Rising Up to the Challenge: Cold Climate Heat Pumps in the Field

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ABSTRACT

Space heating is a major source of greenhouse gas (GHG) emissions in the United States. In colder climates, the average American household using propane or fuel oil to heat their home spends over $1,850 in heating costs alone. Access to optimized, high-efficiency, clean heating technologies is essential for an equitable transition to an electrified future. Electric heat pumps (HPs) are a more efficient and low carbon alternative to fossil fuel-based heating; however, the performance of conventional HPs declines in colder climates. To address this challenge, the U.S. Department of Energy, in partnership with the U.S. Environmental Protection Agency (EPA), Natural Resources Canada (NRCan), launched the Cold Climate Heat Pump (CCHP) Challenge to accelerate the deployment of next generation of centrally ducted electric-only air source heat pumps in residential buildings. These prototypes exceed best-in-class capacity and performance for outdoor temperatures at and below 5 °F. Field validation activities are essential for providing HP technology stakeholders with knowledge and experience to commercialize, deploy, and incentivize CCHP products for future years. The Challenge utilized a robust instrumentation and data acquisition strategy to ensure high-fidelity data collection and high-quality analysis, essential for decision makers to plan for efficiency program incentives. Data were collected at the outdoor unit, indoor unit, indoor conditioned space, and auxiliary heat systems at fine granularity at 22 sites. This paper discusses lessons learned from the field validation aspect of the Challenge, focusing on data collection, management, and analysis methodologies. The paper also discusses challenges such as CCHP installation constraints, data quality, and local A2L refrigerant policies, all of which required special considerations and attention.

Introduction

Space heating is a major source of GHG emissions in the United States. In colder climates, the average American household using propane or fuel oil to heat their home spends over $1,850 in heating costs alone (EIA 2023). Access to optimized, high-efficiency, clean heating technologies is essential for an equitable transition to an electrified future. Electric heat pumps (HPs) are a more efficient and low carbon alternative to fossil fuel-based heating; however, the performance of conventional HPs declines in colder climates. Colder outdoor temperatures lead to higher refrigerant discharge temperatures, which reduces oil viscosity in the compressor and lowers the efficiency of the compression process until eventually the system shuts down (Konrad and MacDonald 2023; Wan and Hwang 2023). Another challenge at low outdoor temperatures is frost forming on the outdoor evaporator heat exchanger coils, which reduces heat exchange at the outdoor unit and can lead to lower system performance if not removed. The most common method for defrosting is reversing the refrigerant flow to provide heating at the outdoor unit and cooling at the indoor unit (Konrad and MacDonald 2023), which under worst-case conditions can cause a drop in heating capacity of up to 29% and a coefficient of performance (COP) reduction of up to 17.4% (Wang et al. 2011). A review by Wan and Hwang (2023) of ten CCHP studies found the COP of existing air-source heat pump technologies ranged from 1.0 to 2.5 with a mean around 1.5 for cold outdoor air temperatures from 5 °F to -22 °F (-15 °C to -30 °C). This compares to COPs of 1.75 to 2.25 at 5 °F (-15 °C) for market-available residential cold climate heat pumps reviewed by Konrad and MacDonald (2023).

Homeowners and utility programs located in cold climates have little incentive to increase deployment of HPs unless performance challenges can be addressed. This paper describes the actions taken to address this challenge via performance specification and validation of pre-commercial residential HP designed for cold climates. Validation took place across two stages – lab testing and then field validation, both of occupied homes and in test homes, from 2022 to 2024.

DOE Cold Climate Heat Pump Challenge

DOE launched the Residential Cold Climate Heat Pump Challenge (CCHP Challenge) specification development process in 2021 through a series of workshops and one-on-one discussions with government and industry partners. The Challenge was envisioned to represent a new, best-in-class, heat pump product that provides high-efficiency heating performance in cold climates, employs environmentally friendly low-Global Warming Potential (GWP) refrigerants, provides advanced grid-interactive capabilities, and could be developed, tested, demonstrated, and commercialized by the 2024 target date. The DOE team, comprising DOE leadership, Pacific Northwest National Laboratory (PNNL), Guidehouse, Stem Integration, National Renewable Energy Laboratory (NREL), Oak Ridge National Laboratory (ORNL), Natural Resources Canada (NRCan), and other key stakeholders, met with manufacturers to discuss the proposed performance targets, laboratory verification procedures, field demonstration protocols, and overall project timelines. Furthermore, the DOE team met with state energy agencies, electric utilities, and other industry organizations to build partnerships that would demonstrate regional support for the CCHP Challenge and serve as a signal to manufacturer teams for future market deployment interest of their Challenge products.

Specifications

The resulting CCHP Challenge specification outlines the key performance criteria and laboratory test procedure for validating performance. The list below highlights the key performance requirements in the specification, with full details and test procedure available on the DOE website (DOE 2021).

- Meets all applicable federal and state standards, regulations and laws governing these types of HPs, including compliance with all safety and environmental standards.

