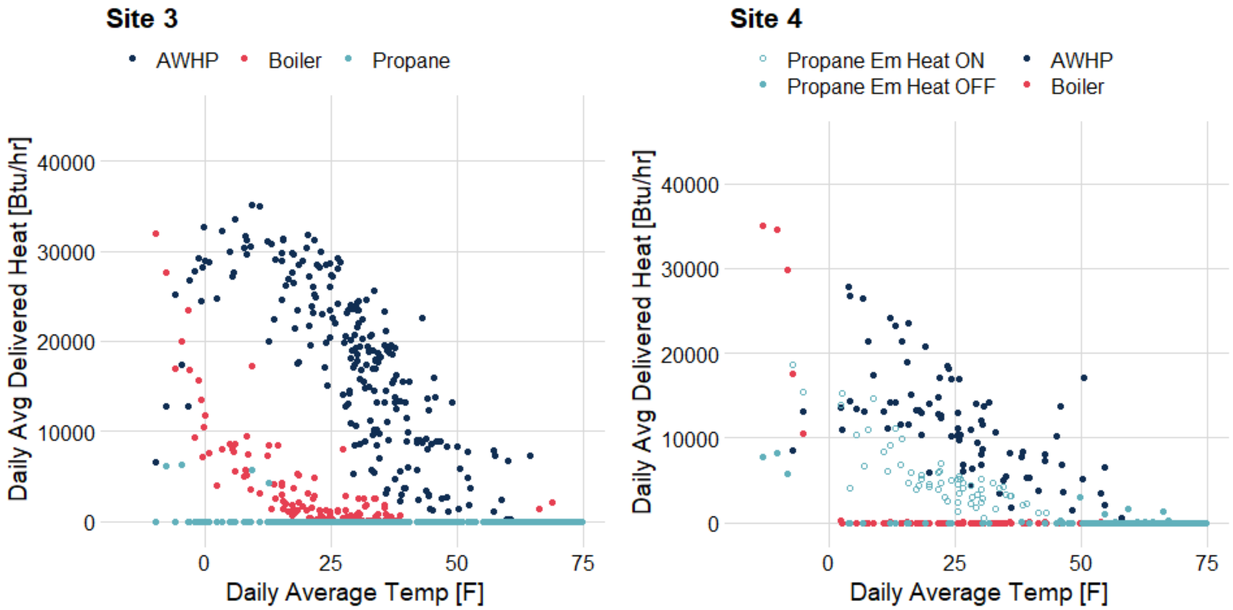

Figure 8 Daily average heat delivered by the AHWP (dark blue), the auxiliary boiler (red), and propane furnace (light blue). Hollow red circles indicate daily average heat delivered by the propane furnace while the upstairs thermostat was in emergency heat mode (AWHP was locked out from that thermostat).

Both test sites with the monobloc AWHP systems had hydronic radiant flooring to serve the homes' basement level along with a hydronic coil on a central air handler to supply cooling or heating to the upper level. The central air handler at both sites was equipped with a propane furnace and hydronic coil. Heat could be delivered by the AWHP and/or the auxiliary boiler simultaneously to the floor and/or air handler. The propane furnace could supply heat through the air handler while the AWHP or boiler heated the floor, but hydronic heat could not deliver to the hydronic coil during propane furnace cycles. The daily amount of heat delivered by each source is plotted in Figure 8 at each monobloc test site. Note that site 4 was monitored for only one heating season and site 3 was observed for approximately 1.5 heating seasons, resulting in differing amounts of data.

Figure 8 shows that the propane furnace operated very infrequently at site 3 while propane use was higher at site 4. During system troubleshooting by the manufacturer, site 4's upstairs thermostat was set into emergency heat mode for about half of the observed heating season. Propane output data from this time period are distinguished as hollow light blue circles in the plot while propane output measured during days with normal controls are plotted with solid light blue circles. When emergency heat mode was engaged at site 4, all calls for heat by the upstairs thermostat resulted in the propane furnace delivering the heat, never the AWHP. The hydronic coil on the air handler was essentially locked out from operation during this time. The AWHP continued to supply heat to the radiant floor in the basement. The emergency heat control setting on a thermostat is usually easy for an occupant to toggle themselves and can significantly impact the amount of auxilliary heat used. In this study, the setting was engaged by the manufacturer for the purpose of troubleshooting. It was not accidentally toggled by the occupants.

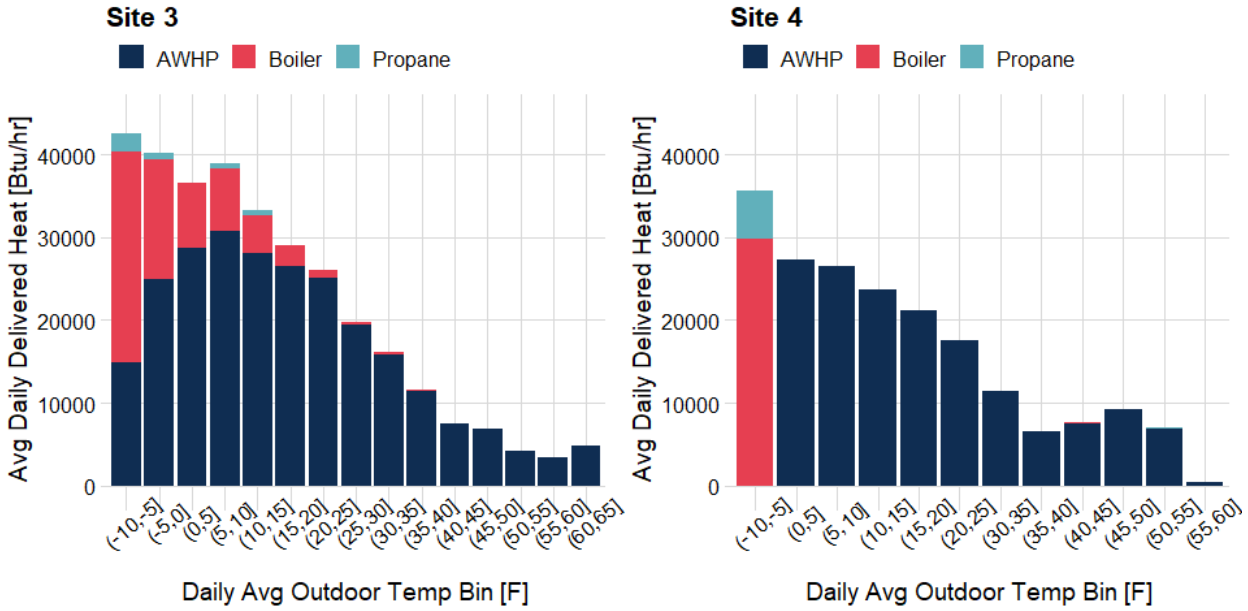

Figure 9: Average daily rate of heat delivered by source on days where the AWHP was fully operational, averaged into 5°F temperature bins

Figure 9 shows the average daily heat output rate by source averaged across 5°F temperature bins at sites 3 and 4. This represents the best seasonal performance we measured at sites 3 and 4, as the averaged data only includes when the AWHP was not locked out from serving any heat calls (i.e., no thermostat was in emergency heat mode). For the average performance over the entire study period, see Appendix D. The plot shows that majority of the heating load was displaced at site 3 down to average daily temperatures of -5°F to 0°F. At site 4, the AWHP was able to essentially displace all heat down to daily average temperatures as low as 0°F. The average daily heat delivery rate from the monobloc AWHPs exceeded as much as approximately 30,000 Btu/hr at daily average temperatures of 5°F to 10°F. Again, note that this is the average daily heat delivery rate. Heating rates from the monobloc AWHPs were measured that exceeded the manufacturer's 55,000 Btu/hr rating from heating cycles at outdoor air temperatures as low as 5°F. See Appendix D for more details.

Heating Supply Temperatures

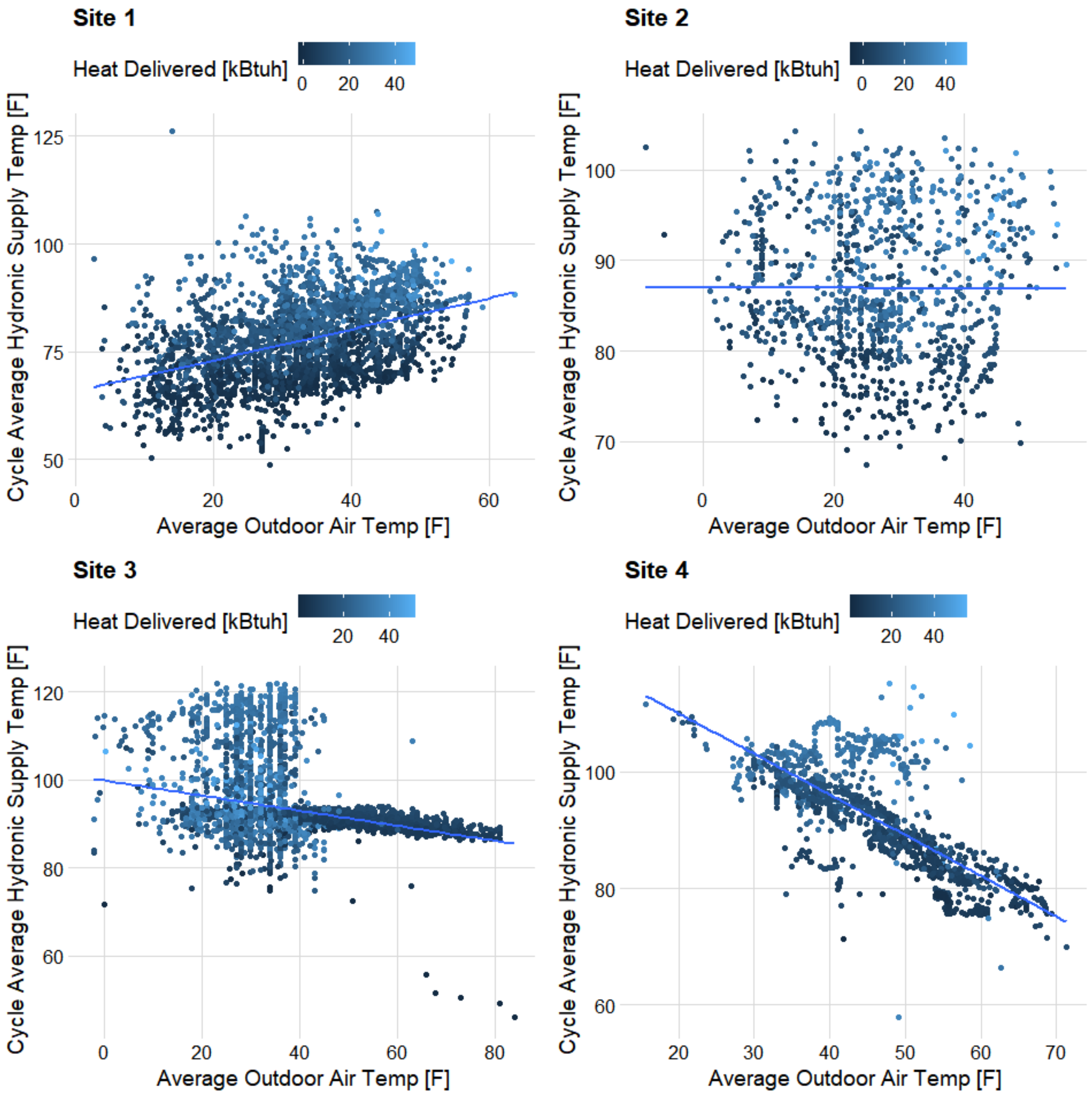

Figure 10: Average AWHP cycle hydronic supply temperatures at each site, as measured exiting the IDU to the load

All four sites' primary heat distribution method was radiant flooring, which can deliver entire home heating loads at modest supply temperatures. That feature is critical to successfully support the tested AWHPs, which had average supply temperatures during heating cycles ranging from 77°F to 93°F. During heating cycles supported by the auxiliary boiler, the average supply temperatures rose to between 86°F and 98°F. The supply temperatures varied by site and, often, by outdoor air temperature. This can be observed in Figure 10 where the average hydronic supply temperature for heating cycles is plotted against the outdoor air temperature at each site. The monobloc sites exhibited outdoor reset controls that adjusted the target supply temperature according to the outdoor air temperature. These controls reduce the hydronic supply temperature as the heating load decreases to further optimize the AWHP performance in warmer weather. The third-party split AWHPs do not have these advanced control capabilities. Instead, the supply temperatures are observed to either not vary with outdoor air temperature (as at site 2) or to decrease with the outdoor air temperature (site 1).

The field-measured supply temperatures do not necessarily represent the achievable range of supply temperatures from these AWHPs. These are simply the supply temperatures delivered at these study sites. For example, site 1's surprising trend of delivering cooler supply temperatures in cooler weather may be due to unusually low setpoints, frequent woodstove use that led to AWHP short cycling, and the IDU's location in an unconditioned space. Especially when AWHP heating cycles are short, the cold space of the IDU can reduce the average supply temperature measured since it will start near the IDU's surrounding temperature. Both site 1 and site 2 had their IDUs located in unconditioned spaces. Additionally, the thermostat setpoint at site 1 was generally 64°F or less with some unoccupied home zones set as low as 50°F. Those unusually low setpoints likely contribute to the low supply temperatures measured at site 1.

Conversely, the monobloc systems were able to adjust their supply temperatures according to the hydronic loads being served. This was observed most frequently at site 3, where the system was controlled to deliver higher temperatures to the central forced air hydronic coil and DHW preheater than the radiant floor. Site 3's system used the hydronic coil most often below 40°F outdoor temperatures. The AWHP at site 3 delivered average supply temperatures to the hydronic coil as high as 124°F, with an overall average of 102°F. These supply temperatures are similar to field measurements of the supply air temperature delivered from air-to-air ASHPs (Schoenbauer 2017). When supporting the DHW preheater, the AWHP delivered hydronic supply temperatures as high as 130°F, with an average supply temperature of 107°F for DHW preheating cycles overall.

Heating Efficiency

Figure 11 shows the daily average system COPs measured at each site during the study as a function of daily average outdoor air temperature. All the daily average data is presented on the left with the data binned into 5°F groups and averaged to summarize the results on the right. These data include all measured in the study and all observed operating regimes with various controls settings. Days with no net heat delivered are filtered out. Daily efficiencies vary significantly based on site and average daily temperature, as expected. For cycle level AWHP data that excludes the contributions of auxiliary heat or standby power, see Appendix D.

In weather with daily averages above about 40°F, the systems at sites 3 and 4 sometimes delivered heating and cooling in the same day. This leads to several daily COPs below 1. Cooling output decreases the net heat delivered per day while increasing the net energy expended, reducing the COP. COPs below 1 can also occur if only very short cycles or tiny amounts of heat are delivered from the AWHP. On those days, the amount of heat delivered doesn't compensate for the system start up, daily standby, and defrost energy expenditures. Site 1 had more low-COP days observed between 10°F and 40°F than other sites due to the occupant’s intermittent use of an independent woodstove for heating. The woodstove could significantly alter the amount of heat load in the home and lead to unusually short cycles.

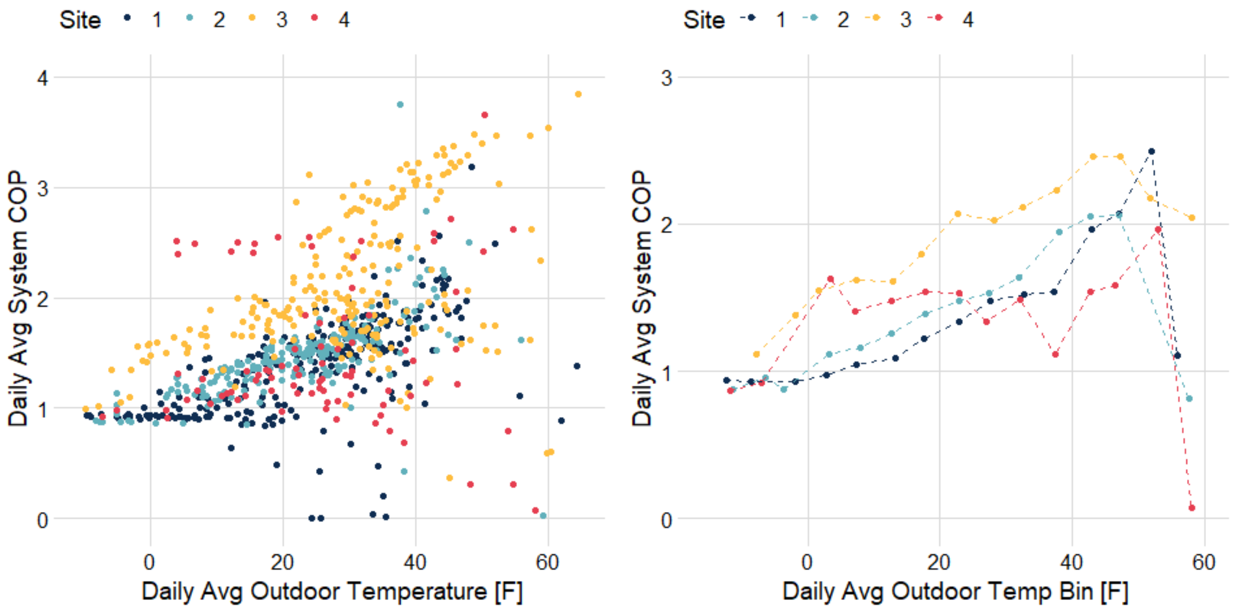

Figure 11: Daily average system COPs by site

On average, the system COPs are a significant improvement over electric resistance or propane heating alone, which always have COPs less than 1. Site 3 had the best average daily system performance, as the only site that did not have a major controls modification related to auxiliary heat use occurring during the study. Comparatively, site 4’s average COP between 10°F and 50°F was substantially reduced by regular auxiliary propane furnace usage (see Figure 8). The third-party split systems at sites 1 and 2 proved less efficient than either monobloc system below about 30°F, but their average performance exceeded that of the monobloc at site 4 above 30°F. As expected, daily COPs were best in the warmest weather, except for above about 55°F wherein the heating load drops to nearly zero at all sites and transient or standby energy consumption have an outsized impact on the daily COP calculation. Below 0°F, all systems’ COPs fell toward that of the auxiliary heat sources. The monobloc systems were able to maintain COPs above 1 to slightly colder temperatures than the third-party split, which had a higher ODU lockout temperature (-4°F vs. -13°F).

To deconvolute the impacts of varied rates of auxiliary heat usage, the same data are presented in Figure 12 but filtered to include only time periods with improved controls settings that reduced auxiliary heat. The binned average data on the right combines all data based on system type to yield a representative average performance curve per AWHP model studied. These binned averages may be suitable for future modeling work to represent real-world AWHP system performance in Minnesota. In these best case data, the monobloc AWHPs achieve daily average system COPs of up to 2.5 and the third-party split AWHPs achieve COPs of up to 2. Both have a largely linear trend between their peak

COPs and COPs at 0°F. The higher efficiency of the AWHP can deliver significant seasonal energy savings compared to conventional electric boiler heating.

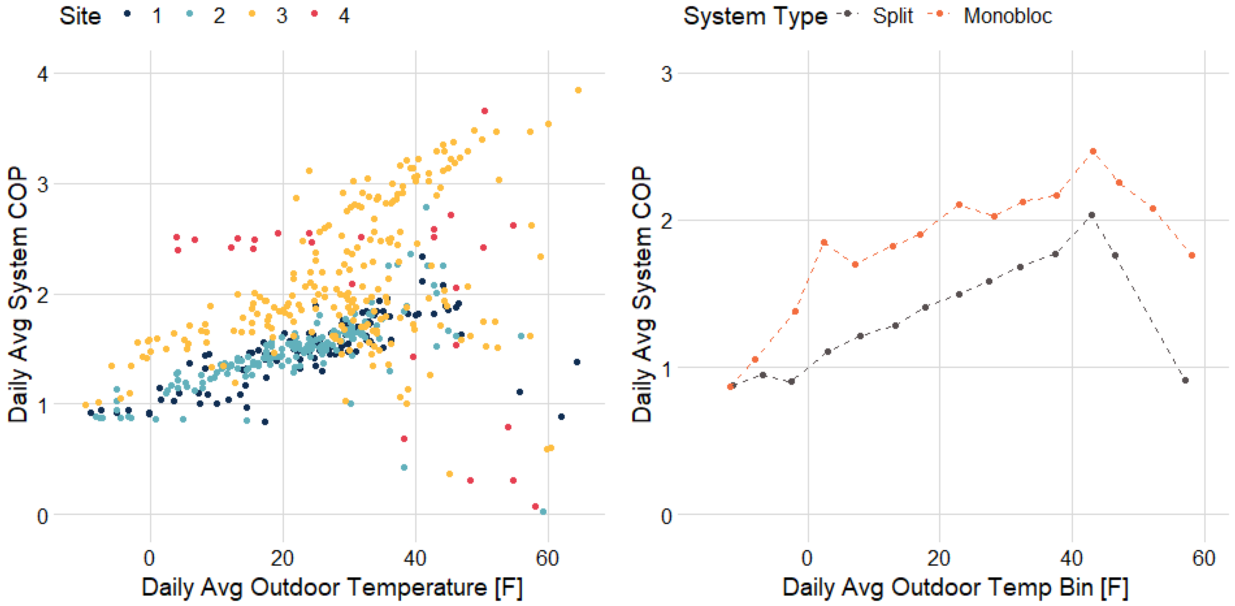

Figure 12: Optimized daily average system heating COPs

Cooling Performance

Like other ASHPs, AWHPs can provide cooling as well as heating. Only hydronic emitters that can drain away moisture are widely accepted for cooling, however. Cooling is not recommended for the radiant floor emitters at sites 1 and 2 due to the propensity to accumulate moisture. The monobloc AWHPs at sites 3 and 4 were equipped with a centrally ducted coil for cooling. These hydronic coils are installed on the preexisting air handlers like the refrigerant A-coils that match traditional air conditioners or air-to-air ASHPs. These same hydronic coils are used to provide forced air heating from the AWHP. Alternatively, some modern radiant fan cassettes may also be suitable for hydronic cooling. However, those emitters were not evaluated in this project.

