PNNL-37127

Performance Results from DOE Cold Climate Heat Pump Challenge Field Validation

January 2025

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Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

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Executive Summary

Space heating accounts for over 43% of energy use in residences in the U.S. and represents a significant component of many homeowners' monthly energy bill. Heat pump technology offers an energy-efficient alternative to traditional heating systems—heat pumps transfer heat from one location to another rather than generate heat themselves, which means they can often more efficiently provide comfortable temperatures for homes. However, in cold climates, performance of heat pumps has traditionally suffered because the units have been unable to efficiently transfer heat from colder outdoor air temperatures to heat the interior space of homes. Optimizing heat pumps for cold climates (5 °F and below) requires coordinated effort to ensure heat pump technologies can be enjoyed by Americans living in these regions.

The U.S. Department of Energy Cold Climate Heat Pump (CCHP) Technology Challenge (the Challenge) sought to address this issue by partnering with industry to develop, test, and validate the performance of new, high efficiency heat pumps in real homes. The Challenge, launched in 2021, brought together leading heating, ventilation, and air conditioning (HVAC) manufacturers to develop prototype units optimized for performance at cold climates. The CCHP prototypes were centrally ducted units with advanced demand response capabilities and electric resistance auxiliary heat backup sources.

One of the key challenges with conventional heat pumps in colder climates has been poor capacity maintenance at colder outdoor air temperatures. A conventional heat pump's heating capacity drops below its rated capacity once outdoor air temperatures drop below 40 °F, and only a fraction of that rated capacity is provided once the outdoor air temperatures go into the teens. This results in a need for supplemental heating to meet the home's thermal load at colder temperatures, which in turn results in higher utility bills for the homeowners. The CCHP prototypes units sought to address this issue by requiring the prototypical units to not only be energy efficient at cold outdoor air temperatures (measured via a coefficient of performance, or COP, at 5 °F) but also to maintain their heating capacity at 100% at 5 °F, thus significantly reducing the need for supplemental heat at colder temperatures.

Bosch, Carrier, Daikin, Johnson Controls, Lennox, Midea, Rheem, and Trane Technologies participated in the Challenge. As of December 2024, four of the eight participating manufacturers have announced plans to bring commercialized versions of the prototypical units tested in this field study to market in 2024 or 2025. Carrier[1], Lennox, Bosch[2], and Trane's[3] public announcements indicate that commercialization of their CCHP prototypes is anticipated by early 2025. The remaining manufacturers are expecting to finalize commercialization plans in the coming year.

Participating manufacturers worked closely with DOE and the National Laboratories throughout the development, laboratory testing, and field-testing portions of the Challenge. They noted the critical value of DOE and industry collaboration for revolutionizing energy-efficient home heating and cooling through the Challenge.[4] This collaboration between government and industry helped to address a persistent gap in the market by providing a common set of performance

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[1] https://www.prnewswire.com/news-releases/carrier-completes-department-of-energys-cold-climate-heat-pump-challenge-transformative-innovation-set-for-2024-commercial-rollout-302245339.html

[2] https://www.bosch-homecomfort.com/us/en/ocs/residential/ids-ultra-inverter-ducted-split-cold-climate-heat-pump-20831889-p/

[3] https://www.trane.com/residential/en/resources/blog/cold-climate-heat-pump-challenge/

[4] https://www.energy.gov/eere/buildings/partners

requirements for which Challenge partners were able to quickly develop high-performance heat pumps prototypes and test performance in both the laboratory and real-world setting. Manufacturers noted that the Challenge has helped increase public awareness and accessibility of these new products, which feature cutting-edge technologies that deliver consistently high efficiencies in colder climates while maintaining occupant comfort. Manufacturers noted that the partnership between industry, DOE, and the National Laboratories not only helped overcome technological barriers that have traditionally slowed the introduction of new technologies to the market, but also provided stakeholders with performance information needed to drive broader industry and consumer adoption.

All prototypes were required to demonstrate the performance required by the Challenge specification[1] in a laboratory as a first step. This report summarizes the findings from the field validation effort of the Challenge, conducted from winter 2022 through early fall 2024. Ultimately, 22 units successfully completed the field validation effort in the United States and Canada. All units installed in the United States were located in occupied homes; units in Canada were installed in a mix of occupied homes and laboratory homes. Homes were monitored between 10 and 91 weeks, with between 898 and 3,099 hours of heating data and 0 and 2,078 hours of cooling data collected and analyzed. Many sites experienced somewhat milder winters than normal for their area, with only eight of the 22 sites having 10 or more hours of heating data below 0 °F.