- Achieves a Heating Seasonal Performance Factor 2 (HSPF2) of 8.5 (Region V)[1]
- Meets the following criteria in heating mode relating to the Challenge specification outdoor air temperature of 5 °F (-15 °C):
    - Minimum COP of 2.4 for systems with a nominal capacity ≥ 24,000 (7 kW) and ≤ 48,000 Btu/h (14 kW)
    - Minimum COP of 2.1 for systems with a nominal capacity > 48,000 Btu/h (14 kW)
    - Capacity ratio of 100% for capacity at 5 °F (-15 °C) compared to capacity at 47 °F (8.3 °C)
    - Compressor low-temperature cut-in (temperature at which the HP compressor starts working) at ≤ -5 °F (-21 °C) and cut-out (temperature at which the HP compressor stops working) at ≤ -10 °F (-23 °C)
    - (Optional) Meets the following criteria in heating mode at -15 °F (-26 °C)
        - Compressor cut-in at ≤ -15 °F (-26 °C) and cut-out at ≤ -20 °F (-29 °C)
    - Minimum turndown ratio (ratio of the minimum capacity to the maximum capacity of the HP) at 47 °F (8.3 °C) ≥ 30%
- Auxiliary electric heating staging requirements
- Refrigerant must have a GWP of no more than 750 (100-year)
- Complies with specific connected product installation capability, communications, consumer feedback and demand response requirements set forth by ENERGY STAR Product Specification for Central Air Conditioner and Heat Pump Version 6.0 (ENERGY STAR 2021)
    - Specifically, the demand response functionality references *AHRI 1380: Standard for Demand Response through Variable Capacity HVAC Systems in Residential and Small Commercial Applications* developed by the Air-Conditioning Heating and Refrigeration Institute (AHRI).

Figure 1 illustrates the comparison of the Challenge specification with commercially available CCHPs at the time of development in 2021.

Timeline and Key Milestones

Figure 2 outlines the CCHP Challenge timeline and key milestones from initial specification development in 2021 through product commercialization and deployment programs in 2024. DOE led the development of the CCHP specification through discussions with government and manufacturer partners over several workshops in summer 2021. Interested manufacturers signed commitment forms starting in fall 2021 stating their intention to participate in the CCHP Challenge and develop, test, and commercialize the next-generation products by 2024. At the same time, utility and state partners started to sign commitment forms agreeing to support the CCHP Challenge initiative, field testing in their region, and the development of incentive, education, and/or outreach programs for the commercialized products.

[1] The DOE Appendix M1 test procedure (DOE 2022) calculates HSPF2 values by conducting laboratory testing under a range of operating conditions and applying the results to a series of temperature bins that serve as weighting factors on expected outdoor operating conditions during the heating season for generalized climate regions (Regions I to VI). Regulatory testing and HSPF2 ratings primarily focus on Region IV which has more moderate winter conditions, whereas the CCHP Challenge Specification uses the temperature bins for Region V, which is more representative for colder climates.

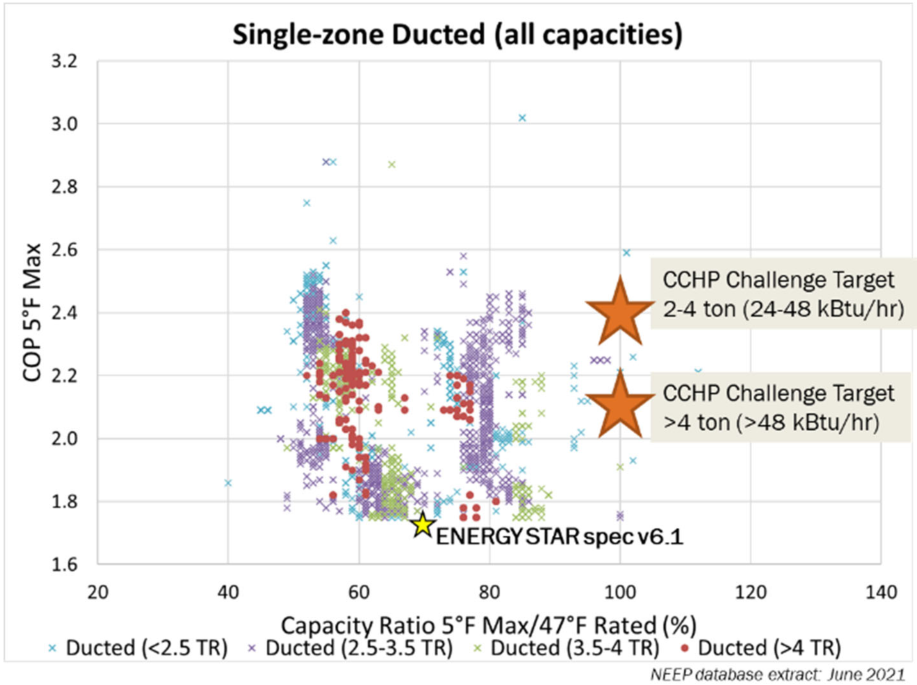

Figure 1. Challenge Specification Compared to Commercially Available Cold Climate Heat Pumps as of June 2021

Following initial launch and public announcements in fall 2021, manufacturers developed their prototypes around the different requirements and test methods in the CCHP Challenge specification. When ready, manufacturers then demonstrated their prototype's performance through laboratory testing at ORNL or other approved testing facilities. The first set of manufacturers (Lennox, Carrier, Trane, and Rheem) completed lab testing in 2022 and proceeded to field testing over the Winter of '22-'23. The second set of manufacturers (Daikin, Midea, Bosch, and Johnson Controls) completed lab testing in 2023 and started field testing for Winter '23-'24. Field testing for all sites continued through mid-2024 to capture winter, shoulder, and summer performance data for one or more years. Manufacturers are incorporating the findings from laboratory and field testing into their final product designs, which are anticipated to be commercialized in late-2024 or early-2025. In parallel, the project team plans to prepare a public report that summarizes field testing results and findings, and coordinate with utility and state partners on how best to support the CCHP products in their regions.