Figure 13 shows the daily average sensible cooling delivered by the AWHP at sites 3 and 4 overlaid with the sensible cooling load model calculated for each site (previously plotted in Figure 5). While site 3 had a slightly greater heating load than site 4, its sensible cooling load is nearly half of that at site 4. Site 4 has unusually high solar gains from large, west-facing windows that significantly increases their cooling load. Both sites' cooling loads are met by their AWHPs, which were sized for heating. Cycle level sensible cooling output data is available in Appendix D.

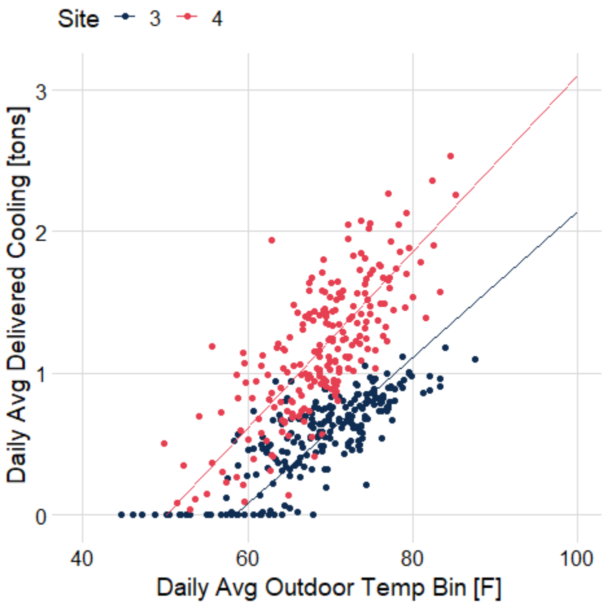

Figure 13: Daily average sensible cooling delivered as a function of temperature

The daily sensible cooling COPs measured at these sites are plotted in Figure 14. Again, we see some days where the COP is calculated as nearly zero. These data points are for days with both heating and cooling that cancel out in the net COP calculation or from days with extremely low net cooling delivered. Site 3 has more days with very little cooling delivered, as seen in Figure 13, because of its lower total cooling load. Multiple performance regimes are observed at both sites, which are coded with solid or hollow data points in Figure 14 below. Figure 14 includes lines of best fit, calculated to only include the best operating regime data represented by the solid circle datapoints. These represent the best sensible cooling performance measured at the field sites. The measured cooling COPs at both sites depended minimally on outdoor air temperature above 70°F. Below 70°F, both sites had such small sensible cooling loads that their daily COPs were reduced due to low output and runtime.

Not included in the cooling performance data here is a quantification of the latent cooling loads. Latent cooling is a result of dehumidification, which can account for a substantial fraction of the total cooling load in humid conditions. Unfortunately, humidity sensors were not included in the monitoring package at these field sites, nor were any measurements made of extracted condensate from the hydronic coil. As a result, the cooling COPs calculated here represent a COP minimum estimation. If latent loads were included in the calculation, the COPs would increase from the greater, properly accounted output. However, as an exercise one can speculate as to what the COPs might be under varying sensible heat ratios (SHR). Even at SHR as low as 50%, where 50% of the load is latent, doubling the above COP values would yield cooling efficiencies that are similar to or marginally better than minimum efficiency cooling systems.

In site 3's COP calculations, periods of time each day where the AWHP was actively heating the DHW preheat tank are removed. Standby periods or time spent recovering the supply lines from cooling to heating (and vice versa) are included in the daily cooling COP calculation. These can cause a notable energy penalty in the daily COP. The solid data points in the plot for site 3 show data measured on days where the DHW preheater was disabled. Hollow circle data points are from days when the AWHP was enabled for preheating DHW. On average, the calculated sensible cooling COP at site 3 above 70°F is 1.54 with the DHW preheating disabled and 1.35 with the DHW preheating enabled. The more than 10% drop in daily sensible cooling COPs are caused by the energy penalty in re-cooling the supply lines after a DHW preheating call. Short cycling likely exacerbates these kinds of transient losses. To be clear, the configuration of these monobloc AWHPs do not allow the unit to dump heat from cooling cycles into the DHW. Such an approach would be more efficient but require significant system modifications that increase complexity and may not even be possible for a monobloc with an indoor DHW tank.

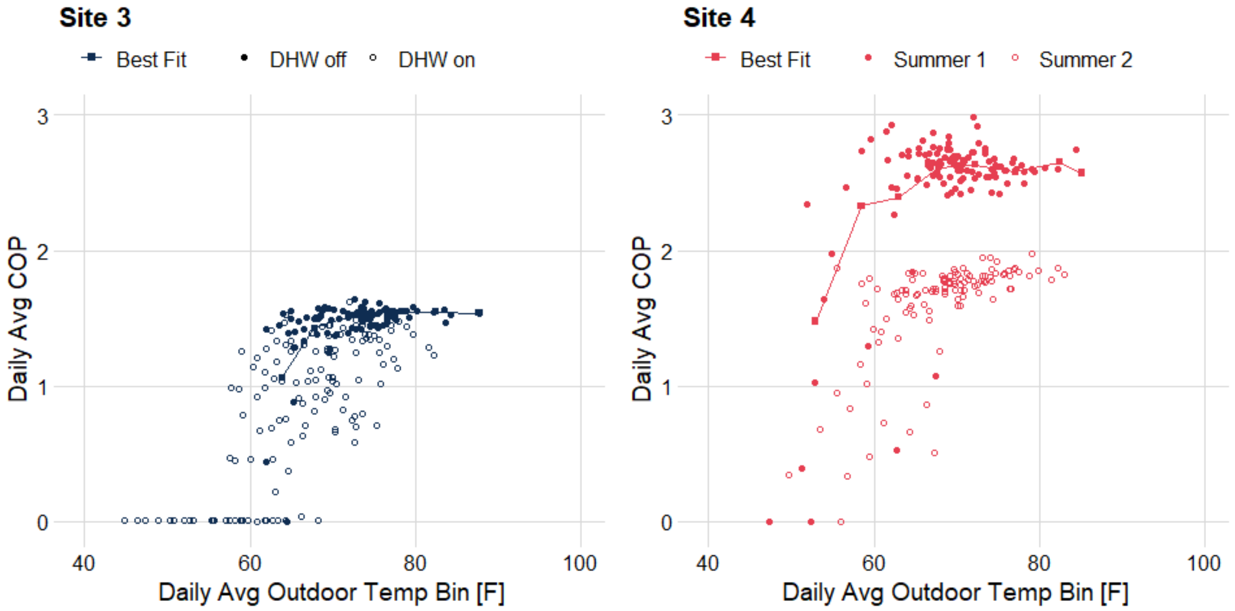

Figure 14: Daily cooling COPs

Site 4 did not have cooling season penalties due to DHW integration, but two efficiency regimes were identified here, too. The solid circles in Figure 14 for site 4 represent data measured in summer 2022, the first year of AWHP operation, while the hollow circles are data from 2023, the second year of operation. During the study, the manufacturer and installer made multiple adjustments to the AWHP at site 4 ranging from tweaking the target supply temperatures to combining radiant floor loops and removing the external hydronic separator. Overall, these adjustments reduced the COPs calculated in the cooling season between the two monitored summers. The average sensible cooling COP above 70°F in summer 2022 was 2.61 while the summer 2023 COP was 1.79 on average.

Operationally, the approximately 30% drop in average sensible cooling COPs was tied to an approximately thirty percent drop in the average hydronic flowrate to the coil. Hydronic flow rates can be adjusted in the IDU settings of the monobloc studied here. The system operated at an average hydronic flow rate of 6.4 gpm in the summer of 2023, while it had operated at an average of 9.5 gpm in the summer of 2022. The sensible cooling output is directly proportional to the hydronic flow rate and the temperature difference between the inlet and outlet sides of the loop. To meet the same load with a lower flow rate, the temperature differential increased across the coil in 2023, primarily driven by increased average return side temperatures. The average cooling cycle power input to the AWHP only increased by about 10% between the two summers to compensate for the increased return side temperatures. This 10% change in power consumption does not account for the 30% change in COP measured across the summers. Instead, the COP drop can better be attributed to an increase in the unquantified latent cooling load delivered. The average cycle duration increased by 38% in summer 2023. Longer cooling cycles are associated with more dehumidification compared to short cycles. Reducing the hydronic flow rate for the second summer was an effective lever to increase the cooling cycle length and likely the net dehumidification.

The hydronic flow rate to the coil at site 3 averaged 5.4 gpm in cooling mode. Latent cooling loads may contribute to site 3’s lower average COPs compared to site 4. Additionally, site 3’s system exhibited significant short cycling from the ODU in the summer. Even with the lower hydronic loop flow rate, the average cooling cycle from the compressor at site 3 was 4.4 times shorter than at site 4 during the summer of 2022. Interestingly, the system would often short cycle the compressor only, while maintaining continuous flow through the central hydronic coil as the compressor cycled on and off. The distribution cycles could encompass dozens of compressor cycles. Site 3’s much lower cooling loads are likely the cause of the compressor short cycling. The AWHP was not able to effectively turn down output low enough to match the load, resulting in rapid cycles of higher-than-needed output. Multiple compressor short cycles in a day can significantly reduce the average COP as transient operations during start up and shut down of the ODU are less efficient and end up representing a significant fraction of the operational time. These short cycling challenges are also possible with air-to-air ASHPs sized for heating loads. This is not a problem unique to air-to-water systems, rather a limitation of the capacity turndown ratio.

Domestic Hot Water

Site 3’s system included a DHW preheater that supplied water to the preexisting DHW electric resistance heating tank. The DHW preheater was configured as a secondary load priority — it did not heat the DHW during space heating or cooling calls. The DHW preheat tank also acted only as an independent load. The system did not have the ability to dump heat into the DHW during cooling cycles, for example, nor did it serve as a buffer or storage tank for space heating.

Figure 15 shows the daily average heat rate delivered to the DHW preheater tank as a function of outdoor weather on the left. Because the DHW is treated as a secondary load, the total heat delivered to the preheat tank is limited by the fraction of time the system supports space heating loads. Figure 15 illustrates this with gradient coloring corresponding to the total time the AWHP supplied space conditioning. Generally, the more time spent on space conditioning loads, the less heat was delivered per day to the DHW. Peak heat delivery to DHW occurred for daily average temperatures between 40°F and 60°F. The balance point measured at site 3 was approximately 58°F. The time and energy penalty for switching back and forth between heating and cooling mode is likely why the DHW receives less output on days slightly warmer than the balance point compared to days slightly colder than the balance point. Also, as previously mentioned, the system could continuously circulate the hydronic loop between the IDU and central coil while in cooling mode rather than cycle the distribution in sync with the compressor. Flow to the DHW was locked out while the system circulated to the central coil, further reducing the opportunity for the AWHP to supply more DHW heat in the summer.

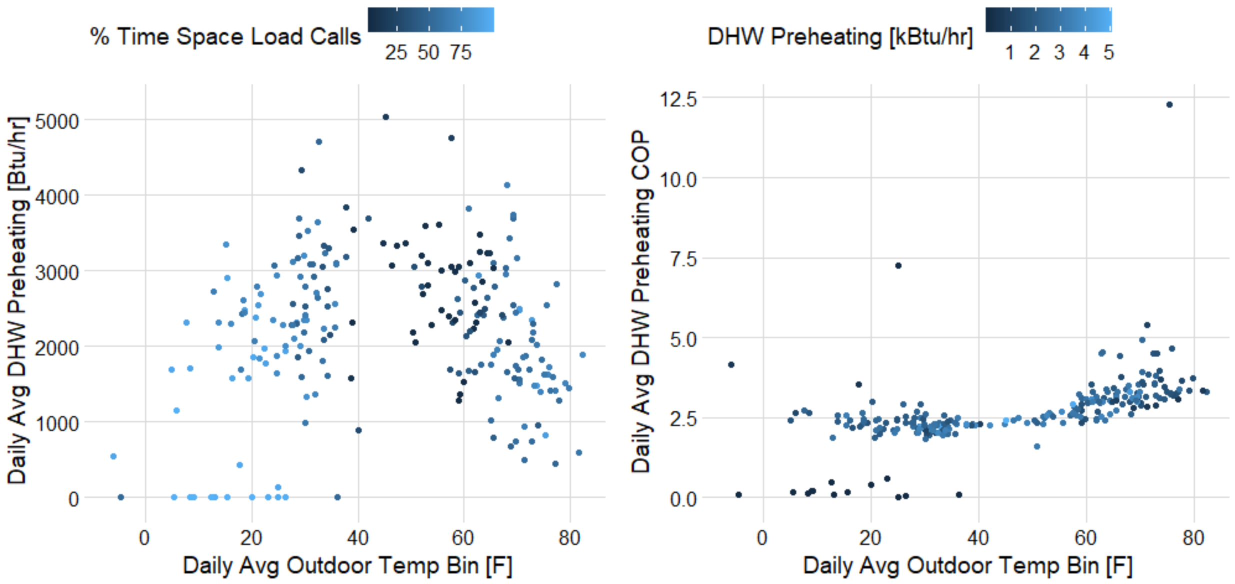

Figure 15: Daily average DHW preheating performance by the AWHP

Figure 15 also shows the daily average DHW preheating COPs measured. Unlike the space conditioning COPs previously shown, the DHW COP accounts for only the periods of time where the system was actively heating the DHW. It does not include standby losses or all losses from reverting back to cooling mode in the summer. Instead, it is more representative of the average COP for all DHW preheating cycles that occur in a day. The average daily DHW preheating cycle COP measured was 2.7. Higher COPs were measured in warm weather, above 70°F.

The total power consumption of the main electric resistance hot water heater was tracked alongside the DHW preheater. The total output from the main DHW tank was not tracked because it would have required adding intrusive sensors to the potable water supply. However, electric resistance water heaters are highly standardized and the DHW heater's COP can be approximated at 1 to estimate the heating output as roughly equal to the energy input measured. It can also be assumed that all sensible heat delivered to the DHW preheater tank is effectively delivered to the DHW supply with minimal losses each day. This assumption is fair, given the high DHW loads at site 3 meant the DHW system had consistently high throughput, reducing the impact of heat losses over time. Based on these assumptions, the fraction of total DHW heating load delivered by the AWHP system can be calculated.

These data are presented in Figure 16 on the left side. The fraction of DHW load covered by the AWHP at site 3 peaked to as much as 79% for daily average temperatures of about 45°F. The fraction of DHW load covered by the AWHP vary approximately by 12% for every 10°F change in daily average temperature from the peak. Applying the average AWHP cycle COPs for DHW preheating to the assumed COP of 1 from the main DHW heater tank, the total system COP can be calculated. This data is presented in Figure 16 on the right. The average total DHW system COP at site 3 is approximately 1.5.

The daily COP ranges from 1.2 at about 7°F to as much as 1.8 at 45°F. Because the AWHP cycle COPs improve in the summer, the total system COPs are also slightly improved in the summer despite the AWHP covering similar fractions of the DHW load as in the winter.

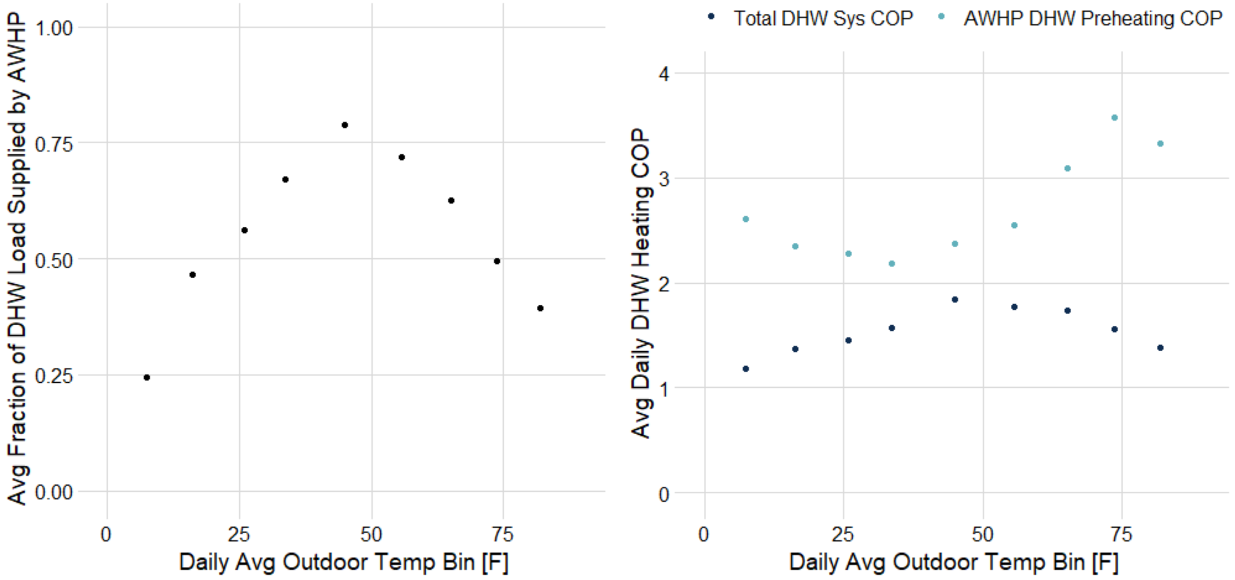

Figure 16: Daily average DHW performance of entire system

These results demonstrate that DHW heating integration is possible with AWHP systems. While the AWHP was unable to cover the entire DHW load at the study site, site 3 did have an average daily DHW load of 26 kWh, approximately twice that of the average Minnesota single-family residence (MN Department of Commerce et al. 2022). The average residential customer might expect an AWHP sized for space heating to be able to supply up to 100% of the DHW load for daily temperatures ranging from approximately 20°F to 80°F. Beyond these temperatures, an auxiliary DHW heater likely remains necessary. Integrating DHW preheating in the space heating season is an obvious energy savings opportunity. In the cooling season, however, the DHW preheating did negatively impact the daily cooling COPs by more than 10% on average (see Figure 14). The net summer savings for a home will depend on the relative size of the space cooling load compared to the DHW heating load combined with the realized COPs. For AWHPs sized for heating, cooling season performance can significantly miss the mark from manufacturer specifications due to a mismatch between the AWHP capacity and the cooling load (see Appendix D for more data). Additional research is required to reliably predict net summer season savings for AWHP systems with integrated DHW.

Interventions

All AWHPs were installed as closely to the provided manufacturer's recommendations as possible and default settings were left in place. Over the course of the project, issues related to auxiliary heat use, short cycling, or self-lockouts of the ODU necessitated some adjustments aimed to improve performance. These adjustments included both hardware and software changes that varied by site.

Thermostat Replacement

The installation of split-configuration AWHPs at sites 1 and 2 did not require new thermostats, so they retained their existing air temperature thermostats for the beginning of the monitoring period. Initial data processing revealed mild-weather use of the auxiliary boiler, which penalized system COPs when the AWHP was expected to yield the greatest benefit to heating efficiency. A discussion with the manufacturer concluded that this could be a result of multiple aspects of the overall controls. To eliminate the thermostats as a potential source, site 1 and 2’s preexisting thermostats were replaced with Honeywell T6 Pro Hydronic units including slab sensors. This specific thermostat was selected because it is familiar to the manufacturer and had been used in their in-house test procedure. Initially, contractors were apprehensive about the addition of a slab sensor because the in-floor heating could be ruptured in the installation process. Further guidance from the manufacturer and the project team eased these concerns and the thermostats were replaced at both sites in October 2022.

Site 1 reported that setting the thermostat control based purely on the slab temperature sensor resulted in their AWHP system running at high capacity for long periods and overheating the space. This issue was resolved when the thermostat setting was adjusted to use a blend of air and slab temperatures. Site 2 did not report comfort changes from the thermostat replacements. Shortly after the thermostat replacements, the IDU controls at sites 1 and 2 were also adjusted based on manufacturer feedback. Unfortunately, the convolution of these changes means the performance impact of the thermostat replacements alone cannot be quantified.

AWHP Controls Adjustments

Controls adjustments made after the first heating season at sites 1 and 2 were focused on reducing auxiliary boiler usage and short cycling of the AWHP. Based on the IDU control manual and manufacturer feedback, the target temperature difference between the IDU’s hydronic inlet and outlet was adjusted from the default difference of 10°F to just 6°F, the minimum allowable setting. If this target is missed, the system engages the auxiliary boiler, assuming the system had been in heating mode long enough to meet time delay requirements. Reducing the target temperature differential gave the AWHP a larger operating window to run without the auxiliary boiler.