Most of the CCHP prototypes in the study sample were 3 tons (36,000 Btu/hour) in capacity, with three 4.5-ton units (54,000 Btu/hour), one 4-ton unit (48,000 Btu/hour) and one 5-ton unit (60,000 Btu/hour). Load calculations were conducted for all sites using Air Conditioning Contractors of America Manual J to ensure that the CCHP prototypes would adequately provide the required heating and cooling upon installation.

Excluding periods with auxiliary heat or defrost, heating COPs were observed to be more tightly clustered at colder temperatures and to increase steadily with increasing outdoor air temperature (OAT). Figure 1 below shows a box and whisker chart of observed heating and cooling performance. The median COPs across all sites at cold temperatures (below 30 °F) are in the range of 1.6 to 2.7. In the 0 to 5 °F OAT bin, the median COP was observed to be 1.9. As a point of comparison, the current Environmental Protection Agency EnergyStar requirements for cold climate heat pumps is a COP above 1.75 at 5 °F, which compares with the Challenge requirement of 2.1 or 2.4. While the laboratory performance of the CCHP prototype units is significantly more efficient, the observed COP of most of the units in the field is also higher than 1.75.

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[1] https://www.energy.gov/sites/default/files/2021-10/bto-cchp-tech-challenge-spec-102521.pdf

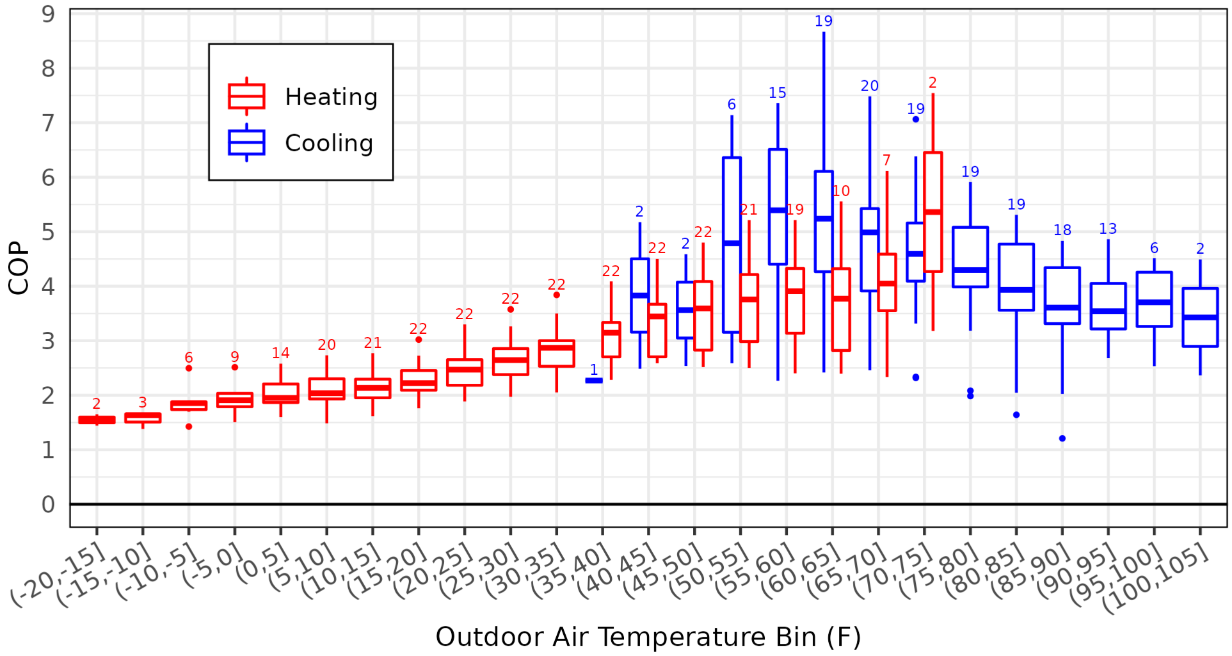

Figure 1. COP for Heat Pump-Only Cooling and Heating by OAT Bin.

Both heating and cooling have a wide range of heating COPs observed at moderate OATs (50-75 °F). The cooling COPs are overall more dispersed than the heating COPs. Two sites were observed to call for cooling at much cooler OATs below 50 °F. These were associated with occupant preferences for nighttime cooling. Excluding these temperature bins, the median cooling COP values across all sites and temperature bins range from 3.4 to 5.2.

All CCHP prototypes included in the study had at least three, sometimes four, stages of auxiliary electrical heat where each element was controlled separately. The staging allowed the CCHPs to optimize the amount of auxiliary heat while minimizing energy demand. For example, most CCHPs that used auxiliary heat to maintain supply air temperatures during defrost mode only engaged the first stage of auxiliary heat, around 5 kW. When higher levels of auxiliary heat were required for supplementing the CCHP in meeting heating loads, staged control was utilized as a more efficient method than having one large, single-staged auxiliary element.