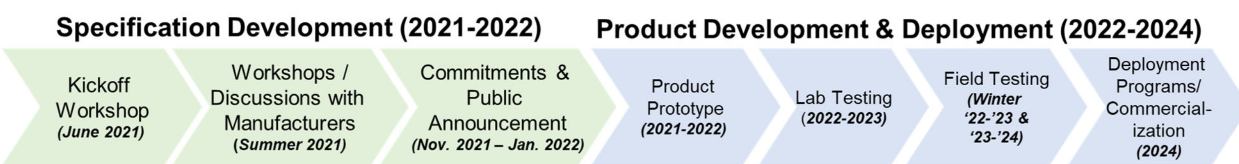

Figure 2. CCHP Challenge Timeline and Key Milestones

Participants

Table 1 highlights the manufacturer, utility, and state participants in the CCHP Challenge. Manufacturers met with the CCHP Challenge project team monthly to review product development, discuss questions on the specification, prepare for laboratory and field testing, and address issues that the teams encountered. The project team also provided periodic updates to the utility and state partners and incorporated feedback on the field-testing methodology and plan. Furthermore, the utility and state partners provided local support for field test sites in their region, including letters of support for discussions with local installation contractors and code officials.

Table 1. Key Participants in the CCHP Challenge

Manufacturer	Utility (State)		State Agencies
Bosch Carrier Daikin Johnson Controls Lennox Midea Rheem Trane	Alaska Electric Light and Power (AK) Bonneville Power Administration (Pacific Northwest) ComEd (IL) Con Edison (NY) Connexus Energy (MN) Consumers Energy (MI) DTE Energy (MI) Efficiency Maine Trust (ME) Efficiency Vermont (VT) Energy New England (MA and Greater New England) Eversource (MA, CT, NH) Focus on Energy (WI) Great River Energy (MN)	Massachusetts Municipal Wholesale Electric Company (MA) Minnesota Valley Electric Cooperative (MN) National Grid (MA, NY) Tri-State Generation and Transmission Association (CO, NE, NM, WY) Upper Peninsula Power Company (MI) Xcel Energy (CO, MN, and several other states)	Alaska Housing Finance Corporation Colorado Energy Office Maine Governor's Energy Office Massachusetts Department of Energy Resources Michigan Department of Environment, Great Lakes, and Energy Minnesota Department of Commerce Montana Energy Office New York State Energy Research and Development Authority Public Service Commission of Wisconsin

Laboratory Testing

To verify that manufacturer's CCHP prototypes met the Challenge specification, the DOE team conducted lab testing at Oak Ridge National Laboratory (ORNL) or other approved sites for each prototype according to the Challenge test procedure. The test procedure augmented the federal test procedure established (Appendix M1 to Subpart B of Part 430 "Uniform Test Method for Measuring the Energy Consumption of Central Air Conditioners and Heat Pumps") for the purpose of evaluating aspects important for cold climate operation that are not fully evaluated by regulatory procedures. In addition to verifying regulatory performance, the test procedure included a native-control controls verification procedure (CVP) for cold climate performance and system controls that affect performance, including demand defrost, auxiliary heat staging, and demand response capabilities. During both laboratory and field testing, National Renewable Energy Laboratory (NREL) acted as the "utility provider" calling in the demand response events. Two types of demand response events were called: a general curtailment event, which required that total system input power be reduced to a maximum of 70% of the rated load power; and a critical curtailment event which required that total system input power be reduced to a maximum of 40% of the rated power. The list below summarizes the key findings from the laboratory testing:

- All prototypes comfortably exceeded the federal minimum cooling (14.3 SEER2) and heating (8.5 HSPF2 Region V) standards.
- CCHP prototypes demonstrated high heating capacity at low ambient temperatures with all prototypes able to provide greater than or equal to 100% of the nominal rated heating capacity at 5 ºF (-15 °C) outdoor temperature. Improved low-temperature heating capacity translates to decreased operation of the backup heating system during very cold conditions.
- CCHP prototypes also demonstrated high-efficiency performance at low ambient temperatures with all prototypes able to operate at a COP greater than the 2.1 or 2.4 (depending on unit's nominal heating capacity) targets at 5 ºF (-15 °C). This translates to being more than twice as efficient as electric resistance heating units (COP of 1).
- Several prototypes participated in the optional -15 °F (-26 °C) Challenge and were also able to demonstrate heat pump heating operation at extremely low temperatures (-15 ºF, -26 °C).
- All prototype units successfully demonstrated compliance with the connected product criteria and advanced demand response functionality, which utilized their variable-speed capabilities to reduce power consumption during both general and critical curtailment demand response events.

Field Validation

The goals of the field-testing component of the study are two-fold: (1) to understand how these highly efficient CCHPs perform in the field under real occupancy conditions, and (2) to collect data and conduct analyses that will support deployment efforts once the units become commercialized.

Approach

After the prototype unit of each participating manufacturer was demonstrated to meet the Challenge specifications in the laboratory environment, they were allowed to proceed to the field validation step. Each manufacturer developed between one and four prototypical units for testing in the field. While most manufacturers developed prototypes to meet the 2-4 TR Challenge specification, some developed prototypes to meet the > 4 TR Challenge specification, and one manufacturer developed one of each.

Due to the varying timelines of product development and laboratory testing for the participating group of manufacturers, field validation was divided in round 1 and round 2. Round 1 installations took place between in winter 2022 and spring 2023, and round 2 installations took place between fall 2023 and early winter 2024. For each unit, at least one year of data is collected, with most round 1 sites expected to have more than one year of data.