The IDU also had a setting to define the time delay between the start of a heat call and when the auxiliary electric resistance heating element could be used. This setting was increased from the default value of 30 minutes to the maximum of 199 minutes. Further monitoring revealed that this delay would be held regardless of whether the AWHP turned on at the start of the heat call, causing comfort issues at site 1 when an equipment failure in the ODU occurred that prevented it from turning on at all. There was an additional setting that defines an outdoor air temperature below which the system is to skip the time delay. The IDU’s default value for this was 0°F, slightly above the normal lockout temperature of the ODU equipment used here. This feature was overlooked originally, so in early 2023 the homeowner at site 1 adjusted their programmed lockout temperature at the IDU controller to slightly above the ODU lockout temperature to ensure the boiler would turn on quickly the next time the ODU conceivably could not. Site 1 also had an ODU lockout set for 10°F for most of the first heating season, which is why the AWHP tended to not run to as low of temperatures as site 2. Overall, as shown in Figure 6, auxiliary heat use was reduced at both split AWHP sites following the suite of controls adjustments.

Several controls adjustments were also made at the monobloc sites. Site 3's home included in-floor hydronic circuits in the garage set to keep the space just warm enough to prevent a potable water line running through the garage from freezing. In colder winter conditions, this would suddenly introduce a considerable heating load to the system, causing issues with the AWHP's ability to meet the whole home load. In March 2023, the manufacturer adjusted site 3's upstairs thermostat to set the hydronic coil switchover to 10°F, allowing for propane to address the upper-level load in colder weather and free up some capacity to accommodate the needs of the hydronic heat in the garage. The impacts of this change are mostly unobserved due to a lack of cold enough weather occurring in the study after the change.

The monobloc AWHP at site 4 experienced several self-lockouts from the AWHP system in the months following the installation. These were repeatedly addressed by resetting the power to the system and adjusting the outdoor reset temperature settings. The outdoor reset temperature was described by the manufacturer as impacting the target supply temperature and flow rate for a given outdoor air temperature. The ideal setting depends on the characteristics of the emitter paired with the AWHP, somewhat complicating its adjustment in a retrofit application. Adjustments of the reset settings were made in June and July 2022, with two further adjustments made in October 2022, each of which were preceded by a few days to a few weeks of the AWHP being offline as the system will self-lockout if it finds it is running inappropriately.

Beyond tweaks to the reset values, comfort concerns in the summer led the manufacturer to decrease the target cooling supply temperature to 44°F at site 4, although this intervention was insufficient to address the participant's concerns. A longer-term period of repeated AWHP lockouts at site 4 between November 2022 and February 2023 required controls and balance of system adjustments over several visits. The manufacturer also took this opportunity to install an upgraded controls package that allowed remote monitoring and diagnostics. None of the reset value adjustments appeared to cause a majorly discernable shift in overall performance, besides reducing the likelihood of a subsequent self-lockout.

Balance of System Changes

Monitoring through the first heating season revealed issues with the monobloc systems' ability to modulate in lower heat load conditions at sites 3 and 4 without short cycling. The manufacturer determined that adjustments to balance system components were necessary for the AWHP to properly adapt to changing loads. To this end, the manufacturer removed external hydronic separators from site 4 in December 2022 and from site 3 in March 2023. The aim was to improve the systems' responsivity and prevent short cycling at full capacity in periods when longer runtimes at lower capacities were optimal. Clear conclusions about the efficacy of these changes cannot be made from this project's data set as too little heating season was left after the change at site 3 and too little had been recorded at site 4 before the change. However, monitoring the AWHP at site 3 will continue beyond this project to evaluate these changes. Following more lockout failures at site 4 in late April 2022, the manufacturer finally consolidated some of the smaller basement radiant floor heating loops which were smaller than the system's minimum design load recommendation. Despite this, issues persisted intermittently and the manufacturer troubleshot controls until mid-May 2023.

Callbacks & System Issues

Multiple callbacks and system issues were reported across all four sites through the monitoring period. While not all of these can be attributed to the new AWHP system, the relative immaturity of this technology introduced some challenges that would be less expected in a more established product segment. These issues spanned the manufacturing, installation, and operation of the monitored systems. The following is a non-exhaustive list of challenges AWHP systems may encounter, and many issues noted here are specific to these products and installations. None of these issues are expected to necessarily impact all AWHP installations. Many problems faced at these sites can be attributed to the risks and uncertainty associated with new products in an emerging market segment. Continued refinement of manufacturing, testing, and product delivery, coupled with continued controls optimization could feasibly remedy all the observed issues, allowing these new AWHP products to more consistently reach or exceed the level of performance demonstrated during this project when they operated without issue.

Hardware Failures

The monobloc AWHP systems experienced several issues that delayed installation and impacted functionality. First, the ODU for site 3 was improperly drained after factory testing, resulting in a damaged refrigerant-to-water heat exchanger after the unit was shipped in freezing weather. A new ODU was required, delaying installation at this site. This same system was shipped with mismatched control components that required disabling the DHW preheater until a replacement was made. Later, an expansion tank failure at site 3 temporarily required the DHW preheater to be locked out again in favor of space conditioning only. Finally, a fatigue failure of a critical component of the monobloc ODU also resulted in a refrigerant leak at site 3. The manufacturer reports have since made an adjustment to the affected part to eliminate this fatigue failure mode moving forward. The manufacturer also addressed each of the previously mentioned failures at no cost to the homeowners.

At site 4, one of the external hydronic pumps was incorrectly wired during the installation. This was corrected a few weeks later by the installer. In winter 2023, a faulty ODU sensor was discovered that affected the ability of the matched monobloc system to provide improved controls through communication between system components. This faulty sensor may have been a contributing factor to some of the repeated self-lockouts that occurred at site 4. Finally, one of the auxiliary boiler elements failed at site 4 late in the 2023 heating season. Like site 3, the installer and manufacturer provided significant support to address these failures. Many of these issues may be associated with new and unfamiliar products to the parties involved.

The ASHP ODUs installed at site 1 and site 2 also experienced failures due to a faulty condenser fan (site 2) and control board (site 1). These failures occurred in the first winter of the study, despite the third-party split ODU being a relatively more established product for air-to-air ASHP applications. These failures were unrelated to the AWHP application; rather, they were ODU manufacturing defects with their replacement under warranty. In both warranty claims, the manufacturer of the third-party ODU originally sent an incorrect replacement part. At site 2, this led to a second fan failure after the first replacement. The fan failure was related to a now obsolete housing design that allowed ice ingress. The ODU manufacturer's original replacement did not ship an updated fan model, leading to a second failure. At site 1, a control board that did not match the correct ODU model size was sent as replacement. The installer identified the issue when they attempted its installation and requested a corrected shipment. No manufacturing defects that could be directly attributed to the AWHP IDU system were experienced at site 1 or 2. This is perhaps a benefit of third-party split AWHP systems, as their construction is relatively simple. The ODU manufacturer (Bosch) had no issue fulfilling warranty claims for the replacement of failed ODU components as they were known product defects.

Other Issues

Outside critical part failures, several visits were required to adjust system settings in response to ongoing performance issues. This is perhaps the only system issue shared by all four sites. Both split and monobloc systems exhibited short-cycling and a lack of modulation at some point in the monitoring period. Controls issues are not inherent to the design and construction of components and pose a different challenge than a part replacement. These problems are more difficult to diagnose and remedy, while also more likely to transcend systems and installations.

The third-party split system controls were adjusted by the project team, informed by manufacturer suggestions and homeowner feedback. The monobloc installations had greater manufacturer involvement, with manufacturer technicians making periodic visits to adjust controls and system components to alleviate issues of short cycling and the overuse of auxiliary heating. At site 1, where the residents were primarily concerned with energy bills, the sustained performance penalty from this short cycling contributed to a behavioral change to their home heating habits. This site began relying more on their woodstove for a portion of their daily heating needs in response to high heating costs with their hydronic system. This in turn affected the project's ability to measure true system performance and usage when the woodstove was in use.

At site 4, the installation of the AWHP brought to attention existing issues with the home HVAC system. Site 4 had ductwork comprised entirely of flexible ducts with poorly sealed connections in the unconditioned utility closet. The home also had very large, unobstructed, west-facing windows. The solar gains introduced by these windows, coupled with the leaky ductwork and large, open stairwell made effectively cooling the upper level difficult. The target cooling supply temperature was lowered to account for this, but ultimately little could be done to improve this situation without addressing the distribution side of the system. The large cooling load also made system failures in cooling season more difficult for the occupants to endure. The combination of critical system failures, control issues, and comfort concerns resulted in the participant at site 4 requesting the removal of the AWHP system and re-installation of their old electric boiler and air conditioner at the end of the monitoring period in September 2023.

Research-related Issues

There was one additional issue attributed to the requirements of the research project rather than the systems themselves. To facilitate the study in isolating the effects from the DHW load, the installer was asked to include valving to completely isolate the DHW indirect water heater tank during the install of site 3's monobloc system. This valve was incorrectly configured at initial installation and went unnoticed as the DHW system was not enabled until the control unit was replaced in June 2022. This resulted in the system initially cooling the DHW supply during space cooling calls in June 2022. The system operated normally once this was corrected in August 2022. This issue is directly a result of the specific needs of the study and is not expected to impact systems installed in typical applications. study and is not expected to impact systems installed in typical applications.

Energy Savings, Costs, and Payback

Energy Savings

The space heating energy savings are given in Figure 17 and Table 4. Prior to heat pump installation, the modeled energy use of electric boilers to meet the space heating load was 22,800 to 34,600 kWh/yr. Following the installation of the AWHP, energy used for space heating decreased by 27% to 51% and ranged between 16,400 and 25,100 kWh/yr. The higher specification Enertech AWHP at sites 3 and 4 led to considerably more energy savings than the NorAire unit at sites 1 and 2. This difference is also reflected in the seasonal average space heating COP, which was 1.35 for the NorAire system, and between 1.8 and 2.01 for the Enertech system. Propane use for space heating was also curtailed by 96% and 62% at sites 3 and 4 respectively by prioritizing the AWHP's hydronic coil over the propane furnace.

Table 4: Calculated space heating energy savings at each site before and after the AWHP installation

Site	Baseline Electric (kWh)	AWHP Electric (kWh)	Total Savings (kWh)	Savings Fraction (%)
1	34,600	25,100	9,500	27%
2	22,800	16,500	6,300	27%
3	32,300	15,700	16,600	50%
4	30,100	16,400	13,700	46%

Overall, these results are consistent with variable speed and cold climate ASHPs in Minnesota, although they fall somewhat short of the expectation of improved COP at low supply temperatures. Based on experience over the course of the study and prior ASHP research, further efficiency improvements and increased space heating savings are achievable and likely for both system types.

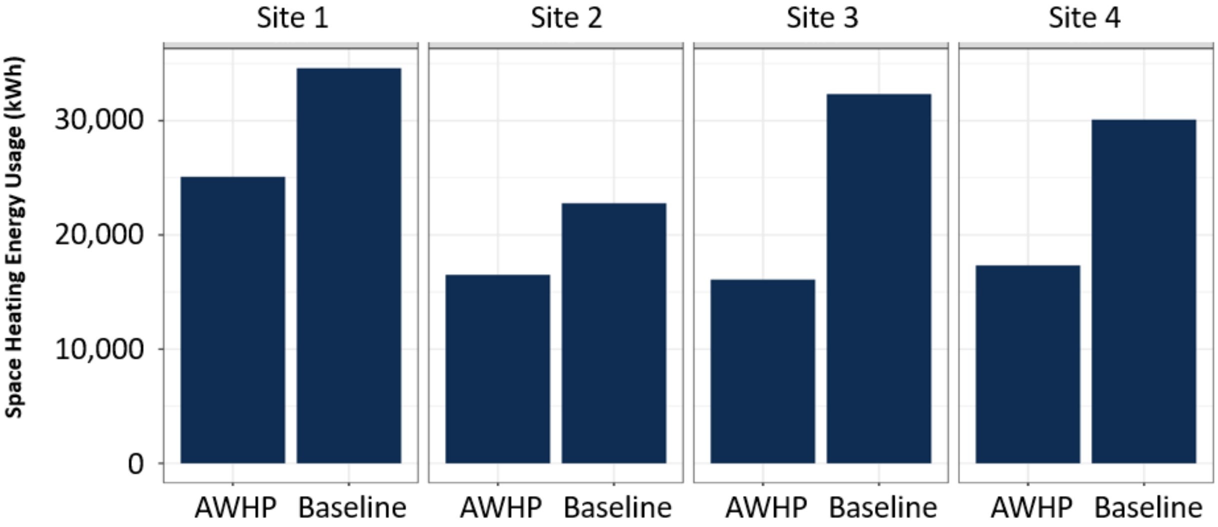

Figure 17: Calculated space heating energy at each site before and after the AWHP installation

At site 3, the AWHP was used extensively as a pre-heater for the domestic hot water. At this site, when not engaged in space heating or cooling, the AWHP displaced just under 30% of the domestic hot water load of 9,500 kWh to yield an annual savings of 4,100 kWh or 41%. It is important to note that the domestic hot water load is exceptionally large at this site, approximately double typical hot water use. While the large absolute savings are attributable to the high load, fractional savings will be larger at sites with more moderate hot water consumption.

At sites 3 and 4, the AWHP replaced the code minimum central air conditioners and provided space cooling over two cooling seasons. However, due to large uncertainty in the cooling load, the cooling energy used by the baseline central air conditioner, and persistent cooling challenges over the course of the project, cooling energy savings estimates are unavailable. Nonetheless, the energy and cost impacts of cooling energy are expected to be minor compared to those of space heating and hot water.

Energy Cost Savings

Installed costs, annual cost savings, and payback period are summarized in Table 5. Even with reduced electricity rates and relatively modest space heating loads, the baseline costs for heating participants' homes are high, ranging from $1,650/yr to $2,260/yr. The heating-only NorAire systems were the cheaper of the two AWHP system types to install with total upfront costs of $14,945 and $18,784. The space heating savings of the NorAire systems were $571/yr and $453/yr at sites 1 and 2 respectively, at their space heating rates of 0.06 and 0.072 $/kWh. Compared to the baseline electric boiler replacement cost of $6,000, these installations have a payback period of 20 and 22 years. For the Enertech AWHP systems that meet heating, cooling, and domestic hot water loads, install costs were significantly higher at $39,985 and $41,160. The incremental cost of the Enertech units are less the cost of a baseline boiler ($6,000) and central air conditioner ($5,400). Site 4 has a payback period of 31 years from $995/yr savings. The larger savings at site 3, $1,450/yr, are due to the $1,161 space heating savings plus an additional $289/yr from the displaced hot water load, yielding a payback similar to the lower cost NorAire systems, but still at or exceeding the expected equipment lifetime. It is noteworthy that because these technologies are so new to the Minnesota residential market, competing bids were not obtained for each site. More experience among installers will lead to lower install costs, particularly for the more complex Enertech installations. Paired with continuous efficiency improvements, better paybacks are anticipated as the technology matures.

Table 5: Total AWHP installation costs, annual cost savings, and payback period at each site

Site	AWHP System	Equipment Cost	Labor Cost	Total Install Costs	Incremental Cost ($)	Cost Savings ($/yr)	Payback Period (yr)
1	NorAire EB-HPH w/ Bosch BOVA	$14,508	$4,276	$18,784	$12,784	$571	22
2	NorAire EB-HPH w/ Bosch BOVA	$12,086	$2,859	$14,945	$8,945	$453	20
3	Enertech Advantage	$33,229	$7,931	$41,160	$28,760	$1,450	20
4	Enertech Advantage	$32,469	$7,516	$39,985	$28,585	$995	29

Conclusions and Recommendations

Developing efficient heating options for homes with hydronic heat will be important to keep up with state and federal goals that continue to require higher levels of efficiency from the residential sector. For centrally ducted homes, the high-efficiency market has been moving toward air-to-air ASHPs. Now, hydronic heated homes can move toward AWHPs. AWHPs can be more attractive than geothermal retrofits with cheaper to install product offerings. The AWHP market can also leverage ASHP development in general to realize high-performance products even faster, especially in the ODU technologies. Significant barriers in the supply chain still exist, however, including an extremely limited workforce, no standard rating methodologies for product comparisons, and limited supply temperature capabilities that shrink the applicable retrofit market size.

Market Readiness

AWHPs have the potential to provide significant energy and cost savings to homeowners with hydronic space heating systems in Minnesota. The technology has already enjoyed significant adoption in other regions, especially Europe, which has helped the technology develop. Given the similarities between air-to-air ASHPs and AWHPs, no inherent technological limitations appear that would preclude cold climate capable AWHPs from delivering savings in Minnesota when commissioned correctly. The AWHP market is currently in its infancy in the Midwest, however, with only a handful of known installations. Significantly strengthening sales channels and developing a qualified workforce are necessary for AWHP adoption to grow in the state.

Finding qualified or even willing installers was a significant hurdle for this field project; homeowners exploring AWHP technologies independently will likely continue to struggle similarly until the market grows. Conventional ASHPs have faced similar market barriers but have recently benefited from significant local, regional, and national collaborative efforts to accelerate their market growth (McPherson et al. 2020). The strategies coalitions use to support air-to-air ASHP technologies can and should be applied to AWHPs to realize their full market potential. The wide variety and complexity of distribution systems that AWHPs can support will tend to amplify the existing market barriers air-to-air ASHPs face. Continued growth and acceptance of air-to-air ASHP technologies should buoy the opportunity for AWHPs to find their niche in the state, but this alone will not be enough.

Matching appropriate hydronic distribution systems with cold climate AWHPs appears particularly challenging compared to air-to-air systems. Residential ASHPs generally provide lower supply temperatures compared to conventional heat sources, with supply temperatures from cold climate ASHPs usually in the range of 80 to 120°F. Fossil fuel furnaces typically deliver slightly warmer supply air, from 120 to 140°F. In comparison, traditional radiators that exist in the region's older housing stock are typically designed for supply temperatures of approximately 160 to 180°F and the heat transfer modes radiators rely on are significantly more sensitive to supply temperatures than forced air systems. For example, fin tubed baseboard radiators are expected to have a 76% heating capacity loss for supply temperatures at 120°F instead of 180°F. Reducing hydronic supply temperatures to radiators can significantly reduce their overall heating capacity, potentially to the point where the system is undersized for the heating load. As a result, AWHPs are not currently considered a drop-in replacement for high temperature hydronic systems.

Opportunities for AWHPs in Minnesota

Unless AWHPs are paired with emitter upgrades or deep weatherization measures to drastically reduce home heat loads, they may not succeed in retrofitting high-temperature hydronic systems. These usually include systems with cast iron panel or baseboard radiators. At best, poor application of AWHPs in high-temperature system retrofits will result in less realized savings than could have been possible. At worst, poor AWHP implementations could set the technology back decades in the arena of public opinion and drastically impede their adoption, even in more suitable applications. Poor experiences with owning and installing early ASHPs can affect contractor and homeowner perceptions of new systems, emphasizing the importance of a good first impression for a new product sector. Early efforts to support AWHPs should thus prioritize successful installations and focus on opportunities that present as the lowest hanging fruit.

Opportunities for early success in Minnesota’s housing market generally include brand new construction and newer construction outfitted with modern, low temperature emitters. Fan coil cassettes, radiant floor heating, and central hydronic coils appear as the simplest emitter types to implement right now. Retrofitting homes with high-temperature radiator emitters is possible, but the additional cost and care needed will be a barrier. This project did not field test the application of AWHPs with high-temperature emitters. More installer experience and product presence in the state should reduce the risk of these more complicated retrofit situations and lower installation costs over time, but additional research may be required to support the market’s expansion into high-temperature applications. Until AWHPs become more common and an experienced workforce develops, ductless air-to-air ASHPs will remain a competitive option for achieving efficiency improvements in high-temperature hydronic system retrofits.

Low-temperature hydronic system retrofits can certainly be served by currently available AWHPs and should realize significant heating savings. However, current findings from the field do not support that AWHPs should be relied on for cooling savings in Minnesota. The centrally ducted hydronic coils studied here did not deliver net cooling season savings from the studied AWHPs. More work needs to be done to improve cooling season and low load performance to extend AWHP savings to the summer months. However, potential cooling season penalties can be overcome by the heating savings AWHPs offer. This is also true when DHW loads are integrated. In addition to space heating savings for low-temperature hydronic systems, this field evaluation demonstrated that significant DHW heating savings can be achieved from AWHPs. While these field results showed that residential DHW heating cannot be served entirely by an AWHP managing space conditioning loads simultaneously, a major fraction of DHW heating can be supported. More data is needed to comprehensively assess the DHW savings opportunity from AWHPs as this field study was able to include only one site with DHW integration.

ECO and Utility Program Recommendations

While the AWHP market remains underdeveloped and national rating standards are not yet in place, consider supporting the market by treating AWHPs the same as other ASHPs as much as possible in ECO. As a sub-category of air-to-air ASHPs, AWHPs can deliver similar amounts of savings and work in fundamentally the same way. Metrics that account for benefits beyond site energy savings including emissions reductions, source energy savings, and costs can bolster the justifications for AWHP programs. In any instance where a cold climate air-to-air ASHP is determined to be beneficial but impractical to implement due to the existing hydronic infrastructure, cold climate AWHPs should be encouraged. ASHPs of any variety can generally achieve significant cost savings when displacing electric resistance or delivered fuels. Cost savings will be more limited for natural gas displacement, based on current fuel rates.

The characteristics of cold climate AWHPs are essentially the same as those of cold climate air-to-air ASHPs: inverter driven compressors sized to meet as much of the homes' heating load as possible at 10°F or less with controls for engaging auxiliary heat as needed (but no more than necessary). Both monobloc and split designs should be specified to include minimum percentages of antifreeze suitable for the climate when antifreeze is used. If manufacturer-reported SEER or HSPF ratings are available for AWHP models, they could be considered comparable to AHRI ratings until an industrywide standard is adopted. Market actors interested in realizing AWHP savings sooner should advocate for standardized ratings comparable to other ASHP technologies, particularly since ductless ASHPs currently represent a compelling alternative to AWHPs for space heating.