Figure 2 shows the percentage of time each auxiliary stage is activated across the range of OATs observed in the study. Periods of defrost operation as well as periods of system idling or system off are excluded from this chart to only show the impact of auxiliary heat in supplemental mode during heating. Data from all sites are pooled together in the chart—to reduce bias, data for an OAT bin is shown only if it has at least five sites that each have a minimum of 5 hours of total heating operation.

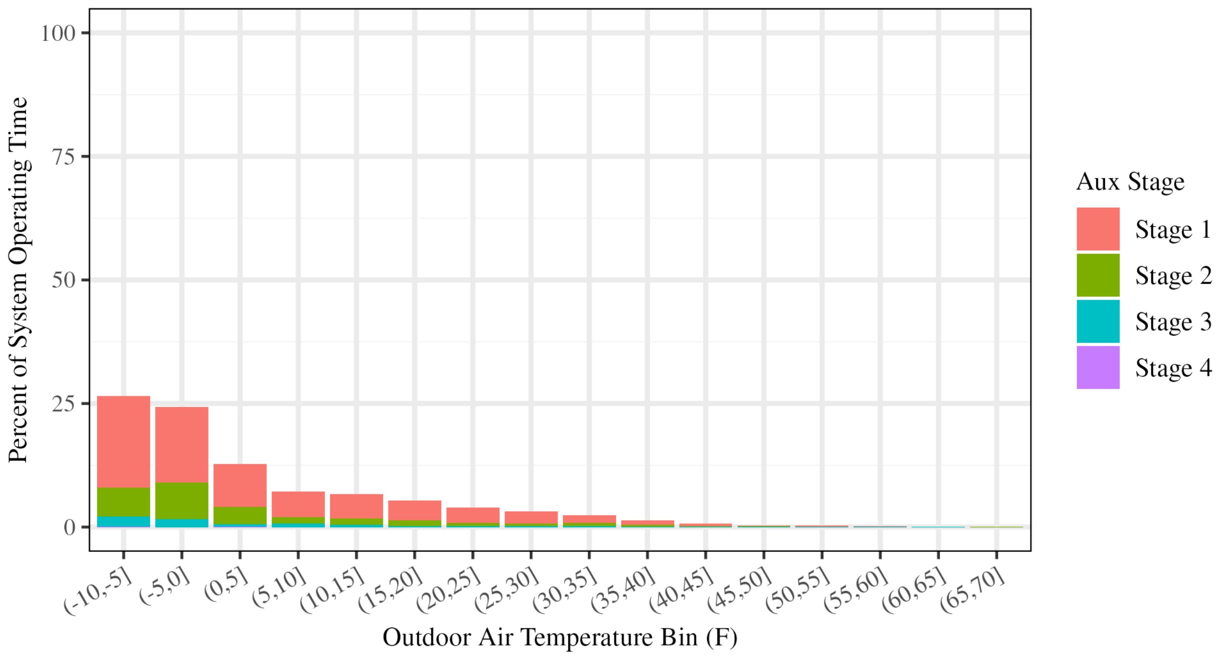

Figure 2. Percent of Time at Each Auxiliary Stage (Defrost Excluded) for All Sites by OAT Bin.

The first stage of auxiliary heat is observed to be the most prominent across all OAT bins, with the higher stages being engaged at the colder temperature bins. The coldest OAT bins (-10 to 0 °F) are observed to utilize auxiliary heat for 25% of time. OATs based on less than five sites are removed to reduce bias; however, it should be noted that the two coldest bins have a sample size of 8 and 11 respectively out of the total 22 sites. Stage 4 auxiliary heat operation was observed to be negligible overall (less than 0.001%) and only occurred at the coldest OAT bin.

Switchover temperature is the outdoor air temperature at which the CCHP goes from operating in HP-only heating mode to needing some supplemental auxiliary heat in addition to the heat provided by the HP. Switchover temperatures are critical to both occupants and utilities because they impact utility bills for the former and electricity demand planning for the latter. Typically, the switchover temperature setpoint is programmed into the thermostat and controls the maximum outdoor air temperature below which the CCHP may call for auxiliary heat. Thus, it is based on the capability of the CCHP to provide HP-only heat at cold outdoor air temperatures. Advanced CCHPs such as those developed through the Challenge and evaluated in this field study can continue to extract heat from outdoor air at much colder temperatures than their conventional counterparts. This extends the efficient HP-only mode operation to much colder temperatures and lowers auxiliary heat use.