Site Selection

The installation site for each unit was selected in close coordination with each manufacturer. This was done to preserve the privacy and data protection due to the pre-commercial nature of the units, as well as to ensure that each unit was placed in a house that was suited for the capacity of the unit. Another primary consideration was selection of sites that would yield cold to very cold temperatures needed to assess the performance of the units adequately as well as diversity in geographic regions. As a result, the process of site selection took several months from the initial inventory to the final selection. Figure 3 illustrates the site selection process used for this study.

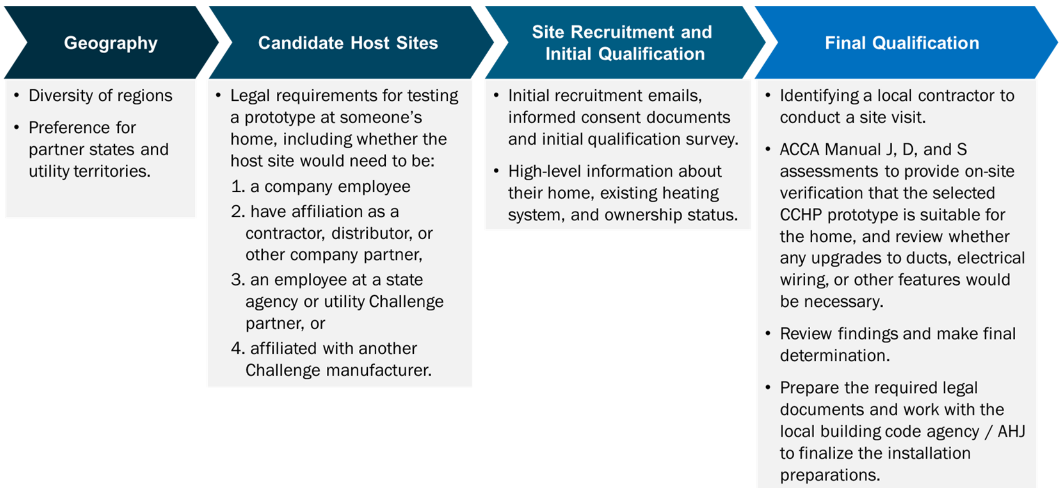

Figure 3: Site Selection Process for the Field Validation Effort

Domestic Field Testing

19 prototypical units were installed across the northern United States for domestic field validation. These units were installed in occupied single-family homes across a range of geographic locations. Most homes had a furnace system in place before the furnace was replaced with the prototype CCHP.

Canadian Field Testing

Field testing was also conducted at the NRCan test home facility in Ottawa, Canada for three prototype units. The units were tested in a facility with simulated occupancy over a period of 2-4 weeks in the winter and 2-4 weeks in the summer. Data collected were cleaned and processed by the research team using the same methodology for consistency.

Installation

Once the final site selection was complete, the research team initiated the informed consent paperwork required by the human subject research aspect[2] of the study for the occupied single-family homes in the sample. The units were installed at the convenience of the homeowners with the full CCHP installation, and measurement and verification (M&V)

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[2] Because the study involves installation and monitoring of pre-commercial CCHPs in real homes where they impact the space temperatures and comfort of humans, the study followed procedures and protocols laid out by the research organization's Institutional Review Board (IRB) process. This included protocols for protection of personal identifiable information (PII), consent forms, surveys etc.

instrumentation installations being completed within an average of 3-5 days. The research team tried to organize the CCHP install at the same time as the M&V install to gain efficiencies in the installation process. However, this was not possible at every site leading to slightly longer total installation times.

Data Collection and Analysis

Due to the pre-commercial nature of the units being developed and studied in this research, the field validation took an extremely granular approach to data collection. Power measurements at the indoor and outdoor unit were taken at 1-second intervals, reversing valves were monitored at 1-second intervals, and each stage of auxiliary heat was instrumented separately to take measurements at 1-second intervals. Because the temperature and relative humidity (RH) readings are not expected to vary as spontaneously as the power measurements, these measurements were taken at 1-minute intervals to balance data volume and accuracy. Temperature and RH were measured at least three different points in the home, and in the supply and return air ductwork. Outdoor air temperatures and RH were measured at 5-minute intervals to optimize battery life for the outdoor sensors. Table 2 summarizes the data points and frequency of the data collected. Additional information about the data collection process is described in Mendon et al. 2024. All data collected in the field were transmitted to the analysis team using a secure encrypted system to protect data.

Table 2. Data Collected and Recording Frequency

System	Parameter	Measuring equipment	Locations	Sampling Interval
Outdoor unit	Power	Power meter + current transducer	Outdoor unit circuit	1 second
	Temperature/RH	TC/RH sensor, solar shield	Outdoors near unit	5 minute
	Voltage	Relay	Reversing valve	1 second
Indoor Unit	Power	Power meter + current transducer	Indoor unit circuit	1 second
			Indoor fan circuit	
	Temperature/RH	TC/RH sensor	Supply air outlet (4 locations)	1 minute
			Return air inlet	
			Unit Ambient	
			Indoor conditioned space (3 locations)	
	Volumetric air flow	Airflow metering plate	Air handler return / filter housing	At installation (airflow correlated with fan power)
Auxiliary Heat	Power	Power meter + current transducer	Electric heat strip (1 per element)	1 second

Energy Performance Metrics

The following are key energy metrics that are used to evaluate the performance of the CCHPs in the field:

- **Heating Capacity**: Delivered heating output is evaluated for various outdoor temperature bins.
- **COP**: COP is calculated for various outdoor temperature bins. This is done both with and without the inclusion of auxiliary heat and defrost operation. Cooling and heating COPs are calculated separately based on the operating mode.
- **Auxiliary Heat Usage**: Auxiliary heat is evaluated using the power consumption of auxiliary heaters at various outdoor air temperatures. The auxiliary heat staging is evaluated by the average duration of time and frequency of each stage by outdoor air temperature bins.
- **Compressor Power**: Compressor power ranges are evaluated to understand how the CCHPs modulate based on the heat demand.
- **Cycle Runtimes**: Average cycle runtime and frequency are evaluated for various outdoor air temperature bins. Sites with frequent, very short runtimes (less than five minutes) are flagged and individually evaluated to assess the behavior of the equipment for short cycling.
- **Defrost Runtimes**: The average frequency and length of the defrost mode is evaluated for various outdoor air temperature bins. These events are evaluated to check for patterns in conditions.
- **Switchover Temperature**: Switchover outdoor air temperature is evaluated based on the outdoor air temperature below which the onset of auxiliary heating to supplement the required heating load is observed consistently.