Given the small size of the current market and lack of standardization, administrators can temporarily identify specific AWHP products for inclusion in programs. This is a strategy Efficiency Vermont is pursuing, who has published a list of qualified AWHPs for their rebate programs starting in 2021 (Efficiency Vermont 2021). Their qualified list specification requires a COP of 1.7 or greater at 5°F outdoor air temperature when delivering water at 110°F. Recently, Ottertail Power Company in Minnesota adopted this same specification for an AWHP rebate program (Otter Tail Power, n.d.), as has Mass Save in Massachusetts (Mass Save, n.d.). The monobloc system studied in this project meets this specification while the third-party split AWHP did not. Programs might also leverage the rating system already in place in the EU (CEN 2022a; CEN 2022b) to create efficiency tiers. No approach is currently comprehensive, unfortunately, as not all products overlap across the regional markets and not all products have been rated uniformly.

Future Work

The primary achievement of this work was capturing a snapshot of the state of the AWHP market in Minnesota and demonstrating that AWHPs available today can deliver significant annual energy savings for both space conditioning and hot water heating in retrofit applications. Further work is required to realize the full potential of AWHP technologies in Minnesota. Much of the work is related to market development: workforce development, program development, and standardization. Some research work also remains, such as clarifying the performance of different emitter types not included in this study, evaluating if or how AWHPs can retrofit high temperature hydronic systems, optimizing further controls, improving cooling season performance, reducing system installation complexity, and integrating thermal energy storage or buffer tanks for extended performance gains. Continued monitoring will be conducted at Site 3 to measure changes to system heating performance through the 2023–2024 heating season as a result of balance of system and control changes made by the manufacturer in spring 2023. Once available, these results will be made public via the AWHP project page on CEE's website.[1]

Taking a long view, monobloc AWHPs are increasingly touted as a key technology to meet tightening refrigerant regulations. Because they don't require field charging or refrigerant lines within the building envelope, they may one day become the default type of ASHP.

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[1] Available from https://www.mncee.org/discovering-air-water-heat-pumps

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Appendix A: Equipment Characterization Data

Distributions

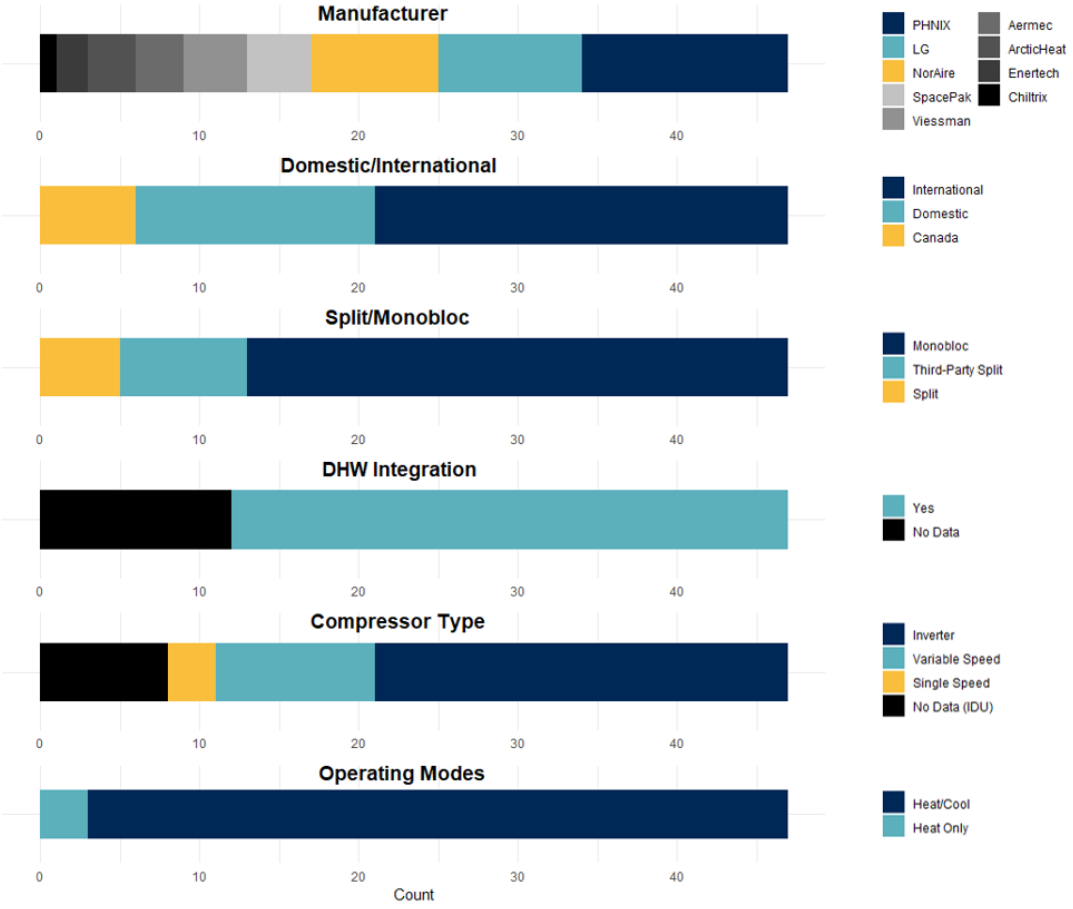

Figure 18: Characteristics of domestically available AWHP systems

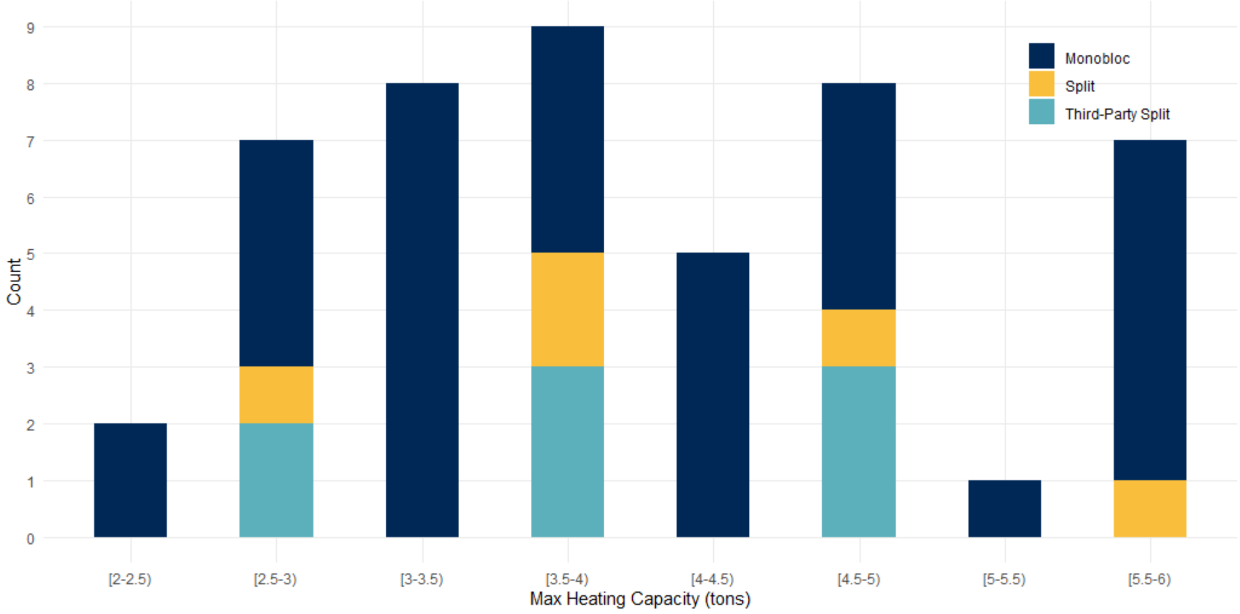

Figure 19: Max heating capacity of compatible systems

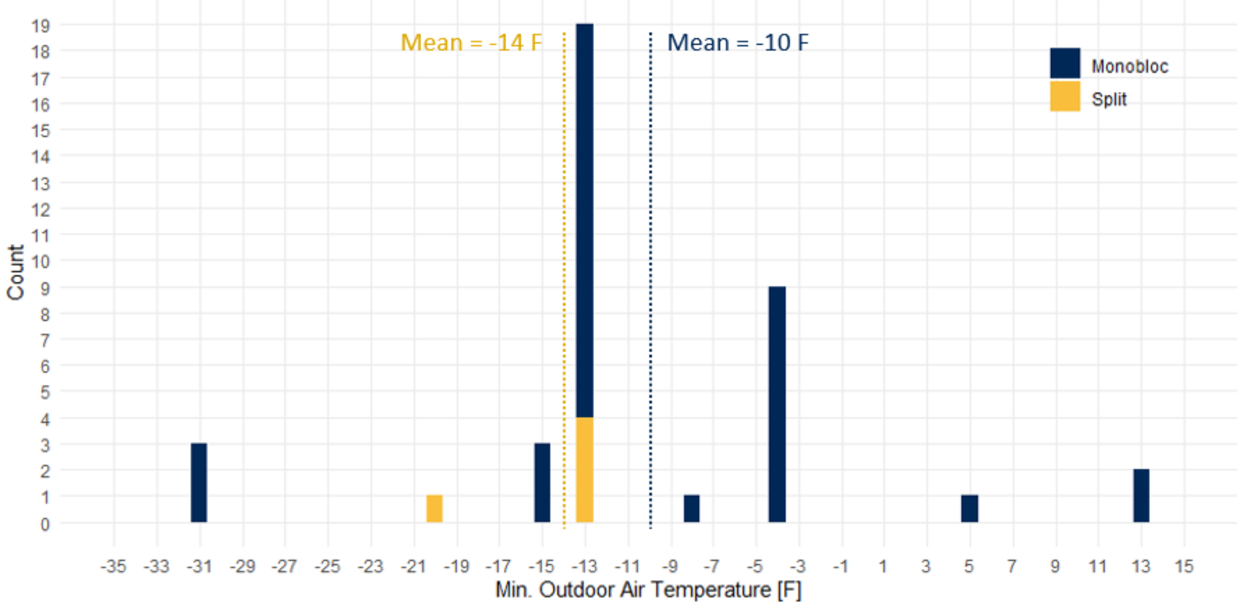

Figure 20: Distribution and mean of the minimum ambient temperature for monobloc and split system ODUs as stacked bars.

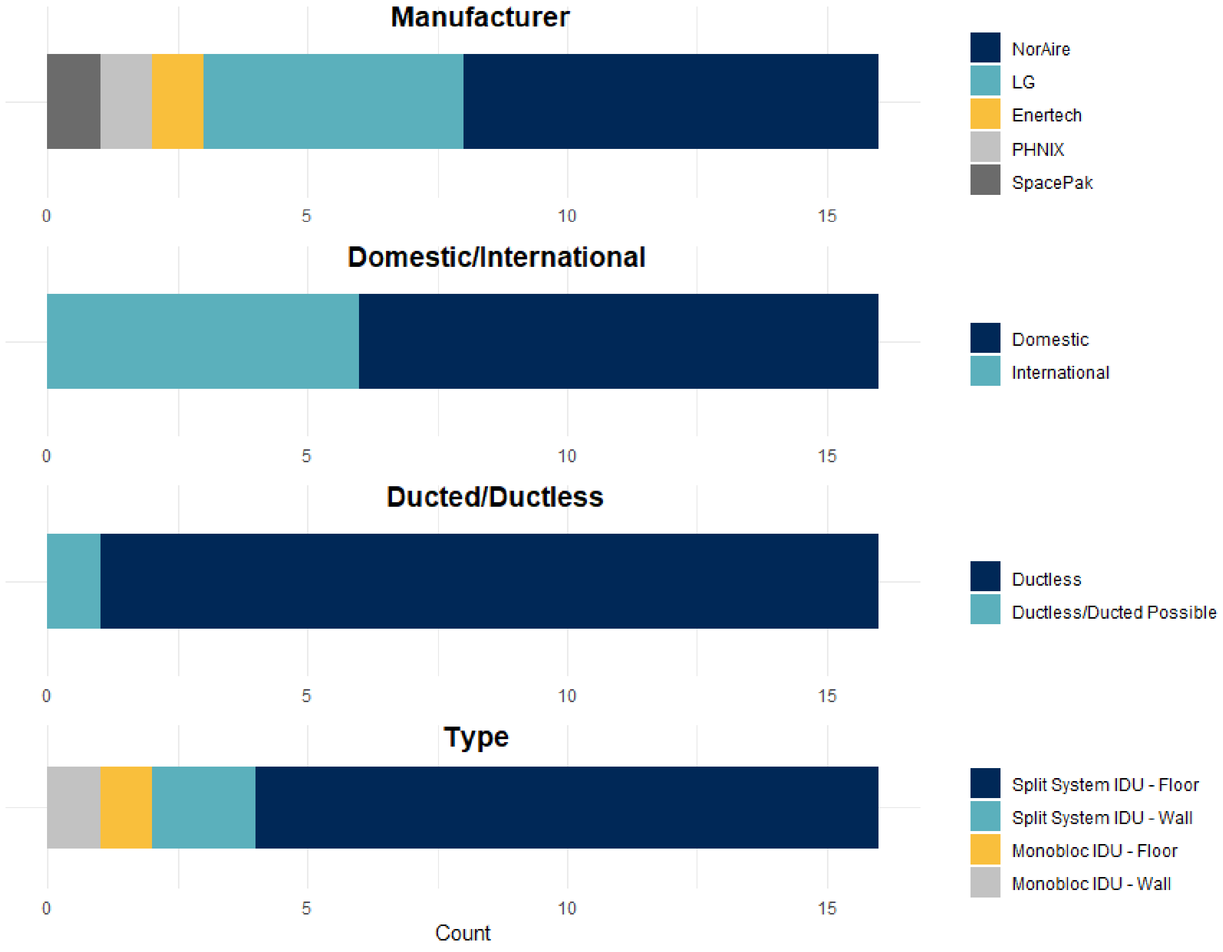

Figure 21: Characterization of all compatible IDUs

Characteristic Tables

Table 6: Characteristics and ratings for 47 shortlisted products

Product	Configuration	Operating Modes	Compressor Type	DHW Capable?	IPLV EER	Min EER	Max EER
Aermec ANK 030 (H°/P/A)	Monobloc	Heat/Cool	Single Speed	Yes	14.88		10.7
Aermec ANK 045 (H°/P/A)	Monobloc	Heat/Cool	Single Speed	Yes	14.5		10.43
Aermec ANK 050 (H°/P/A)	Monobloc	Heat/Cool	Single Speed	Yes	15.46		11.15
Arctic Heat Pumps 02A	Monobloc	Heat/Cool	Variable Speed	Yes			
Arctic Heat Pumps 04A	Monobloc	Heat/Cool	Variable Speed	Yes			
Arctic Heat Pumps 06A	Monobloc	Heat/Cool	Variable Speed	Yes			
Chiltrix CX34 Small Heat Pump Chiller	Monobloc	Heat/Cool	Variable Speed	Yes	23		35
Enertech Advantage AV030	Monobloc	Heat/Cool	Variable Speed	Yes	17.8		
Enertech Advantage AV060	Monobloc	Heat/Cool	Variable Speed	Yes	16.6		
LG Therma V R32 Monobloc HM091M U43	Monobloc	Heat/Cool	Variable Speed	Yes		2.6	4.2
LG Therma V R32 Monobloc HM121M U33	Monobloc	Heat/Cool	Variable Speed	Yes		2.7	4.6

Product	Configuration	Operating Modes	Compressor Type	DHW Capable?	IPLV EER	Min EER	Max EER
/ HM123M U33							
LG Therma V R32 Monobloc HM141M U33 / HM143M U33	Monobloc	Heat/Cool	Variable Speed	Yes		2.6	4.3
LG Therma V R32 Monobloc HM161M U33 / HM163M U33	Monobloc	Heat/Cool	Variable Speed	Yes		2.5	4
LG Therma V R32 Silent Monobloc HM091MRS U33	Monobloc	Heat/Cool	Variable Speed	Yes		3	5
LG Therma V R32 Split HU091MR U44	Split	Heat/Cool	Variable Speed	Yes		2.6	4.2
LG Therma V R32 Split HU121 U33 / HU123 U33	Split	Heat/Cool	Variable Speed	Yes		2.98	4
LG Therma V R32 Split HU141 U33 / HU143 U33	Split	Heat/Cool	Variable Speed	Yes		2.81	3.9
LG Therma V R32 Split HU161 U33 / HU163 U33	Split	Heat/Cool	Variable Speed	Yes		2.7	3.61
NorAire EB-HPH 3	Third-Party Split	Heat Only					

Product	Configuration	Operating Modes	Compressor Type	DHW Capable?	IPLV EER	Min EER	Max EER
NorAire EB-HPH 4	Third-Party Split	Heat Only					
NorAire EB-HPH 5	Third-Party Split	Heat Only					
NorAire NC-FE 036	Third-Party Split	Heat/Cool					
NorAire NC-FE 048	Third-Party Split	Heat/Cool					
NorAire NC-FE 048 w/ Backup Boiler	Third-Party Split	Heat/Cool					
NorAire NC-FE 060	Third-Party Split	Heat/Cool					
NorAire NC-FE 060 w/ Backup Boiler	Third-Party Split	Heat/Cool					
PHNIX HeatPro KV15A	Monobloc	Heat/Cool	Variable Speed	Yes			
PHNIX HeatPro KV15T	Monobloc	Heat/Cool	Variable Speed	Yes			
PHNIX Hero H15B	Monobloc	Heat/Cool	Variable Speed	Yes			
PHNIX Hero H8A	Monobloc	Heat/Cool	Variable Speed	Yes			
PHNIX Hero Plus P10A	Monobloc	Heat/Cool	Variable Speed	Yes			
PHNIX Hero Plus P10T	Monobloc	Heat/Cool	Variable Speed	Yes			

Product	Configuration	Operating Modes	Compressor Type	DHW Capable?	IPLV EER	Min EER	Max EER
PHNIX Hero Plus P17A	Monobloc	Heat/Cool	Variable Speed	Yes			
PHNIX Hero Plus P17T	Monobloc	Heat/Cool	Variable Speed	Yes			
PHNIX Hero Plus P6	Monobloc	Heat/Cool	Variable Speed	Yes			
PHNIX Hero Premium PASRW040-BP-PS-B	Monobloc	Heat/Cool	Variable Speed	Yes			
PHNIX Hero Pro HP10	Monobloc	Heat/Cool	Variable Speed	Yes			
PHNIX Hero Pro HP14	Monobloc	Heat/Cool	Variable Speed	Yes			
PHNIX Hero Pro HP18	Monobloc	Heat/Cool	Variable Speed	Yes			
SpacePak Solstice Extreme	Monobloc	Heat/Cool	Variable Speed				
SpacePak Solstice SIM-036	Monobloc	Heat/Cool	Variable Speed			8.77	12.97
SpacePak Solstice SIM-060	Monobloc	Heat/Cool	Variable Speed			8.23	11.6
SpacePak Solstice SIS-060A4	Split	Heat/Cool	Variable Speed			7.12	18.05
Viessman Vitocal 200A	Monobloc	Heat/Cool	Variable Speed	Yes			

Product	Configuration	Operating Modes	Compressor Type	DHW Capable?	IPLV EER	Min EER	Max EER
Viessman Vitocal 222A	Monobloc	Heat/Cool	Variable Speed	Yes			
Viessman Vitocal 300A	Monobloc	Heat/Cool	Variable Speed	Yes			
Viessman Vitocal 350A	Monobloc	Heat/Cool	Variable Speed	Yes			

Table 7: Efficiency and capacity vs OAT for 47 shortlisted products

Product	Configuration	Min OAT (°F)	COP at 5°F	Heat Btu/h at 5°F	COP at 17°F	Heat Btu/h at 17°F	Min. Heat COP at 17°F	Max. Heat COP at 17°F	Min. Heat Btu/h at 45°F	Max. Heat Btu/h at 45°F	Min. Cool EER at 95°F	Max. Cool EER at 95°F	Min. Cool Btu/h at 95°F	Max. Cool Btu/h at 95°F
Aermec ANK 030 (H°/P/A)	Monobloc	-4							37,670	37,670			30,000	30,000
Aermec ANK 045 (H°/P/A)	Monobloc	-4							51,967	51,967			39,600	39,600
Aermec ANK 050 (H°/P/A)	Monobloc	-4							57,957	57,957			48,000	48,000
Arctic Heat Pumps 02A	Monobloc	-15												
Arctic Heat Pumps 04A	Monobloc	-15												
Arctic Heat Pumps 06A	Monobloc	-15												
Chiltrix CX34 Small Heat Pump Chiller	Monobloc	-4				22,237			33,813	33,813			30,049	30,049

Product	Configuration	Min OAT (°F)	COP at 5°F	Heat Btu/h at 5°F	COP at 17°F	Heat Btu/h at 17°F	Min. Heat COP at 17°F	Max. Heat COP at 17°F	Min. Heat Btu/h at 45°F	Max. Heat Btu/h at 45°F	Min. Cool EER at 95°F	Max. Cool EER at 95°F	Min. Cool Btu/h at 95°F	Max. Cool Btu/h at 95°F
Enertech Advantage AV030	Monobloc	13			3.2		5.1	5.1						
Enertech Advantage AV060	Monobloc	13			3.4		4.8	4.8						
LG Therma V R32 Monobloc HM091M U43	Monobloc	-13					3.5	4.2	18,426	30,709	2.6	4.2	30,709	30,709
LG Therma V R32 Monobloc HM121M U33 / HM123M U33	Monobloc	-13					3.5	4.6	37,534	40,946	2.7	4.6	40,946	40,946
LG Therma V R32 Monobloc HM141M U33 /	Monobloc	-13					2.8	4.5	40,946	47,770	2.6	4.3	47,770	47,770