Proxy Data

Over the monitoring and data collection period, the research team dealt with some sensor failures which required identification and usage of proxy data. The most common failure was the battery life of the outdoor temperature and RH sensors. The batteries of the sensors installed in many of the round 1 sites, started failing much sooner than the research team had anticipated, resulting in data loss before the team could visit the sites to replace the batteries. At two sites, the outdoor temperature and RH sensor had persistent connectivity issues resulting in large gaps in the data collected. To address these issues, the research team utilized outdoor dry bulb temperature and RH data provided by the National Weather Service.[3] Data were downloaded for the weather station located closest to the site in question.

High-level Results

Overall, all installed units demonstrated strong heating and cooling season performance, across a range of home efficiencies, geographic regions, and occupant behavior and preferences. Data for the two NRCan sites will be added to those for the US sites in a future report.

[3] www.weather.gov/documentation/services-web-api

Heating Season Energy Performance

The heating performance of the units was evaluated primarily by the calculated COP. Figure 4 shows the COP comparing compressor only operation to the total COP including compressor, auxiliary heat and defrost operation. The data is shown as a boxplot that represents the average COP for each site at each outdoor air temperature bin as one data point. The number of sites with data for each outdoor air temperature bin is labeled on top of each boxplot. The COPs increase at warmer temperatures generally, and the COPs are lower with defrost and auxiliary heat included as expected. The gap between the COP with defrost and auxiliary heat excluded and included grows smaller at warmer temperatures as less defrost operation and auxiliary support is noted. Overall, the heating season COPs for compressor heating only are observed to range between 1.8 at the coldest temperatures of -15 ºF to 3.5 at temperatures of 45-55 ºF.

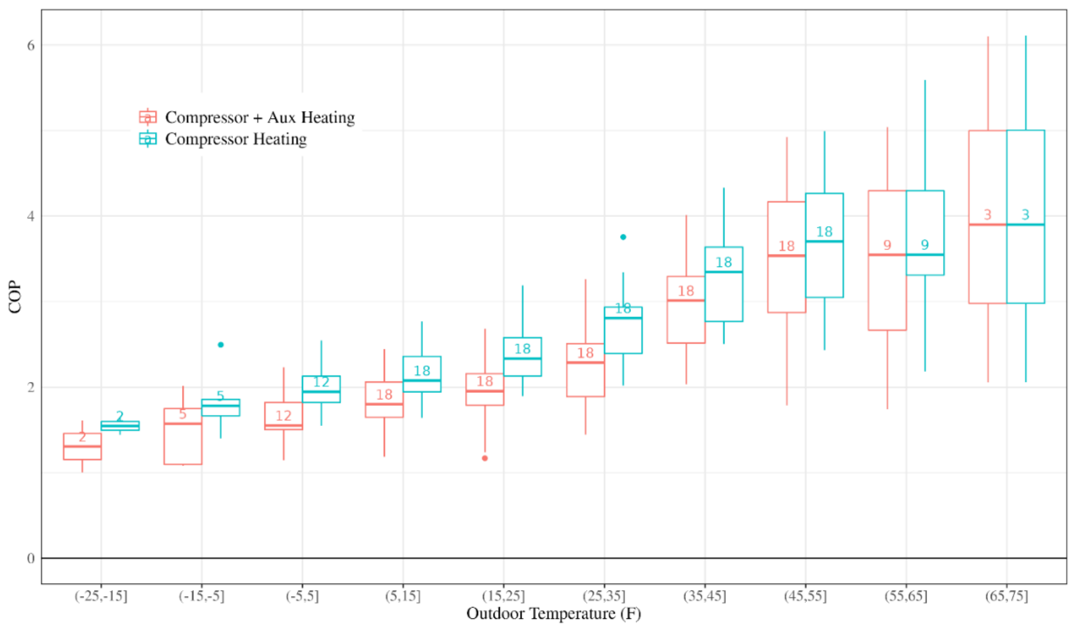

Figure 4. Heating COP by Outdoor Air Temperature Bin. The count of sites with data used for each boxplot is labeled within the box.

The modulation of the CCHP to support smaller thermal loads was evaluated using compressor power measurements. Figure 5 shows the range of compressor power observed at each site in compressor only heating mode (i.e., auxiliary support and defrost operation excluded), categorized by units that are greater than 4 TR and the units that are 2-4 TR. It is interesting to compare the first quartile (below which 25% of the data falls) to the maximum values (outliers are excluded from the chart) for each site. The low values in power readings at each site tend to come from cycling on and off, and the first quartile is a better representation of the minimum power level supported by the unit.