Product	Configuration	Min OAT (°F)	COP at 5°F	Heat Btu/h at 5°F	COP at 17°F	Heat Btu/h at 17°F	Min. Heat COP at 17°F	Max. Heat COP at 17°F	Min. Heat Btu/h at 45°F	Max. Heat Btu/h at 45°F	Min. Cool EER at 95°F	Max. Cool EER at 95°F	Min. Cool Btu/h at 95°F	Max. Cool Btu/h at 95°F
HM143M U33														
LG Therma V R32 Monobloc HM161M U33 / HM163M U33	Monobloc	-13					2.8	4.4	40,946	54,594	2.5	4.0	54,594	54,594
LG Therma V R32 Silent Monobloc HM091MRS U33	Monobloc	-13					2.8	5.1	20,473	30,709	3.0	5.0	30,709	30,709
LG Therma V R32 Split HU091MR U44	Split	-13					3.5	4.7	18,426	30,709	2.6	4.2	30,709	30,709
LG Therma V R32 Split HU121 U33 / HU123 U33	Split	-13					2.5	4.6	35,145	42,652	3.0	4.0	26,956	35,486
LG Therma V R32 Split	Split	-13					3.5	4.4	36,851	47,770	2.8	3.9	29,003	40,946

Product	Configuration	Min OAT (°F)	COP at 5°F	Heat Btu/h at 5°F	COP at 17°F	Heat Btu/h at 17°F	Min. Heat COP at 17°F	Max. Heat COP at 17°F	Min. Heat Btu/h at 45°F	Max. Heat Btu/h at 45°F	Min. Cool EER at 95°F	Max. Cool EER at 95°F	Min. Cool Btu/h at 95°F	Max. Cool Btu/h at 95°F
HU141 U33 / HU143 U33														
LG Therma V R32 Split HU161 U33 / HU163 U33	Split	-13					3.5	4.3	40,775	54,594	2.7	3.6	30,368	44,358
NorAire EB-HPH 3	Third-Party Split									33,300				
NorAire EB-HPH 4	Third-Party Split									44,400				
NorAire EB-HPH 5	Third-Party Split									59,100				
NorAire NC-FE 036	Third-Party Split									33,000				35,000
NorAire NC-FE 048	Third-Party Split									46,000				47,000
NorAire NC-FE 048 w/ Backup Boiler	Third-Party Split									46,000				47,000

Product	Configuration	Min OAT (°F)	COP at 5°F	Heat Btu/h at 5°F	COP at 17°F	Heat Btu/h at 17°F	Min. Heat COP at 17°F	Max. Heat COP at 17°F	Min. Heat Btu/h at 45°F	Max. Heat Btu/h at 45°F	Min. Cool EER at 95°F	Max. Cool EER at 95°F	Min. Cool Btu/h at 95°F	Max. Cool Btu/h at 95°F
NorAire NC-FE 060	Third-Party Split									55,000				57,000
NorAire NC-FE 060 w/ Backup Boiler	Third-Party Split									55,000				57,000
PHNIX HeatPro KV15A	Monobloc	-13					4.1	4.1	53,571	53,571	2.9	2.9	39,240	39,240
PHNIX HeatPro KV15T	Monobloc	-13					4.1	4.1	53,571	53,571	2.9	2.9	39,240	39,240
PHNIX Hero H15B	Monobloc	-13					4.2	3.8	17,061	59,030	3.1	2.6	13,649	49,476
PHNIX Hero H8A	Monobloc	-13					3.1	3.9	8,530	36,851	2.0	2.9	6,824	34,121
PHNIX Hero Plus P10A	Monobloc	-13					4.3	3.7	16,038	42,651	2.5	2.5	10,919	38,557

Product	Configuration	Min OAT (°F)	COP at 5°F	Heat Btu/h at 5°F	COP at 17°F	Heat Btu/h at 17°F	Min. Heat COP at 17°F	Max. Heat COP at 17°F	Min. Heat Btu/h at 45°F	Max. Heat Btu/h at 45°F	Min. Cool EER at 95°F	Max. Cool EER at 95°F	Min. Cool Btu/h at 95°F	Max. Cool Btu/h at 95°F
PHNIX Hero Plus P10T	Monobloc	-13					4.3	3.8	16,038	42,651	2.5	2.5	10,919	38,557
PHNIX Hero Plus P17A	Monobloc	-13					4.7	3.4	23,885	69,949	3.7	2.6	18,766	52,888
PHNIX Hero Plus P17T	Monobloc	-13					4.7	3.5	27,297	69,949	3.7	2.7	18,766	52,888
PHNIX Hero Plus P6	Monobloc	-13					3.8	4.6	7,848	28,321	2.9	2.8	6,824	20,814
PHNIX Hero Premium PASRW040-BP-PS-B	Monobloc	-13					4.7	4.4	15,354	42,651	2.5	2.4	10,578	35,827
PHNIX Hero Pro HP10	Monobloc	-31					3.5	3.0	14,331	40,946	3.0	2.4	12,274	32,757
PHNIX Hero Pro HP14	Monobloc	-31					3.5	3.1	19,108	50,500	2.6	2.2	14,331	36,179
PHNIX Hero Pro HP18	Monobloc	-31					3.4	2.9	24,567	68,243	3.0	2.4	21,496	56,300

Product	Configuration	Min OAT (°F)	COP at 5°F	Heat Btu/h at 5°F	COP at 17°F	Heat Btu/h at 17°F	Min. Heat COP at 17°F	Max. Heat COP at 17°F	Min. Heat Btu/h at 45°F	Max. Heat Btu/h at 45°F	Min. Cool EER at 95°F	Max. Cool EER at 95°F	Min. Cool Btu/h at 95°F	Max. Cool Btu/h at 95°F
SpacePak Solstice Extreme	Monobloc	-8	2.12	42,240	2.35	46,440	3.3	3.3	66,480	66,480	2.4	2.4	40,000	40,000
SpacePak Solstice SIM-036	Monobloc	-4	1.93	19,468	2.75	25,048	3.7	4.0	12,116	38,755	9.4	10.7	8,025	34,594
SpacePak Solstice SIM-060	Monobloc	-4	1.96	38,219	2.47	49,099	2.8	3.7	18,150	70,666	9.3	10.1	14,847	58,021
SpacePak Solstice SIS-060A4	Split	-20	1.91	42,109	2.2	50,609	2.7	3.1	20,330	76,023	10.9	9.9	23,203	63,125
Viessman Vitocal 200A	Monobloc	5					3.8	3.9	16,992	34,531	2.6	3.2	13,990	30,027
Viessman Vitocal 222A	Monobloc	-4					3.6	4.5	8,906	29,481	2.7	4.0	17,061	31,392
Viessman Vitocal 300A	Monobloc	-4					3.9	3.0	23,885	40,946	2.5	2.5	21,769	30,812

Product	Configuration	Min OAT (°F)	COP at 5°F	Heat Btu/h at 5°F	COP at 17°F	Heat Btu/h at 17°F	Min. Heat COP at 17°F	Max. Heat COP at 17°F	Min. Heat Btu/h at 45°F	Max. Heat Btu/h at 45°F	Min. Cool EER at 95°F	Max. Cool EER at 95°F	Min. Cool Btu/h at 95°F	Max. Cool Btu/h at 95°F
Viessman Vitocal 350A	Monobloc	-4					4.0	3.4	43,334	70,290				

Appendix B: Field Instrumentation

Site 1

Location: Foley, MN 56329

Install Date: 11/05/2021

System Installed: Electro NorAire EB-HPH Heat Only Indoor Unit (IDU) with Bosch BOVA ASHP Outdoor Unit (ODU)

Table 8: Field Instrumentation for Site 1

Measurement	Type	Source	Logger	Reason for Measurement
Field Measurements:				
IDU Supply Temperature	Temperature	Type T Surface Thermocouple	Campbell CR3000	Calculation of load delivered; characterization of system behavior
IDU Return Temperature	Temperature	Type T Surface Thermocouple	Campbell CR3000	Calculation of load delivered; characterization of system behavior
ODU Supply Temperature	Temperature	Type T Surface Thermocouple	Campbell CR3000	Calculation of load delivered; characterization of system behavior
ODU Return Temperature	Temperature	Type T Surface Thermocouple	Campbell CR3000	Calculation of load delivered; characterization of system behavior
ODU Current	Amperage	Split-Core Current Transformer (CT)	Campbell CR3000	Calculation of power consumed; characterization of system behavior
Hydronic Loop Flow Rate	Flow Rate	Badger Mechanical Flowmeter	Campbell CR3000	Calculation of load delivered; characterization of system behavior
Mains Voltage	Voltage	eGauge Energy Meter	eGauge Energy Meter	Calculation of power consumed; characterization of system behavior
IDU Current	Amperage	Split-Core CT	eGauge Energy Meter	Calculation of power consumed; characterization of system behavior

Measurement	Type	Source	Logger	Reason for Measurement
Pump Current	Amperage	Split-Core CT	eGauge Energy Meter	Calculation of power consumed; characterization of system behavior
Indoor Air Temperature	Temperature	HOBO Temperature Data Logger	HOBO Temperature Data Logger	Logging temperature at the thermostat
Indoor Air Temperature	Temperature	Govee Temperature Sensor	Govee Temperature Sensor	Identifying periods of fireplace usage
Other Data:				
Outdoor Air Temperature	Temperature	NOAA LCD: St. Cloud Regional Airport		Correlation of performance and load with local weather

Site 2

Location: Garfield, MN 56332

Install Date: 12/07/2023

System Installed: Electro NorAire EB-HPH Heat Only Indoor Unit (IDU) with Bosch BOVA ASHP Outdoor Unit (ODU)

Table 9: Field Instrumentation for Site 2

Measurement	Type	Source	Logger	Reason for Measurement
Field Measurements:				
IDU Supply Temperature	Temperature	Type T Surface Thermocouple	Campbell CR3000	Calculation of load delivered; characterization of system behavior
IDU Return Temperature	Temperature	Type T Surface Thermocouple	Campbell CR3000	Calculation of load delivered; characterization of system behavior
ODU Supply Temperature	Temperature	Type T Surface Thermocouple	Campbell CR3000	Calculation of load delivered; characterization of system behavior
ODU Return Temperature	Temperature	Type T Surface Thermocouple	Campbell CR3000	Calculation of load delivered; characterization of system behavior
Hydronic Loop Flow rate	Flow Rate	Badger Mechanical Flowmeter	Campbell CR3000	Calculation of load delivered; characterization of system behavior
Mains Voltage	Voltage	eGauge Energy Meter	eGauge Energy Meter	Calculation of power consumed
Pump Current	Amperage	Split-Core CT	eGauge Energy Meter	Calculation of power consumed; characterization of system behavior
ODU Current	Amperage	Split-Core CT	eGauge Energy Meter	Calculation of power consumed; characterization of system behavior
IDU Current	Amperage	Split-Core CT	eGauge Energy Meter	Calculation of power consumed; characterization of system behavior

Measurement	Type	Source	Logger	Reason for Measurement
Indoor Air Temperature	Temperature	HOBO Temperature Data Logger	HOBO Temperature Data Logger	Logging temperature at the thermostat
Other Data:				
Outdoor Air Temperature	Temperature	NOAA LCD: Alexandria Chandler Field		Correlation of performance and load with local weather

Site 3

Location: Faribault, MN 55021

Install Date: 01/20/2022

System Installed: Enertech EAV060 Monobloc AWHP Heat + Cool + Domestic Hot Water (DHW)

Table 10: Field Instrumentation for Site 3

Measurement	Type	Source	Logger	Reason for Measurement
Field Measurements:				
IDU Supply Temperature	Temperature	Type T Surface Thermocouple	Campbell CR3000	Calculation of load delivered; characterization of system behavior
IDU Return Temperature	Temperature	Type T Surface Thermocouple	Campbell CR3000	Calculation of load delivered; characterization of system behavior
ODU Supply Temperature	Temperature	Type T Surface Thermocouple	Campbell CR3000	Calculation of load delivered; characterization of system behavior
ODU Return Temperature	Temperature	Type T Surface Thermocouple	Campbell CR3000	Calculation of load delivered; characterization of system behavior
DHW Supply Temperature	Temperature	Type T Surface Thermocouple	Campbell CR3000	Calculation of DHW load delivered; characterization of system behavior
DHW Return Temperature	Temperature	Type T Surface Thermocouple	Campbell CR3000	Calculation of DHW load delivered; characterization of system behavior
Air Supply Temperature	Temperature	Type T Thermocouple	Campbell CR3000	Calculation of load delivered; characterization of system behavior
Air Return Temperature	Temperature	Type T Thermocouple	Campbell CR3000	Calculation of load delivered; characterization of system behavior
Hydronic Coil Supply Temperature	Temperature	Type T Surface Thermocouple	Campbell CR3000	Calculation of load delivered; characterization of system behavior

Measurement	Type	Source	Logger	Reason for Measurement
Hydronic Coil Return Temperature	Temperature	Type T Surface Thermocouple	Campbell CR3000	Calculation of load delivered; characterization of system behavior
Home In-Floor Circuit Pump Current	Amperage	Split-Core CT	Campbell CR3000	Calculation of power consumed; characterization of system behavior
Garage In-Floor Circuit Pump Current	Amperage	Split-Core CT	Campbell CR3000	Calculation of power consumed; characterization of system behavior
Hydronic Coil Pump Current	Amperage	Split-Core CT	Campbell CR3000	Calculation of power consumed; characterization of system behavior
IDU Pump Current	Amperage	Split-Core CT	Campbell CR3000	Calculation of power consumed; characterization of system behavior
ODU Pan Heater Current	Amperage	Split-Core CT	Campbell CR3000	Calculation of power consumed; characterization of system behavior
Primary Hydronic Loop Flow rate	Flow Rate	Badger Mechanical Flowmeter	Campbell CR3000	Calculation of load delivered; characterization of system behavior
DHW Loop Flow rate	Flow Rate	Badger Mechanical Flowmeter	Campbell CR3000	Calculation of load delivered; characterization of system behavior
Mains Voltage	Voltage	eGauge Energy Meter	eGauge Energy Meter	Calculation of power consumed
Furnace and Blower Current	Amperage	Split-Core CT	eGauge Energy Meter	Calculation of power consumed; characterization of system behavior
ODU Current	Amperage	Split-Core CT	eGauge Energy Meter	Calculation of power consumed; characterization of system behavior
IDU Current	Amperage	Split-Core CT	eGauge Energy Meter	Calculation of power consumed; characterization of system behavior

Measurement	Type	Source	Logger	Reason for Measurement
Backup DHW Current	Amperage	Split-Core CT	eGauge Energy Meter	Calculation of power consumed; characterization of system behavior
Indoor Air Temperature	Temperature	HOBO Temperature Data Logger	HOBO Temperature Data Logger	Logging temperature at the thermostat
Blower Air Flow Rate	Flow Rate	TEC DG-1000 Digital Pressure and Flow Gauge + TEC Digital TrueFlow	TEC DG-1000 Digital Pressure and Flow Gauge	One-time measurements for calculation of load delivered and correlation with blower power consumption
Other Data:				
Outdoor Air Temperature	Temperature	NOAA LCD: Faribault Municipal Airport		Correlation of performance and load with local weather

Site 4

Location: Garfield, MN, 56332

Install Date: 04/28/2022

System Installed: Enertech EAV060 Monobloc AWHP Heat + Cool

Table 11: Field Instrumentation for Site 4

Measurement	Type	Source	Logger	Reason for Measurement
Field Measurements:				
IDU Supply Temperature	Temperature	Type T Surface Thermocouple	Campbell CR3000	Calculation of load delivered; characterization of system behavior
IDU Return Temperature	Temperature	Type T Surface Thermocouple	Campbell CR3000	Calculation of load delivered; characterization of system behavior
ODU Supply Temperature	Temperature	Type T Surface Thermocouple	Campbell CR3000	Calculation of load delivered; characterization of system behavior
ODU Return Temperature	Temperature	Type T Surface Thermocouple	Campbell CR3000	Calculation of load delivered; characterization of system behavior
Air Supply Temperature	Temperature	Type T Thermocouple	Campbell CR3000	Calculation of load delivered; characterization of system behavior
Air Return Temperature	Temperature	Type T Thermocouple	Campbell CR3000	Calculation of load delivered; characterization of system behavior
Hydronic Coil Supply Temperature	Temperature	Type T Surface Thermocouple	Campbell CR3000	Calculation of load delivered; characterization of system behavior
Hydronic Coil Return Temperature	Temperature	Type T Surface Thermocouple	Campbell CR3000	Calculation of load delivered; characterization of system behavior
Radiant Heating Manifold Supply Temperature	Temperature	Type T Surface Thermocouple	Campbell CR3000	Calculation of load delivered; characterization of system behavior

Measurement	Type	Source	Logger	Reason for Measurement
Radiant Heating Manifold Return Temperature	Temperature	Type T Surface Thermocouple	Campbell CR3000	Calculation of load delivered; characterization of system behavior
Primary Hydronic Loop Flow rate	Flow Rate	Badger Mechanical Flowmeter	Campbell CR3000	Calculation of load delivered; characterization of system behavior
Mains Voltage	Voltage	eGauge Energy Meter	eGauge Energy Meter	Calculation of power consumed
ODU Current	Amperage	Split-Core CT	eGauge Energy Meter	Calculation of power consumed; characterization of system behavior
IDU Current	Amperage	Split-Core CT	eGauge Energy Meter	Calculation of power consumed; characterization of system behavior
IDU Pump Current	Amperage	Split-Core CT	eGauge Energy Meter	Calculation of power consumed; characterization of system behavior
Hydronic Coil Pump Current	Amperage	Split-Core CT	eGauge Energy Meter	Calculation of power consumed; characterization of system behavior
Radiant Heating Pump Current	Amperage	Split-Core CT	eGauge Energy Meter	Calculation of power consumed; characterization of system behavior
Furnace and Blower Current	Amperage	Split-Core CT	eGauge Energy Meter	Calculation of power consumed; characterization of system behavior
ODU Pan Heater Current	Amperage	Split-Core CT	eGauge Energy Meter	Calculation of power consumed; characterization of system behavior
Indoor Air Temperature	Temperature	HOBO Temperature Data Logger	HOBO Temperature Data Logger	Logging temperature at the thermostat
Blower Air Flow Rate	Flow Rate	TEC DG-1000 Digital Pressure and Flow Gauge + TEC Digital TrueFlow	TEC DG-1000 Digital Pressure and Flow Gauge	One-time measurements for calculation of load delivered and correlation with blower power consumption

Measurement	Type	Source	Logger	Reason for Measurement
Other Data:				
Outdoor Air Temperature	Temperature	NOAA LCD: Alexandria Chandler Field		Correlation of performance and load with local weather

Appendix C: Detailed Site Summaries

Site 1

Site description:

Site 1 is a single-family home built in 2007 totaling 3,200 square feet of conditioned space. The home is a single story, slab on grade home with hydronic loops embedded throughout the floor. The attached garage is generally unheated but has hydronic loops and could be heated based on homeowner preference. The site was recruited through their utility. The homeowner had previously reached out to their utility due to high heating bills. The homeowner even had an existing quote for an AWHP but found the AWHP too expensive to pursue by themselves. We proceeded with the existing quote for this project.

AWHP system:

NorAire EB-HPH-5-20 with Bosch BOVA condenser and built-in 20 kW auxiliary electric resistance boiler were installed in November 2021.

Displaced system:

The displaced system was a Hydroshark II Tempra 29 (29kW) boiler, with Aube TH-140A-28 programmable thermostats for indoor zones and a non-programmable garage thermostat.

Issue summary:

Installation at this site went smoothly. During the study period, the outdoor condenser did experience a failure related to the control board. The board was replaced under warranty by the manufacturer. The auxiliary electric resistance (ER) boiler and wood stove kept the home warm while the ODU was offline.

Interventions:

After one season of monitoring, we installed Honeywell model T6 Pro Hydronic thermostats with slab sensors below the wall’s bottom plate. Backup boost controls at the IDU were adjusted to reduce ER runtime and promote AWHP runtime and extend cycle length. The main controls change was to increase the time delay between the start of a heat call and when the auxiliary ER heater could turn on from 30 minutes (default) to 199 minutes (maximum). We later found that the system would hold this timed delay whether the heat pump turned on at the start of the heat call or not, so we adjusted the programmed lockout temperature at the IDU controller to be slightly above the ODU lockout temperature in late winter in early 2023.

Customer comments:

The occupants have provided minimal feedback on the system. However, they changed their heating habits substantially during the project and chose to use a woodstove for much of the cold winter during the study period. The woodstove is a localized heat source located within the home's centrally-located and open-concept kitchen and dining area. The stove has no heat distribution features and heats the immediate area primarily through radiation and natural convection. Because it does not maintain even temperatures or heat the entire house, the motivations for its use seem primarily economic, with wood being a very low-cost option for the occupants given their rural homestead location. Reducing heating costs was a driving factor for this homeowner's interest in AWHPs.

Site 2

Site description:

Site 2 is a slab-on-grade single-family home built in 2009, with roughly 2,600 square feet of conditioned space. The home is primarily laid out over a single story, with the addition of a single room above the attached garage with ER baseboard. Hydronic loops supply in-floor heat through all but the garage, where hydronic loops exist but are disconnected due to insufficient insulation in the garage slab. The home does not have any ductwork. This site was recruited through their electric utility, Runestone Electric Association. The homeowners had previously reached out to the utility over cost concerns.