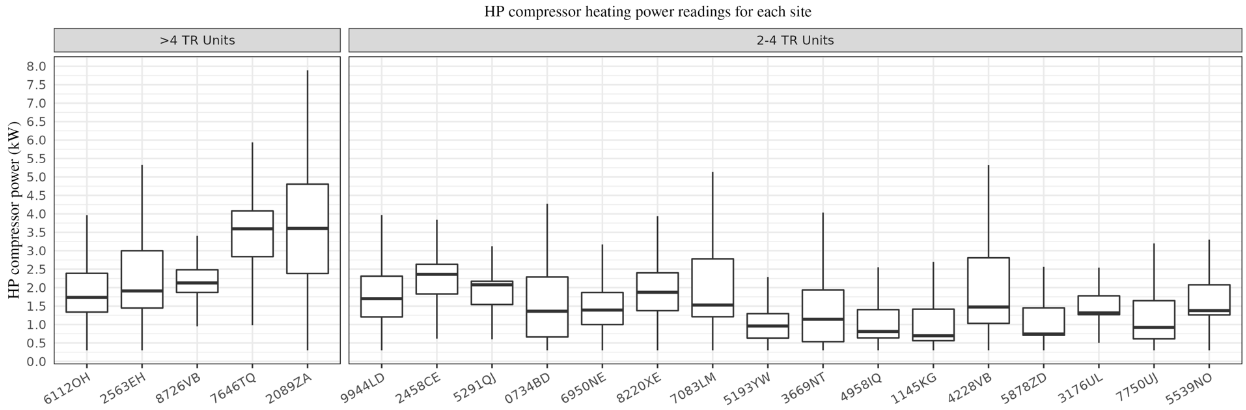

Figure 5. Compressor Power Categorized by Unit Size.

Auxiliary heat is an important component of CCHP units and a major factor in the overall heating performance and energy consumption of the units. Figure 6 shows the contribution of auxiliary heat to the total energy consumption at each site excluding auxiliary heat used during defrost operation. The boxplots show the range of values observed at each site with one data point represented for each site at each 5 ºF outdoor air temperature bin.[4] At very cold outdoor air temperatures, there is a wide range of auxiliary contribution across sites from almost 0% to up to 90%. The auxiliary contribution decreases across almost all sites at outdoor air temperatures above 0 ºF. These patterns in auxiliary heat usage are expected to originate from the differences in occupant thermostat preferences, control setting and the performance of the CCHPs themselves at the lowest outdoor air temperature bins.

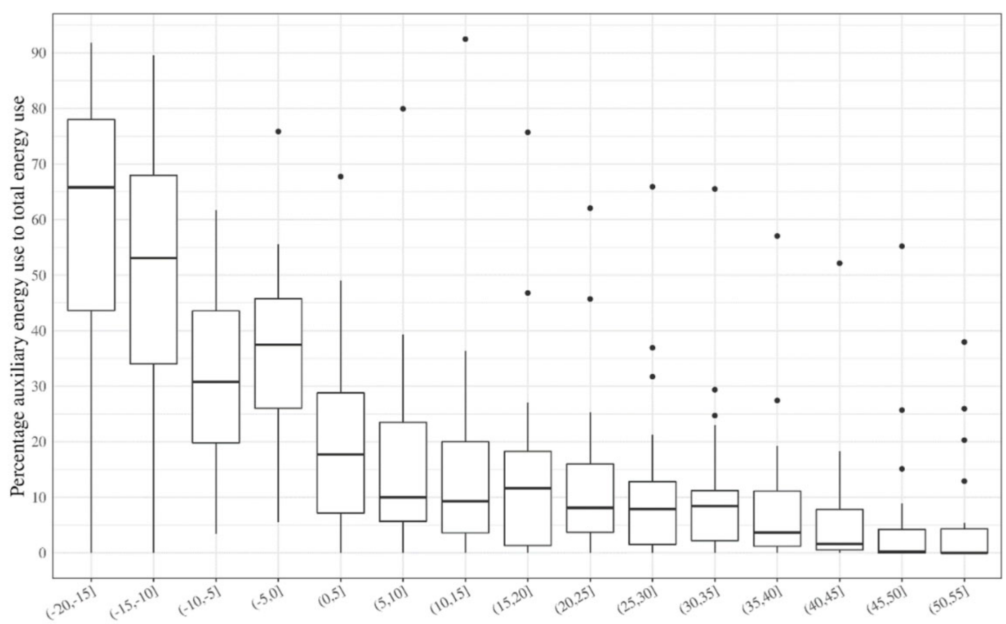

Figure 6. Auxiliary Heat Support by Outdoor Air Temperature Bin.

[4] Data points with fewer than four hours of heating operation in the outdoor air temperature bin were removed from the visualization.

Cooling Season Energy Performance

The cooling performance of the units were evaluated by the calculated COP. Figure 7 shows the COPs for cooling mode only by outdoor air temperature bin. The data is shown as a boxplot that represents the average COP for each site at each outdoor air temperature bin as one data point. The number of sites with data for each outdoor air temperature bin is labeled on top of each boxplot. The COPs generally decrease at warmer temperatures as expected, but there is significant variation between sites in some bins. Overall, cooling COPs were observed to range between 3.8 at moderate temperatures to just under 3.0 at hotter temperatures of 90-95 ºF.

It should be noted that the available cooling season data available to date is more limited compared to the heating season data. There are fewer sites with cooling performance data available because only the round 1 sites currently have cooling performance data resulting in a smaller data sample. Additionally, several round 1 sites lost cooling data towards the end of the summer due to supply and return air temperature sensor batteries failing before they were able to be replaced. These shortcomings are further discussed under the Challenges section.