AWHP system:

NorAire EB-HPH-5-20 with Bosch BOVA condenser and built-in 20 kW auxiliary electric resistance boiler were installed in December 2021.

Displaced system:

The existing heating system was a 27 kW Thermolec B-27U electric boiler.

Issue summary:

Initial installation at this site was smooth and relatively quick compared to the other installations. However, issues appeared not long after the install date. This unit experienced an ODU fan motor failure in late December 2021, identified as a design defect in the motor control housing that permitted ice ingress. This component was replaced in late January 2022, after which the unit displayed normal operation. The auxiliary ER boiler kept the home warm while the ODU was offline.

A second failure was discovered in April 2022 which was determined to be due to the replacement fan motor failing in a similar way to the previous failure. It was found that the previously provided replacement component was a faulty part as well and likely had been sent by mistake. This was replaced with an updated fan motor model within the month.

After year one, we installed Honeywell model T6 Pro hydronic thermostats with slab sensors positioned below the wall's bottom plate. Backup boost controls were adjusted to reduce ER runtime and promote AWHP runtime and cycle time. The main controls change was to increase the time delay between the start of a heat call and the when the auxiliary ER heater could turn on from 30 minutes (default) to 199 minutes (maximum).

Customer comments:

The occupants of this site have had no system concerns except following system failures. They are using the system consistently, despite having a propane fireplace as an alternative heating source.

Site 3

Site description:

This site is a two-story single-family home with approximately 2,600 square feet of conditioned living space, with a heated 4-stall garage and attached workspace. The lower level is a partially finished walk out basement heated with in-floor radiant hydronic circuits. The basement contains the mechanical room within conditioned space. The upper-level living space is heated and cooled using a centrally ducted forced air system, which interfaces with the AWHP system via a ducted hydronic A-coil. The two levels are connected by a narrow open stairway. A four stall heated garage is attached to the upper-level living area and includes a heated addition for a bar and workspace. The garage and addition are heated using in-floor hydronic circuits and do not have ductwork for cooling. The homeowners typically keep the garage and workspace just warm enough to avoid freezing the domestic water supply in the workspace. While the setpoint temperature is low, the total garage space is large, which increases the heat load in peak winter conditions.

AWHP system:

Enertech Advantage EAV060 5-ton Monobloc heat pump (EAV060A1AAABTSS) with IDU (EME000A1AAA) and Turbomax indirect water heater were installed in February 2022. The IDU includes 9 kW electric resistance elements capable of providing supplemental heat in conjunction with the heat pump. The system retained the existing propane furnace, Marathon tank water heater, and heat recovery ventilator.

Displaced system:

Electro Industries TS Series Electro-Boiler, Trane XR90 forced air central propane furnace, Marathon tank water heater, Broan HRV90H ducted heat recovery ventilator.

Issue summary:

Installation at this site was delayed twice. The site location for the ODU at this site had a relatively steep grade that required some footing work to be completed prior to placement. As a result, the installers needed to wait for suitable weather conditions before installation, despite the equipment having already been delivered. Once the ODU was in place, however, it was discovered that the delivered ODU had been improperly drained following factory testing. Water had remained in the ODU heat exchanger. This water had frozen and damaged the equipment while it waited to be installed. A separate unit was ordered to replace the original ODU.

Additionally, the domestic hot water preheating tank, the TurboMax, was found to have arrived with an incorrect/out-of-date control module installed. The manufacturer ordered and installed the correct controller in late June 2022, after which the TurboMax was enabled. However, due to the unique set up of our experiment, we requested the installer to include valving which allowed us to completely isolate the TurboMax tank. This valving was not correctly configured when the TurboMax was initially enabled, and the system initially cooled rather than heated the domestic water supply. Upon discovering the issue, which was uniquely due to the experimental set up, the valve configuration was fixed and the TurboMax tank operated properly by the end of August 2022.

In early January 2023, the system experienced an ODU failure. The installer identified the issue as a refrigerant leak and repaired the system by the end of January 2023. Refrigerant leaks are expected to be unusual for monobloc AWHPs as they are charged in the factory rather than onsite. The auxiliary boiler and central propane furnace kept the home warm while the ODU was not operating.

In mid-March 2023, the AWHP manufacturer elected to remove the pre-existing external hydronic separator and pumps and made some controls wiring modifications. They describe the external hydronic separator removal as a strategy to try to improve the AWHP systems response. Specifically, they hoped to reduce short cycling and the systems' tendency to operate at maximum capacity even when heat loads could be satisfied at lower compressor speeds. In the control modifications, they also adjusted the thermostat to increase the hydronic coil switchover to 10°F. Their goal with this adjustment was to have the propane fire more often during the coldest weather to relieve the AWHP of some of the home heating load just as the garage space heating load increases. The heated garage at this home is large and generally kept with a setpoint just above freezing for the safety of a potable water supply plumbed inside it.

In early April of 2023, it was discovered that the expansion tank within the IDU was malfunctioning. It took multiple troubleshooting visits to identify the issue and resulted in the installer locking out the TurboMax domestic hot water preheating tank, which seemed to temporarily alleviate the worst of the issue. However, due to staff constraints, the tank has was not replaced until mid-June 2023. The system continued to operate to cool the home while the TurboMax was offline due to the broken expansion tank.

Customer comments:

The occupants of this home shared the most positive feedback. The homeowners reported being happy with reduced bills and propane usage and did not report comfort concerns.

Site 4

Site description:

Site 4 is a 2,240 square foot single-family home built in 2002. The home borders a 5 – 6-acre pond on its west side and features floor-to-ceiling windows with a vaulted ceiling for viewing the westward pond. It has a finished basement relying on in-floor hydronic circuits to heat the living space. The HVAC room is also in the lower level, along with some storage space, a kitchenette, and family room with a fireplace. The upper level has forced air heating and cooling, with the large west-facing windows allowing afternoon sunlight into the primary living area. The living room also has a propane fireplace. The two levels are connected via a large open stairwell beneath the west windows.

AWHP system:

Enertech Advantage EAV060 5-ton Monobloc heat pump (EAV060A1AAABTSS) with IDU (EME000A1AAA) was installed in late April 2022. The IDU includes 9 kW electric resistance elements capable of providing supplemental heat in conjunction with the heat pump. The existing furnace was replaced with an Armstrong A951E unit because the existing furnace was approaching end of life age. The existing heat recovery ventilator and humidifier were retained. The attached garage has a Sterling LPG ceiling-mounted heater but does not interface with the home’s heating system in any way.

Displaced system:

The pre-existing furnace was a Carrier WeatherMaker 9200 at end-of-life. The system also included an Electro EB-R-13 13.5 kW boiler, a Carrier central AC for cooling, a Thermolec ACU-5 humidifier, and a Carrier HRVCCSVU ducted heat recovery ventilator.

Issue summary:

Shortly after the installation at this site, a distribution pump failed due to being wired incorrectly. It was corrected about one month later. The summer following the springtime installation was scattered with system failures that were typically addressed by resetting the power to the AWHP and adjusting the control settings slightly, especially the outdoor reset values. This value is described by the manufacturer as impacting the target supply temperature and flow rate, given the current outdoor air temperature. Adjustments of this sort were made once in each of June and July of 2022, with two adjustments made in October of 2022. Each adjustment was preceded by a few days to a few weeks of the AWHP being offline. The system had no backup for cooling but was supported by the auxiliary ER boiler and propane furnace in heating mode.

Despite the changes, the system delivered unsatisfactory levels of cooling for the homeowner, which had been an issue for the home in the past. The home has large west-facing windows that allow significant solar heat gains in midsummer and the existing ducting system comprised of only flexible ducts with poorly sealed connections within the unconditioned HVAC room. These factors substantially impact the ability of the system to adequately cool the home’s upstairs while simultaneously causing overcooling in the basement. Given the poor-quality ductwork, high solar gains upstairs, and large, open staircase, much of the cooling that is delivered remains in the basement. The cooling performance of the AWHP is significantly hampered by the insufficient distribution system. To try to improve the performance, the manufacturer lowered the target delivery temperatures to the hydronic coil to 44°F.

The system failed again in early November 2022 and remained offline except for the auxiliary boiler until the end of December. At this time, the manufacturer decided to remove the pre-existing external hydronic separator and external distribution pumps. They describe the external hydronic separator removal as a strategy to try to improve the AWHP system’s response. Specifically, they hoped to reduce short cycling and the systems’ tendency to operate at maximum capacity even when heat loads could be satisfied at lower compressor speeds. The system operated for less than a week before locking itself out, like in past failure modes. The system was reset in the first week of January 2023. This sort of failure occurred again in mid-January. The manufacturer troubleshooted the system in multiple visits, making more controls adjustments, including turning the propane thermostat into emergency heat mode (so that it operated consistently instead of using the AWHP) and they upgraded the AWHP to their latest controller so they could remotely monitor the system themselves. By early February, the system was operational again, following the replacement of a faulty sensor in the ODU.

More lockout failures occurred in late April, however. In response, the manufacturer consolidated a few of the smaller radiant floor heating loops to try to limit issues they believe were related to very small heat loads from the basement floor zones. Issues persisted intermittently with the manufacturer troubleshooting controls until mid-May 2023.

Customer comments:

The homeowner at this site is dissatisfied with their AWHP system, especially during the cooling season. They report that on warm days the upstairs slowly creeps up a few degrees over the course of the day, rather than maintaining setpoint. They have been extremely frustrated by the system repeatedly locking itself out from operation and providing no cooling at all in the summer when the lockouts occur. In the winter, the ODU lockouts result in no energy savings as the system switches to ER and propane heating only. The homeowner additionally is dissatisfied that they cannot heat and cool at the same time. They would like to be able to warm the basement while cooling the upstairs. They also prefer to use their thermostat in “auto” mode, wherein it will automatically switch from heating or cooling mode, based on the temperature. As their system works now, they must do this manually and it is an issue to remember on warm days followed by cool nights. Finally, they are dissatisfied with the combination of their basement heating zones as a measure to improve the AWHP performance. Given these issues, a perceived lack of cost savings, and low confidence that the manufacturer can address their concerns, the homeowner has requested their AWHP be removed and replaced with their old electric boiler and air conditioning unit.

Appendix D: Additional Field Data

Average Daily Heat Delivered by Source – All Data

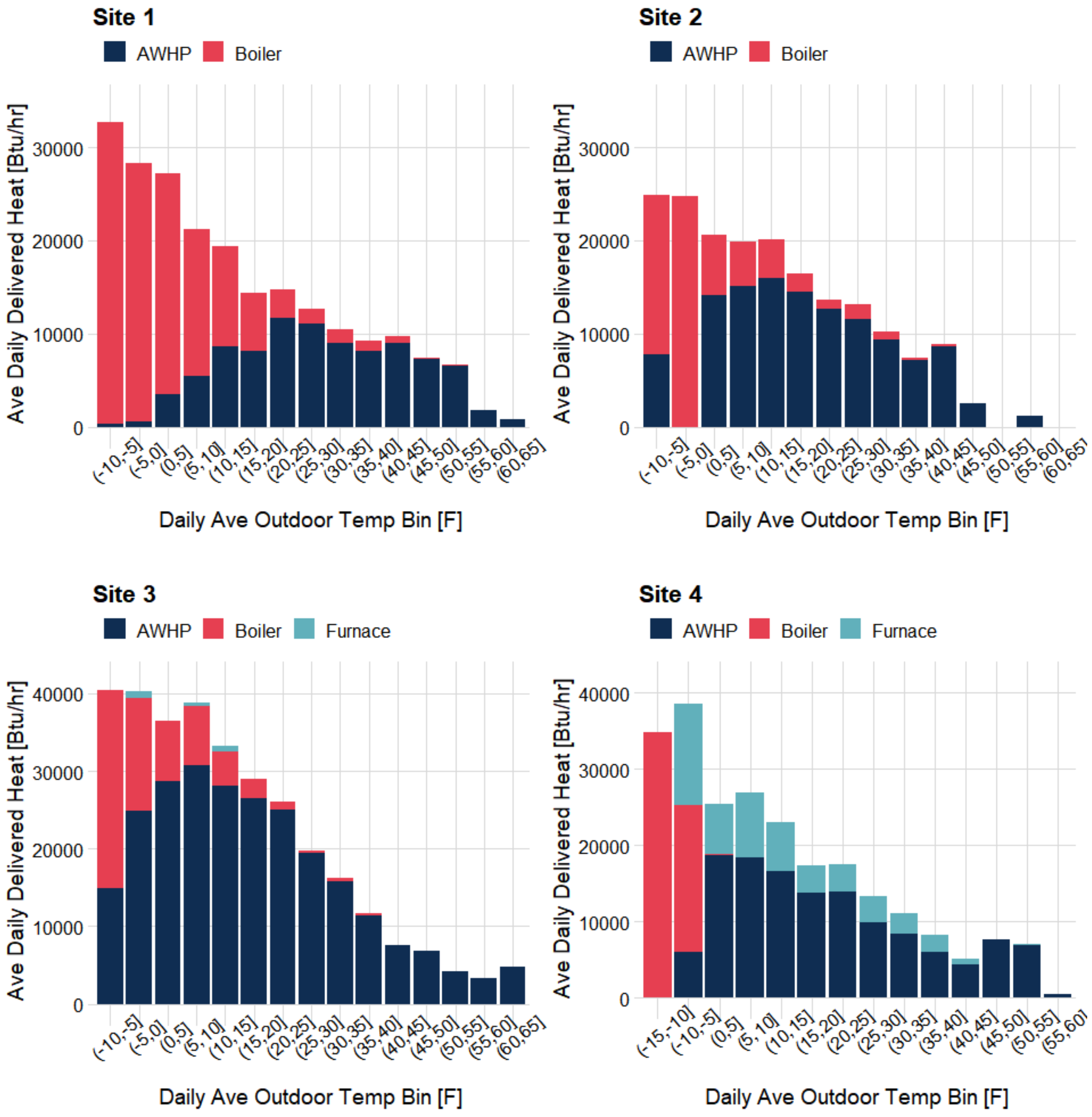

Figure 22: Average daily rate of heat delivered by source, averaged into 5°F temperature bins and inclusive of all auxiliary controls operating regimes observed for all sites.

The average fraction of heat delivered by AWHP systems can vary significantly depending on auxiliary control settings. Data presented in Figure 22 show the average daily heat rates observed over the entire monitoring period for each site in 5°F temperature bins. The data is averaged over periods of time with both significant and minimal auxiliary heat usage, including all data in Figure 6 and Figure 8. In contrast, Figure 23 shows the fraction of load met by the AWHP under the best controls conditions, where supplemental heat was minimized.

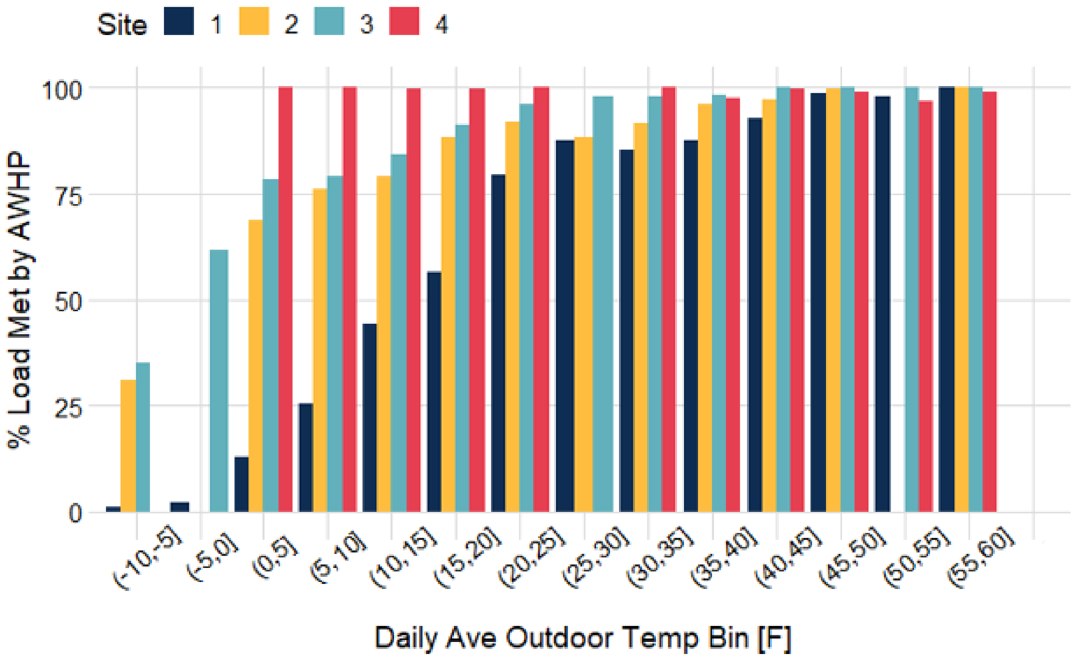

Figure 23: Average daily percent of heating load met by the AWHP instead of auxiliary heat at each site.

AWHP Heating – Cycle Level Capacity

Understanding an AWHP's heating capacity as a function of temperature is critical for their successful application in cold climates. For variable speed systems, like the ones monitored in this study, the heat pump typically has a range of possible capacities rather than a single output at a given temperature. Manufacturers of air-to-air heat pumps have standardized laboratory methods to specify the expected minimum and maximum output of their systems in a comparable way. They typically report maximum and minimum outputs at specific temperatures: 5, 17, 47, 82 and 95°F. A comparable testing standard has not yet been established for AWHP systems in the United States.

The field data collected in this project can be used to better understand the output capabilities of AWHPs. While the following section presents field monitored results alongside standardized or manufacturer-reported testing results, comparison of these two data types must be nuanced and the following caveats should be kept in mind. Data collected in the field is generally not equivalent to laboratory testing data. Many real-world factors ranging from weather, transient loads, or balance of system variation cannot be captured in the laboratory. Likewise, it is difficult to impossible to observe long, steady state heat pump operation at specific compressor speeds in a field installation. Laboratory and field data are compared here simply to confirm they are directionally aligned.

Third Party Split

Manufacturer or third-party data is not available to predict the system capacity of the third-party split AWHP system tested in this study. However, the Bosch BOVA compressor used at sites 1 and 2 has data available to describe its performance when configured with specific A-coils in an air-to-air heat pump configuration. Figure 24 shows in yellow the range of available performance data for such an air-to-air system. The range is bound by the highest maximum and lowest minimum output ratings available for coil-only rated systems. The average daily load model is plotted as a black line. The average output measured from the third-party split systems is plotted in dark orange, binned into 5°F temperature increments. The average maximum cycle output is plotted likewise in teal for each site. The average maximum cycle output was calculated using only data from cycles at least 20 minutes long. Short cycles tended to have lower heat outputs due to transient effects. It is difficult to distinguish periods of low output from transient cycle behavior in the dataset. The average minimum output is therefore not presented.

Despite differences in total load requirements at site 1 and 2, similar heating capacities were measured at each site. The maximum output of the AWHP system falls very close to the maximum output rating of the ODU had it been configured in an air-to-air system. These results suggest that AWHPs can deliver similar, if not the same, maximum outputs as air-to-air ASHPs can. Additionally, the overall average cycle output measured is near the minimum rated output of the ODU. The cycle average data presented here does include transient effects that can bias the cycle output lower. Overall, these data do suggest that third-party AWHPs have similar capacity ranges as the air-to-air compressor units they use.

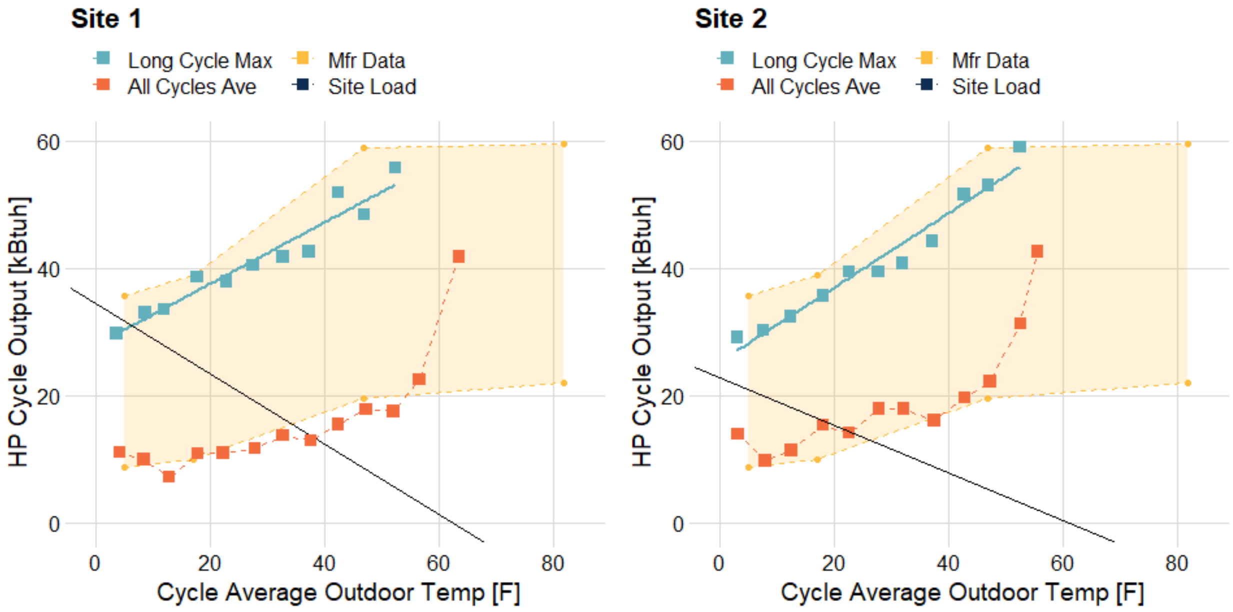

Figure 24: Observed cycle maximum and average output from third party split AWHPs as compared to the expected output range for air-to-air applications and the studied home heat load.

Monobloc

The monobloc systems under study did not have an air-to-air analog ODU like the third-party split systems. Instead, the limited manufacturer provided data available is plotted in Figure 25. The manufacturer specified that these capacities are rated for supply water temperatures of 95°F in heating mode and 44°F in cooling mode. The average output we measured per heat pump cycle from the monobloc systems is plotted in dark orange, binned into 5°F temperature increments. The average cycle maximum output is again presented in teal in the same 5°F temperature increments.

In mild weather, the specified capacity exceeds our test sites' heat loads by a factor of two or more. As a result, the system does not need to operate near its maximum capacity to meet the load. In fact, operating at a lower capacity is ideal. The monoblocs tested appear to have rarely operated at their expected maximum capacity for daily average temperatures above 40°F. This is a good indicator that the monobloc AWHP is modulating in mild weather as intended. In colder weather below 30°F, the maximum cycle output averages meet or exceed the manufacturer's specification. A wide variation in the maximum heat pump output occurred in the coldest weather. Periods of very high output were observed from the heat pump lasting only two to four minutes in the coldest weather. This may be a cause for the wide variation in maximum output measured. Cycle data was smoothed from per second to per minute averages before calculating the maximum output per cycle, so variation is not likely caused by very transient behavior. The average cycle output varied considerably less than the maximum output per cycle.

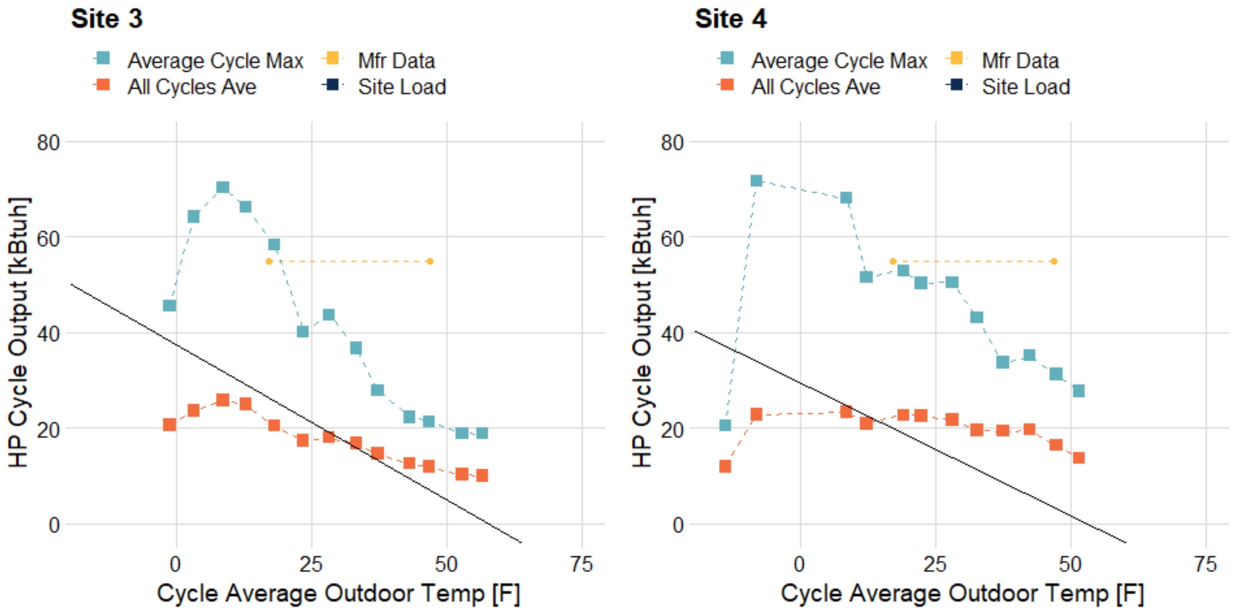

Figure 25: Observed cycle maximum and average output from monobloc AWHPs as compared to manufacturer reported capacity and the studied home heat load.

AWHP Cooling – Cycle Level Capacity

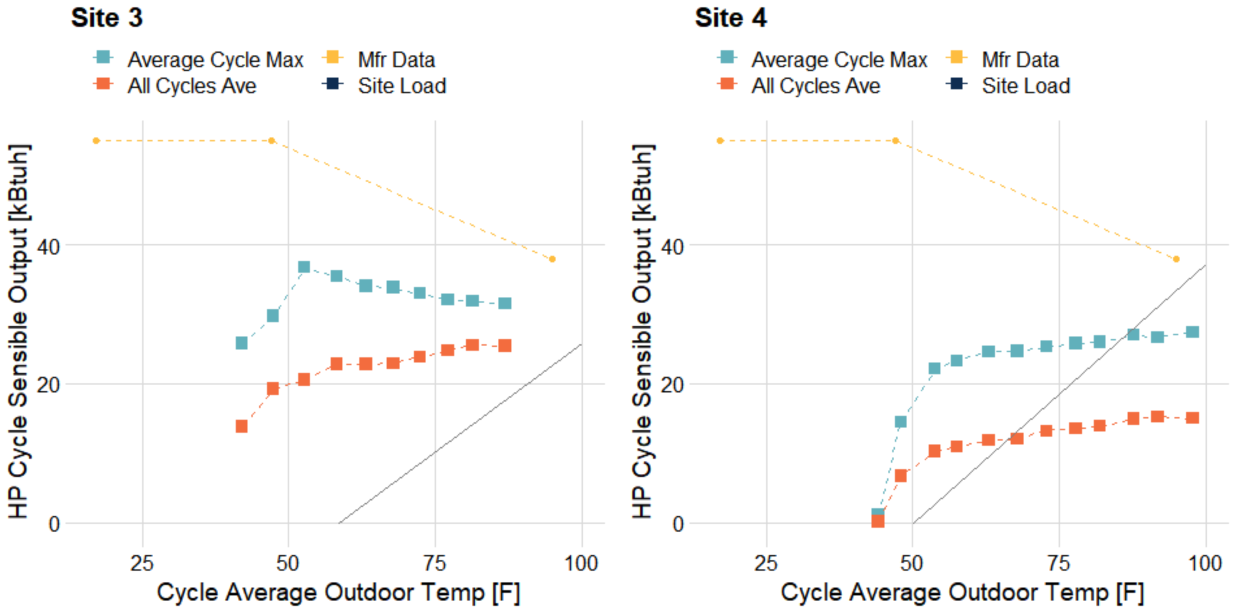

Figure 26: Observed cooling cycle maximum and cycle average sensible output alongside manufacturer reported cooling capacities.

The same cycle level analysis was applied to cooling data. A major caveat to this data is that only sensible cooling was measured; dehumidification is not included. Thus, the fact that the measured capacity range does not meet or exceed the manufacturer specification is not evidence that these systems cannot meet the total expected cooling output specified by the manufacturer.

AWHP COP – Cycle Level Performance

Auxiliary heat performance will vary depending on specific controls or system design features, so isolating the AWHP performance can be useful to understand the range of efficiency the AWHP alone can provide. To this end, the field data was analyzed to identify individual AWHP cycles. Energy output and consumption over the span of individual AWHP cycles were summed and taken as a ratio to calculate the cycle-wise COPs. These COPs include the energy consumption from the distribution system (hydronic pump or air handler) but do not include standby power or auxiliary heat source energy consumption. The cycle-wise COP data was binned by outdoor air temperature and averaged to develop cycle-level COP performance curves. These data can be compared to manufacturer specifications to ensure directional alignment despite the varied measurement approaches. Cycle-level performance is also helpful for modeling approaches that treat standby energy considerations separately.

Third Party Split

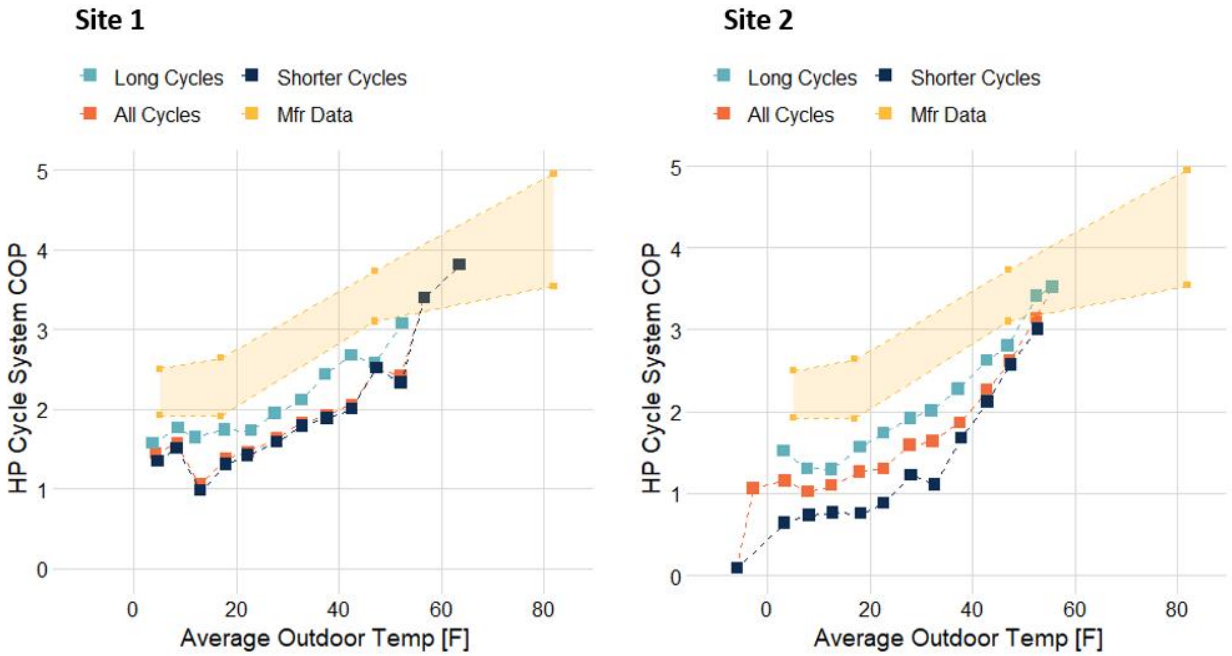

Figure 27: Field-measured average cycle COP as a function of outdoor air temperature of third party split AWHP systems compared to range of rated performance of the compressor when used in air-to-air applications

In Figure 27, manufacturer (Mfr) data represents the range of available performance data of the 5-ton Bosch BOVA condenser when configured with an A-coil on a centrally ducted air hander. Data is not currently available for this VSHP with any hydronic third party split system. During the monitoring, frequent AWHP short cycling was observed at both sites 1 & 2. Short cycle performance is limited by the outsized impact transient operational modes have on the average energy consumption and output. With this consideration in mind, the data is presented with the overall average in orange but also with the average COP for long cycles in teal and short cycles in dark blue. Longer cycles were defined as at least 20 minutes long so that most of the cycle is not necessarily transient, even if a defrost cycle occurs. Defrost cycles were observed up to about 10 minutes long. Site 1 had more issues with short cycling than Site 2, which is evidenced by the fact that the average cycle COP matched that of the average short cycle COP, despite higher COPs being observed from long cycles. The average cycle COP measured at site 2 lies between that of short and long cycles. Overall, the field measured COPs observed were slightly lower than the COP the ODU is rated for in air-to-air combinations. The discrepancy may be due, in part, to differences in measurement procedures – ratings are developed from near-steady-state laboratory measurements rather than field evaluations.

Monobloc Systems - Heating

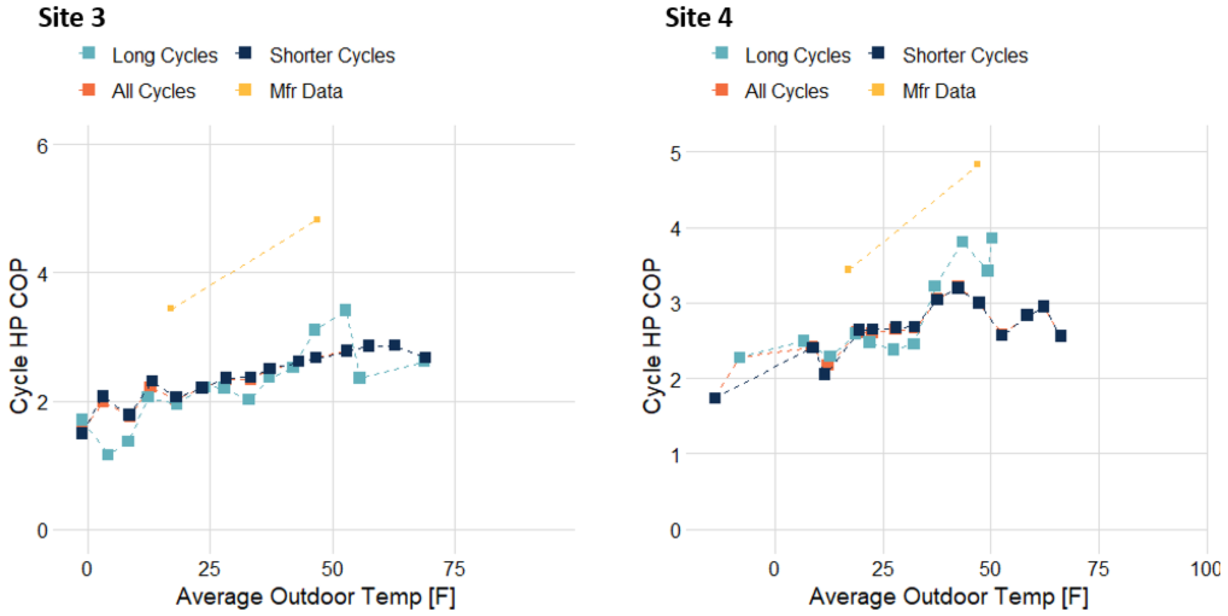

Figure 28: Field-measured average cycle COP as a function of outdoor air temperature of monobloc AWHP systems compared to manufacturer-reported performance.

The monobloc system has limited manufacturer (Mfr) performance data available as shown in yellow Figure 28. The average heat pump COP is split into long (>20 minute) cycles and shorter (<20 minute) cycles in the provided performance plot to provide insight performance with and without substantial transient cycle effects. At both sites, the average cycle COP more closely follows that of short cycles, indicating that these systems are frequently short cycling. Overall, the field measured COPs observed were lower than the COP reported by the manufacturer. The discrepancy may be due, in part, to differences in measurement procedures.

Daily Data

Heating Season

Site 1

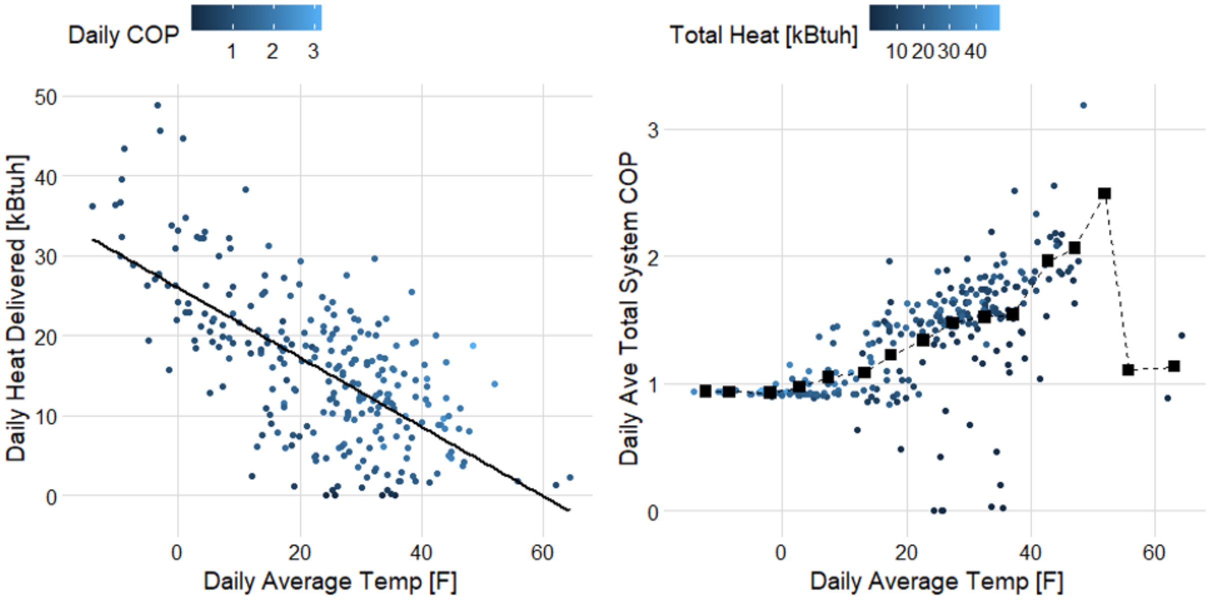

Figure 29: Daily total system output and COP data measured from site 1.

Site 2

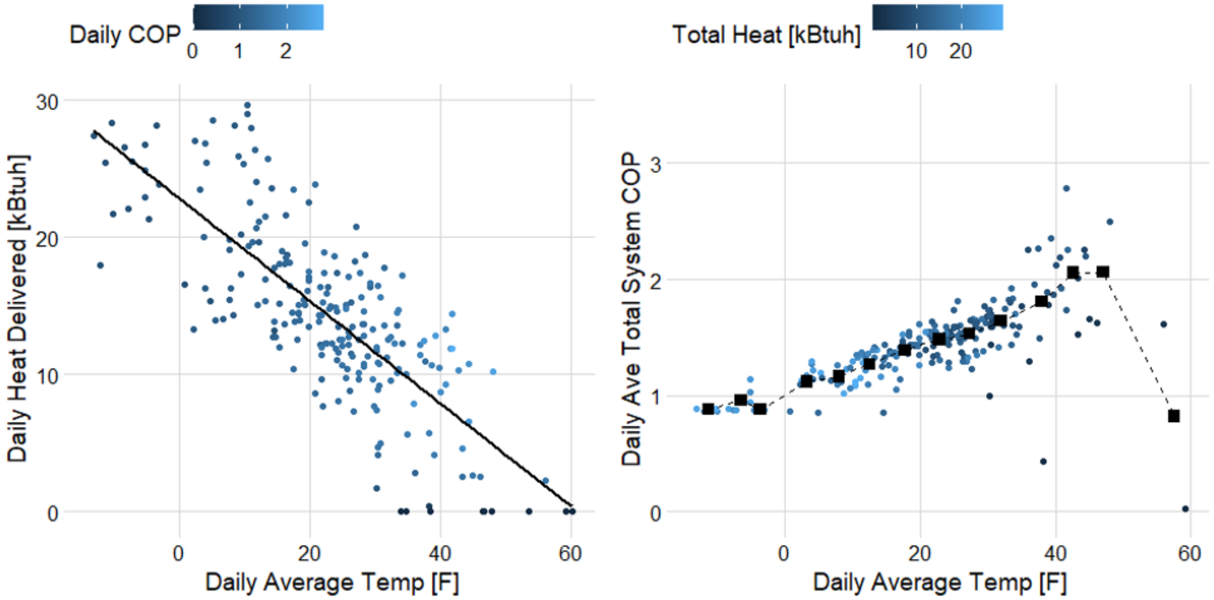

Figure 30: Daily total system output and COP data measured from site 2.

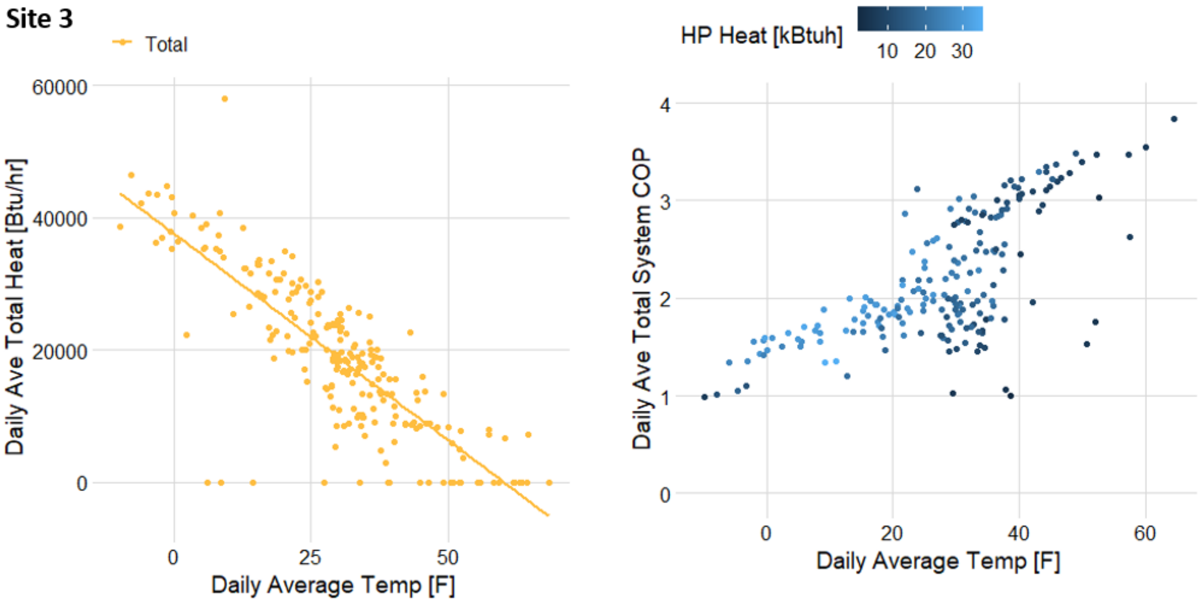

Figure 31: Daily total system output and COP data measured from site 3 in heating season.