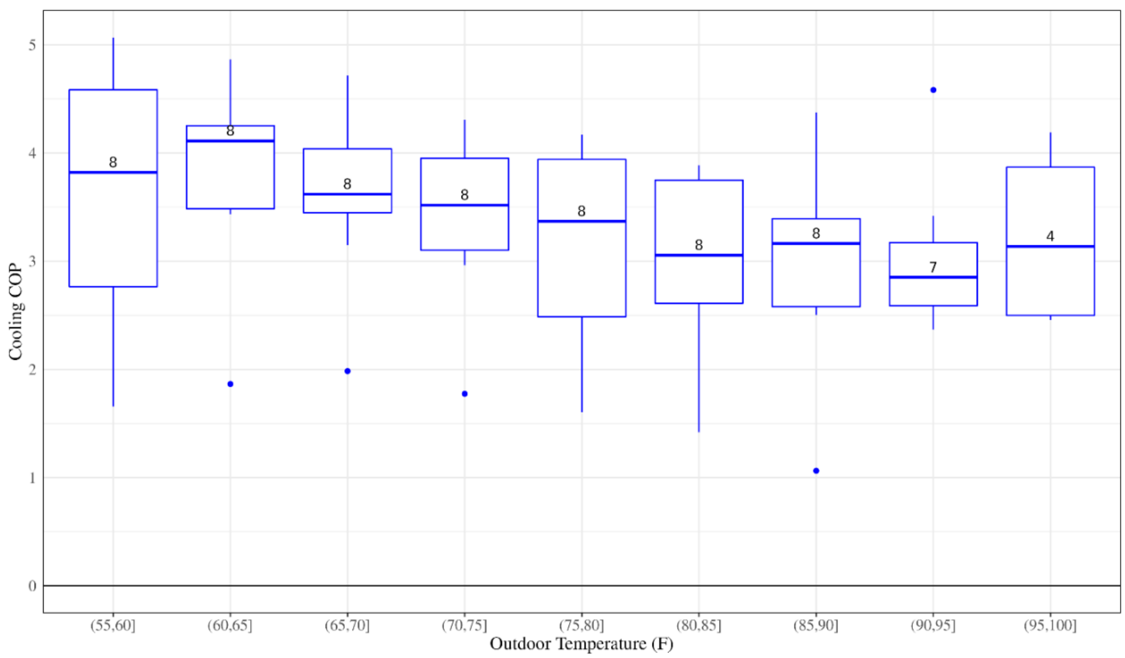

Figure 7. Cooling COP by Outdoor Air Temperature Bin. The count of sites with data used for each boxplot is labeled within each box.

Non-Energy Performance

In addition to the energy metrics calculated from the metered data, comfort, reliability, and other non-energy benefits of the CCHP prototypes were evaluated using pre- and post-installation surveys administered by the research team. At the start of the field study, the research team asked the homeowners to complete pre-installation surveys to assess the overall levels of noise, comfort, satisfaction, and reliability of their current heating and cooling systems. After several months of use, each homeowner was asked to complete post-installation surveys to assess the same metrics with their new CCHP system. Two post-installation surveys have been conducted to date: one at the end of winter 2022-2023 to gauge heating performance, and the other at the end of summer 2023 to gauge cooling performance.

Figure 8 summarizes the homeowner survey responses over the first winter heating and summer cooling seasons. Homeowners generally noted an improvement in comfort with the new CCHPs compared to their old heating systems and overall satisfaction with the performance of the units. Some respondents noted increased noise especially at very low outdoor air temperatures. This is likely due to the higher airflow rates used by CCHPs compared to fuel-fired furnaces which were the previous heating systems in most of the participating homes. Several respondents also noted a reduction in their use of supplemental heating sources compared to the older systems. Overall, the CCHPs have reliably maintained indoor temperature setpoints and either maintained or increased comfort and overall satisfaction for most of the test homes when compared with the previous gas or electric furnace heating systems. These findings are consistent across sites that have a range of outdoor temperature conditions.

Homeowner Survey Responses Summary

SITE ID	Maintain Temperature?		Noise Issues?		Comfort Issues?		Needed HVAC Support?		Overall Satisfaction (1-5)		Would Recommend?	
	Winter '22-'23	Summer '23	Winter '22-'23	Summer '23	Winter '22-'23	Summer '23	Winter '22-'23	Summer '23	Winter '22-'23	Summer '23	Winter '22-'23	Summer '23
2563EH	YES	YES	YES	YES	NO	NO	NO	YES	4	4	NO	NO
3176UL		YES		NO		NO		NO		5		YES
4228VB	YES	YES	NO	NO	YES	NO	NO	NO	4	5	YES	YES
5539NO	YES	YES	NO	NO	NO	NO	NO	NO	4	5	YES	YES
6112OH	YES	YES	YES	YES	NO	NO	NO	NO	4	4	YES	YES
6950NE												
8220XE	YES		YES		NO		NO		5		YES	
8726VB	YES	YES	YES	NO	NO	NO	NO	NO	4	5	YES	YES
9944LD		YES		NO		YES		NO		4		NO

Figure 8. Summary of Homeowner Survey Responses

Challenges

A wide range of challenges were encountered during the project, starting with challenges during the CCHP installation, data collection, management of large volumes of data and sensor failures.

Field Installation

Researchers were able to observe and collect notes during the installation of the prototype units. Consistent challenges among installers and install configurations included duct resizing, new equipment familiarity, and installing equipment in cold outdoor conditions.

All homes included in the study required at least some duct modification, and some homes required major modifications. In some cases, ducts were hidden within finished walls, floors, or ceilings. In others, the ductwork was accessible through unfinished areas of the home. During this project's equipment installations, some installers experienced trouble accessing existing ductwork, properly sealing new and existing ductwork, and designing duct configurations that were both implementable with minimal intrusion and acceptable within the sizing design.