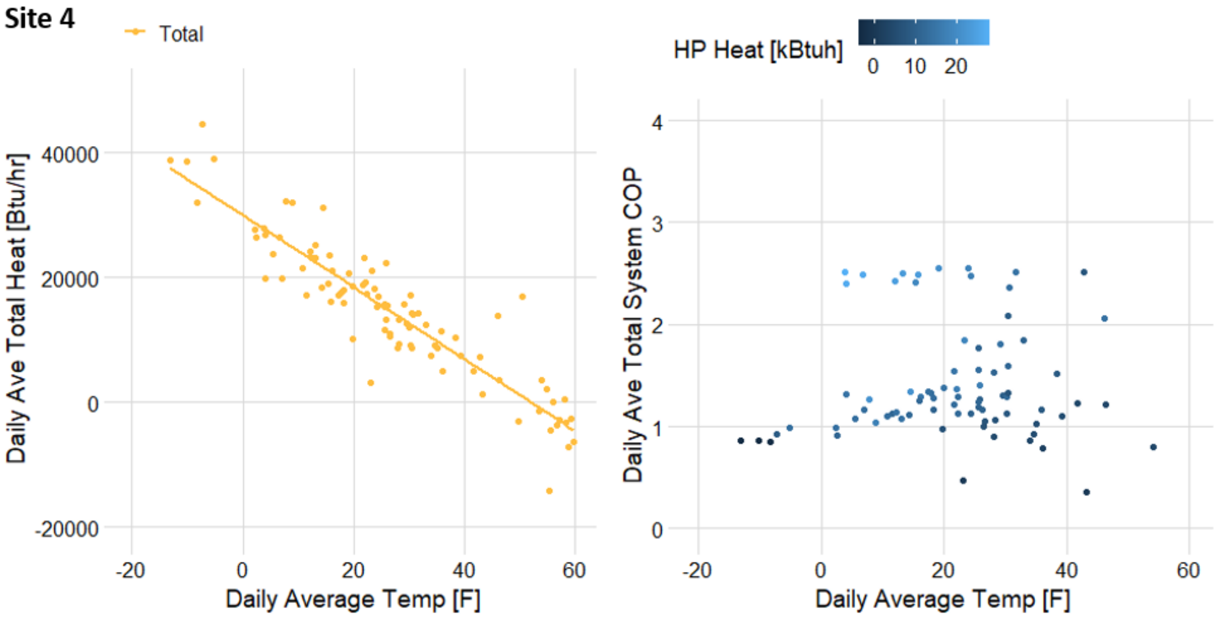

Figure 32: Daily total system output and COP data measured from site 4 in heating season.

Cooling Season

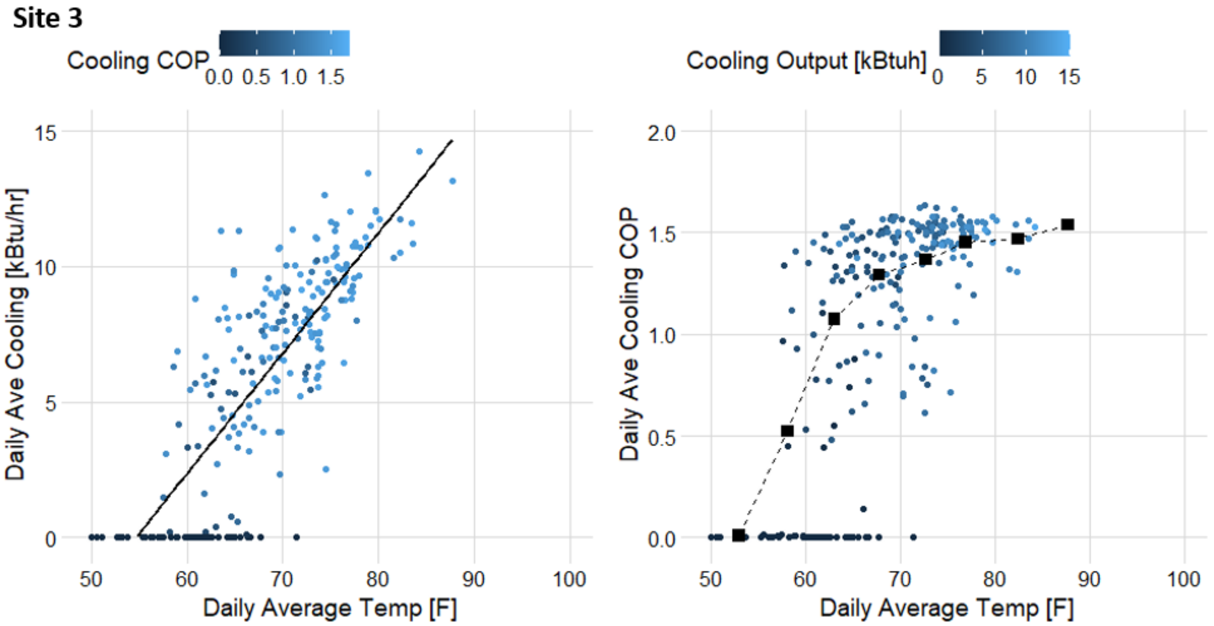

Figure 33: Daily total system sensible output and estimated COP data measured from site 3 in cooling season.

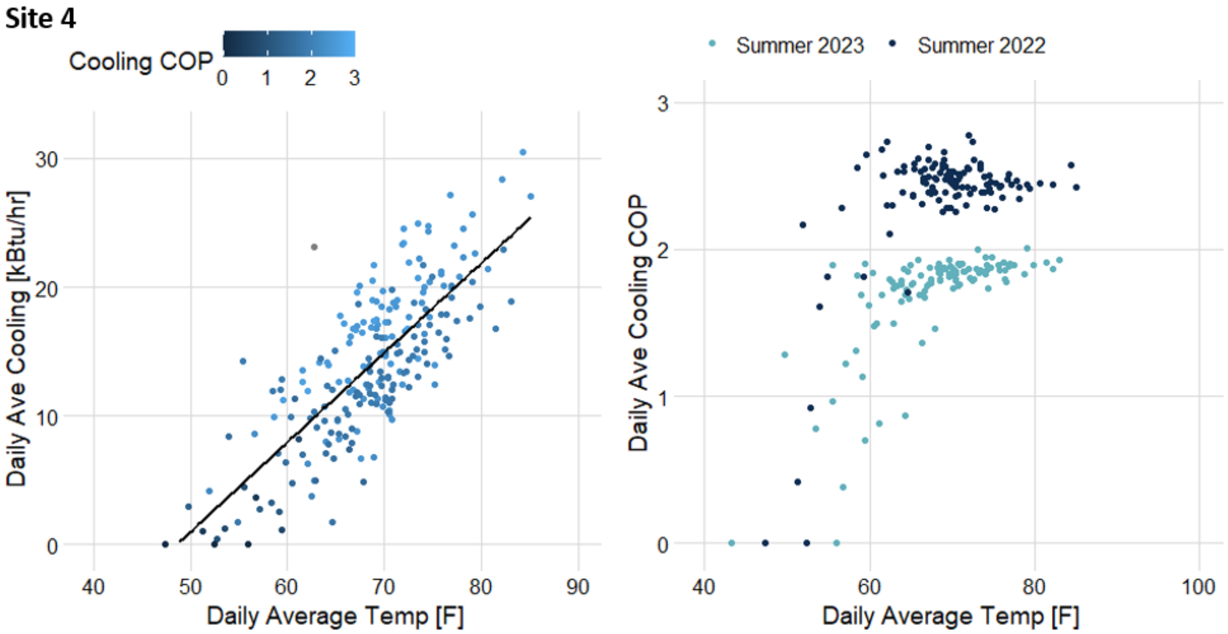

Figure 34: Daily total system sensible output and estimated COP data measured from site 4 in cooling season.

DHW Data

Heating Season

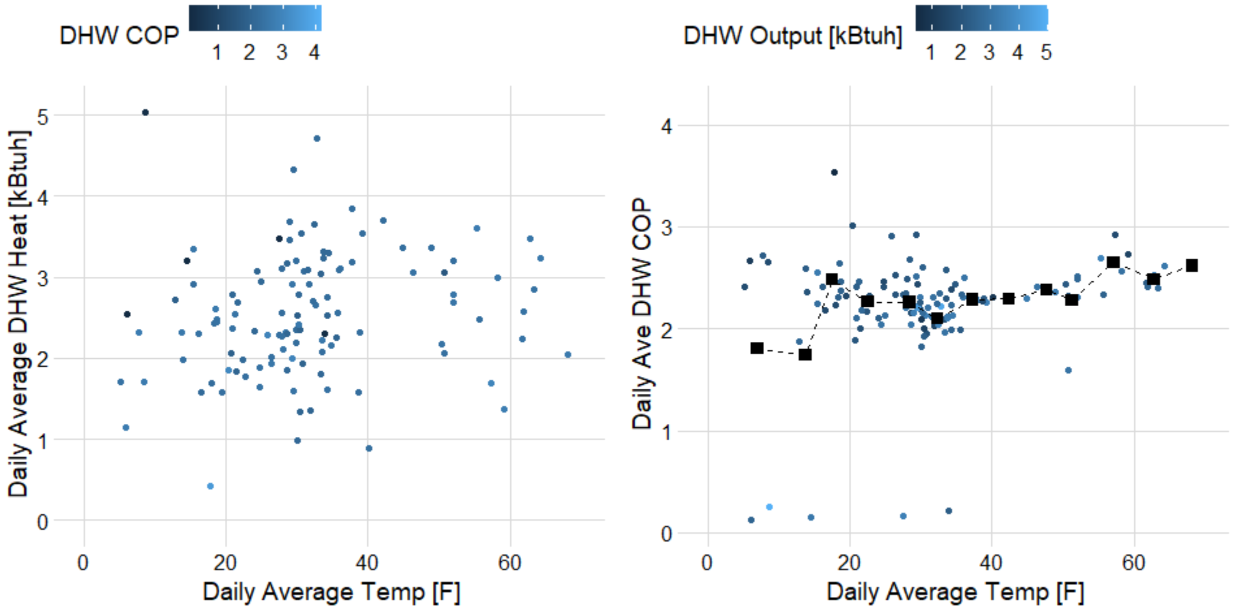

Figure 35: Daily average DHW performance at site 3 in the heating season.

Cooling Season

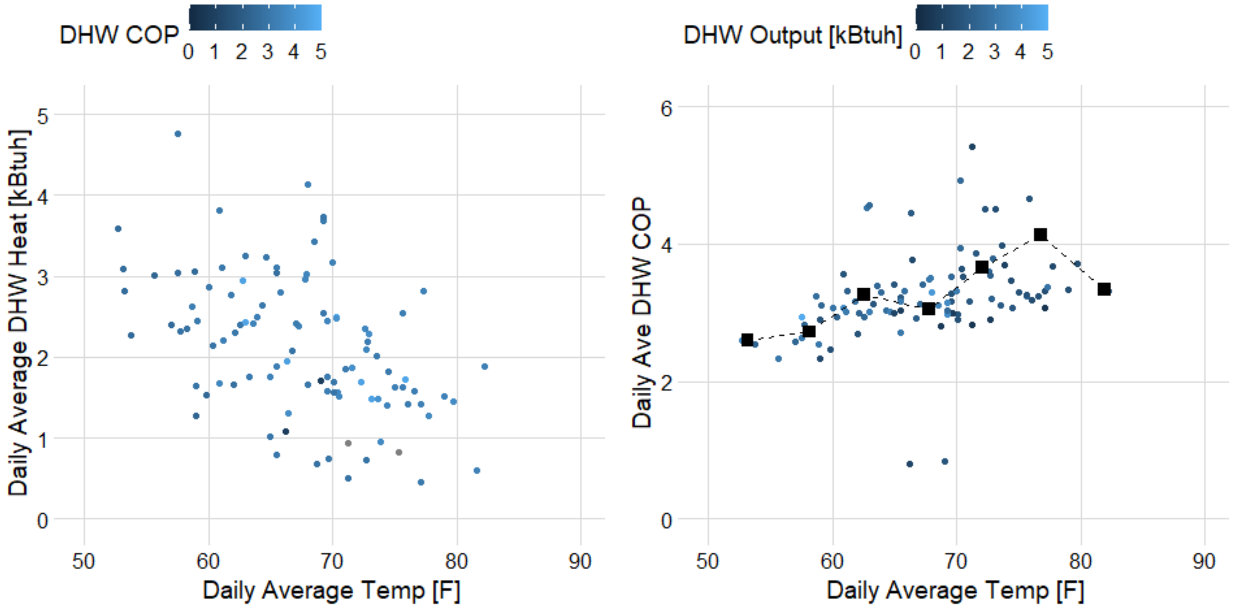

Figure 36: Daily average DHW performance at site 3 in the cooling season.

Appendix E: Site Specific Space Heating Savings Estimates

The savings presented in the main report body are the transferable savings, calculated using the normalized loads for each site and the equipment performance maps obtained from this study. These differ from the actual savings realized at each site due to unique factors impacting savings and the significant intervention at each site over the course of the study. These actual savings can be calculated from utility meter data and circuit power measurements, but the portion of savings attributed to the AWHP efficiency cannot be easily disaggregated from the results.

For space heating energy savings, the difference between the utility meter data from before and after the AWHP installations at each site, normalized by heating degree days, yields the space heating energy savings. These savings are impacted by equipment downtime, standby energy, control adjustments, behavioral changes, and various other issues specific to each site and this project. For example, due to high sensitivity to electric costs, site 1 increasingly used their wood stove for primary heat over the course of the project, yielding observable savings on the utility meter that were distinct from the AWHP, yet difficult to disaggregate. Additional sensitivity at site 3 led to significantly less use of the hydronic loops serving the garage space, which were also additive to heat pump savings.

For sites 3 and 4, baseline cooling energy was estimated from the main utility meter by performing a regression fit of the monthly electric use as a function of the outdoor air temperature and adjusting for baseline electric consumption. However, large uncertainty in non-cooling energy, the weak correlation between monthly cooling energy and average outdoor air temperature, and large differences in cooling degree days, precluded cooling energy and savings estimates with any degree of confidence.

At sites 3 and 4, propane energy savings are independently estimated as the difference between the participant's pre-AWHP annual estimated propane use for heating and the propane consumption measured during the study. Propane use during the study was estimated from the propane furnace runtime and input rate.

The annualized heating space energy savings realized at each site during this project are given in Figure 37 and Table 12. Prior to heat pump installation, electric boilers used 14,200 to 26,000 kWh/yr for space heating. Additionally estimated propane use at sites 3 and 4 was 250 gal/yr and 650 gal/yr. Following the installation of the AWHP, energy used for space heating decreased substantially and ranged between 10,700 and 15,100 kWh/yr. Space heating energy heating reductions of 9,000 to 15,700 kWh were realized across all four sites (inclusive of all fuels). At site 3, propane use was nearly eliminated and propane use at site 4 was reduced by 2/3 at site 4.

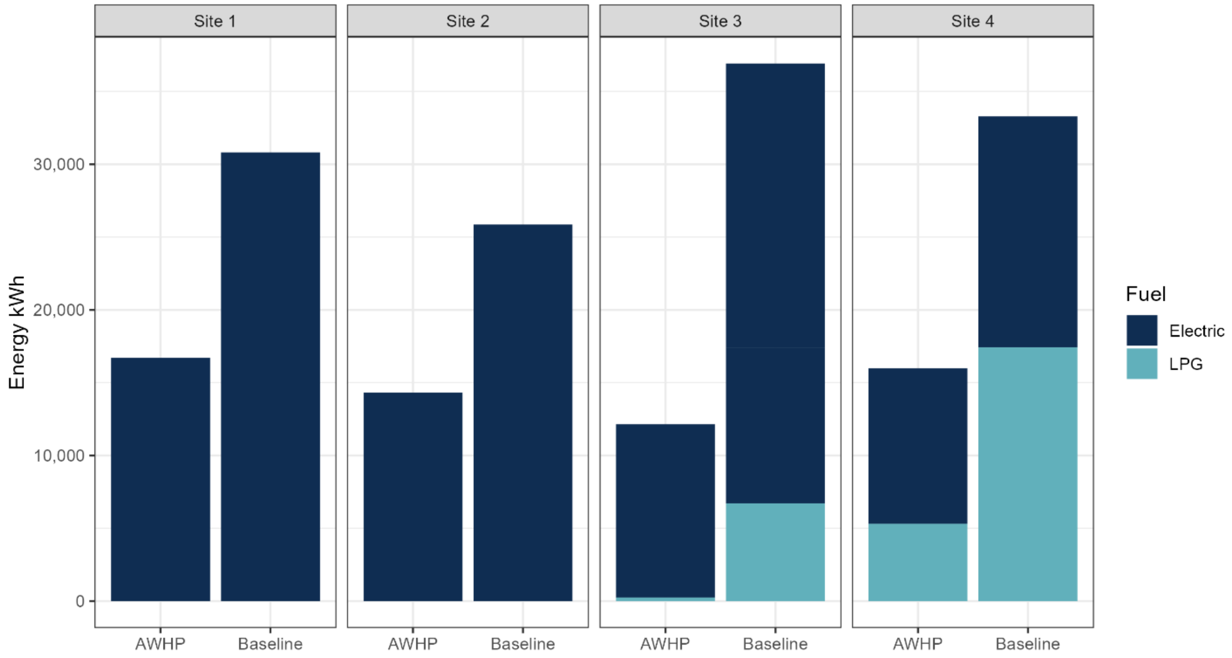

Figure 37: Annualized space heating energy measured at each site before and after the AWHP installation.

Table 12: Annualized space heating energy measured at each site before and after the AWHP installation

	Baseline		AWHP		Savings		
Site	**Electric (kWh)**	**Propane (gal)**	**Electric (kWh)**	**Propane (gal)**	**Elec Savings (kWh)**	**Propane Savings (gal)**	**Total Savings (kWh)**
1	30,900	-	16,700	-	13,400	-	13,400
2	25,800	-	14,300	-	11,900	-	11,900
3	19,500	250	11,900	10	7,600	240	13,900
4	15,900	650	10,700	250	5,200	400	15,800

The total heating cost savings at each site before and after the AWHP installation are given in Figure 38 and Table 13. Savings are generally higher than calculated due to additional savings due to sites' use of free backup heat (wood stove) and curtailing garage space heating.

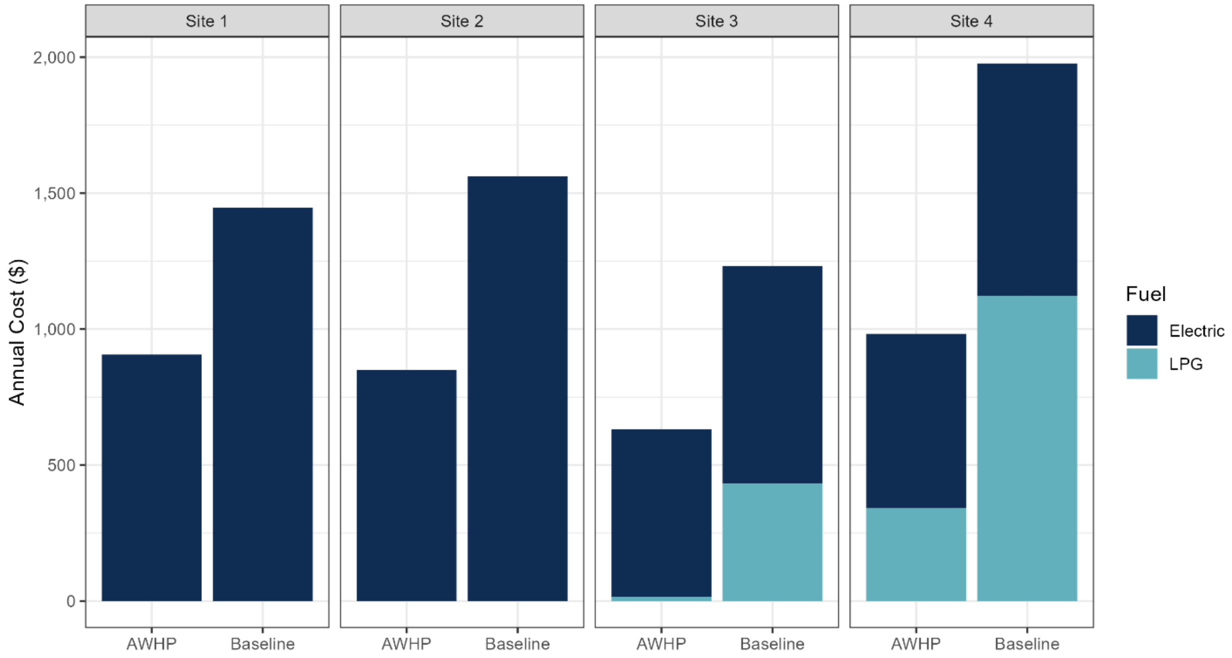

Figure 38: Annualized space heating costs at each site before and after the AWHP installation.

Table 13: Space heating dollar savings at each site according to utility meter data

	Baseline		AWHP		Savings		
Site	Electric ($/yr)	Propane ($/yr)	Electric ($/yr)	Propane ($/yr)	Elec Savings ($/yr)	Propane Savings ($/yr)	Total Savings ($/yr)
1	1,848	-	1002	-	846	-	846
2	1,552	-	860	-	692	-	692
3	1,172	432	616	15	184	417	973
4	952	1,122	641	341	213	781	1,092