When installing the new equipment, challenges arose with the configuration and setup of new wiring schemes, thermostat controls, testing controls, and general setup controls. These challenges are likely amplified in this sample, as the equipment is prototypical, but some of the challenges will likely persist as this new equipment enters the market and installers become adequately familiar with the requirements. It is important for installers to have a thorough understanding of the thermostat control options available to them so they can accurately and efficiently set the system up to operate as intended. Additionally, wiring schematics and equipment testing capabilities and methods should be provided to the installers for new equipment to ensure that the installation team has every opportunity to conduct a quality installation.

Finally, the project timeline meant that many of these units were installed in the late fall or winter months, meaning that outdoor conditions were often cold and sometimes wet. These conditions can make any HVAC installation more difficult, but that difficulty is amplified in refrigerant system installations due to the precision of pressure testing required and the state-change nature of the refrigerant itself. The research team noted that the field teams often had to pre-warm the refrigerant canister before charging the equipment. This is a standard practice already, and standardized methodologies may be developed to inform decision making. One method of pre-warming the refrigerant canister was for an installer to move the canister to their work truck, turn on the heat, and leave the canister in the warm vehicle for ~30 minutes. This is a reasonable method, but direct suggestions on how to effectively warm refrigerant canisters may help the installation community. Additionally, low outdoor air temperatures make refrigerant system testing more difficult. When pressure testing a refrigerant system in cold conditions, standard analog gauges may not provide accurate pressure readings, as air temperatures can impact pressures as explained by the ideal gas law, sometimes suggesting pressure values that are driven by the current air temperature rather than the generalized system conditions. Digital smart diagnostics tools, which use current air temperature information to compensate for changes in pressure that are driven by the current temperature, would help ensure that pressure changes during the test are due to leakage and not environmental conditions.

Instrumentation and Sensor Failures

Field evaluation projects that require highly granular data require a well-planned and precise instrumentation strategy. This project required dozens of sensors, multiple data aggregation devices, network capabilities, and creative thinking for successful data collection deployment. To deploy a project of this nature, robust methods were developed and upheld to track and maintain sensor uptime. Failure points were mainly related to failing batteries and cellular modem connectivity. Due to uncertain power consumption, sensor placement conditions (air temperature and moisture), and other unknown factors, the temperature and relative humidity sensors experienced “dead” batteries sooner than expected. Due to robust sensor tracking, the M&V teams were able to identify dead or low batteries and replace them before large amounts of data were lost. Similarly, cellular network coverage was not always available as expected due to the rural nature of some sites. By monitoring connection strength through a cellular modem’s networking settings, M&V teams were able to identify sites with poor connectivity. In cases where the cellular connection was consistently unreliable, a different cellular provider with better coverage in the area was chosen and a new Subscriber Identity Module (SIM) card was purchased.

Data Collection and Management

This study collected 1-second power measurements at various points on the CCHP, 1 minute temperature and RH readings at multiple points at the CCHP and inside the home, and 5-minute outdoor temperature and RH readings. The granularity of the data collection, the length of the monitoring period and the number of sites resulted in large volumes of data that had to be transferred, cleaned, and processed on a weekly basis. While the research team conducted much of the round 1 analysis on local computers, running scripts locally quickly became inefficient and had to be transferred to the research organization's High-Performance Computing (HPC) system. Using the HPC allowed the analysis team to run the scripts and process data much faster. Because the data is collected from pre-commercial units and contains PII, stringent data protection and access controls were implemented throughout the project.

Next Steps

Most participating manufacturers plan to make the Challenge prototype units commercially available by late 2024-early 2025. Over the rest of 2024 and into 2025, the research team plans to work closely with stakeholders and engage utilities in helping the deployment of these CCHPs by leveraging the field data collected and analyzed for this study. This includes supporting the development of Technical Resource Manuals (TRM), exploring potential tier structures for incentives, next set of high-performance CCHP designations, and alignment across regions. Performance observations and results from the field validation will be compiled into de-identified aggregated trend level information in a public facing report towards the end of 2024. Eventually, data collected from the study in an aggregated and de-identified form will be made available for other researchers and interested entities through DOE's Heat Pump and Heat Pump Water Heater Field Database.[5] Additionally, the research team plans to explore the development of Challenge specifications for more product classes.

Lessons Learned and Conclusions

This study comprised of an exhaustive field validation of pre-commercial Challenge CCHPs. Extremely granular and detailed data was collected and are being analyzed for a sample of 22 sites across 8 different manufacturers. Installation of the prototype units in various configurations and geographic regions have resulted in the identification of many challenges as well as best practices. While some installations were more challenging than others due to adverse weather conditions, installers were successfully able to install CCHPs efficiently and were able to work with next-generation low GWP refrigerants as well as the CCHP's leak detection and mitigation systems. The CCHPs were installed in various configurations and spaces successfully as replacements for old furnaces, thereby indicating their strong retrofit potential in the push towards residential decarbonization. In the field, the CCHPs were observed to be reliable and were able to provide equal or better comfort to the homes compared to the previous furnace systems. Initial evaluations of the performance and efficiency of the units indicate promising

[5] heatpumpdata.energy.gov

results with all units capable of providing heat with little assistance from auxiliary elements even during the coldest weather, resulting in strong COPs. Further evaluation and additional winter data as well as demand response (DR) testing will provide a more robust basis for supporting deployment efforts of the units. Finally, a strong set of government, manufacturing, utility, and other industry partners have been actively engaged in the whole process and continue to be engaged as the process shifts from the development and testing to deployment phase.

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