The research team did not have access to the thermostat information. Thus, data collected from the field was used to determine the switchover temperature based on when each unit was observed to switch to auxiliary support. This temperature was observed to be different for different sites, even within the same manufacturer group, indicating that there were other variables affecting the switchover temperature. The team attributes these differences to be most likely due to differences in thermostat programming and occupant behavior driving calls for auxiliary heat at higher OATs. Further research on switchover temperature controls and occupant behavior may help shed light on the main contributors to this difference and ensure that American homeowners are getting the full benefit of heat pump technology.

Research regarding occupant satisfaction was also conducted, though utility billing analysis was not a part of the research scope. In participant satisfaction surveys conducted in the second year of the study, satisfaction with the prototypical units increased for both heating and cooling compared to pre-installation surveys, with roughly 75% of homeowners increasing or maintaining their satisfaction ratings for both heating and cooling. For heating, the average satisfaction rating increased from 3.61 to 3.88 on a scale of 1 to 5 (with 1 corresponding to “not satisfied at all” and 5 corresponding to “extremely satisfied”). For cooling, the average satisfaction rating increased from 3.61 in the pre-installation survey to 3.86 in the 2024 cooling survey. Between the 2023–2024 heating season and 2024 cooling season, 13 out of 14 homeowners maintained or increased their satisfaction, suggesting that there were no widespread issues with CCHPs during the cooling season.

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Members of the measurement and verification teams include Joel Pertzsch, Eric O’Neill, Jake Millette, Liz Balvanera, and Zack Thompson at Michaels Energy, and Jordan Pratt, Meg Waltner, and Andy Krall at Energy350.

Acronyms and Abbreviations

AHRI	Air-Conditioning, Heating and Refrigeration Institute
AIM	American Innovation and Manufacturing Act
ASHP	air-source heat pump
BTO	Building Technologies Office
CCHP	cold climate heat pump
COP	coefficient of performance
DOE	Department of Energy
DR	demand-response
GWP	Global warming potential
HFC	hydrofluorocarbon
HP	heat pump
HSPF	Heating Seasonal Performance Factor
HVAC	heating, ventilation, and air conditioning
HVAC&R	heating, ventilation, air conditioning, and refrigeration
MITO	maximum indoor temperature offset
NREL	National Renewable Energy Laboratory
NRCan	Natural Resources Canada
OAT	outdoor air temperature
PFAS	poly-fluoroalkyl substances
PNNL	Pacific Northwest National Laboratory
SEER	Seasonal Energy Efficiency Ratio
TRM	Technical Resource Manual
VFD	variable frequency drive

Contents

Figures

Tables

1.0 Introduction

This report summarizes the field validation results of the U.S. Department of Energy's (DOE's) Building Technologies Office (BTO) Cold Climate Heat Pump Technology Challenge (the Challenge) for residential cold-climate heat pumps (CCHP). The Challenge focuses on the development and laboratory testing CCHP prototypes with new and advanced performance capabilities, followed by field validation at test sites across the United States and Canada.

The Challenge launched in 2021 with the development of Challenge specification, which outlined key performance characteristics to advance the performance of CCHP technologies above that of currently available products at the time while also continuing to meet consumer and stakeholder expectations (DOE 2021). The Challenge specification focused on residential, centrally ducted, electric-only heat pumps. Table 1 presents a summary of the Challenge specification, and Table 2 summarizes the electric heat staging requirements. Products with heating capacity greater than 48,000 Btu/hr have a slightly lower coefficient of performance (COP) target than those having capacities less than 48,000 Btu/hr based on the physical constraints that larger systems face during installation in existing homes, which can affect system performance.

Table 1. Summary of the Challenge Specification.

HP nominal capacity (Btu/h)[1]	**Seasonal Heating Performance**		**Heating at 5 °F (−15 °C)**				**Heating at −15 °F (−26 °C) *(optional)***	
	Min. Heating Seasonal Performance Factor 2	**Min. turn-down ratio**	**COP at 5 °F (−15 °C)**	**Capacity ratio**	**Low-temperature compressor cut-out at 5 °F (−15 °C)**	**Low-temperature compressor cut-in at 5 °F (−15 °C)**	**Low-temperature compressor cut-out at −15 °F (−26 °C)**	**Low-temperature compressor cut-in at −15 °F (−26 °C)**
≥24,000 and ≤36,000	8.5 * (1 + capacity factor[2]) * (1 + COP factor[3])	30%	2.4	100%	≤ −10 °F (−23 °C)	≤ −5 °F (−21 °C)	≤ −20 °F (−29 °C)	≤ −15 °F (−26 °C)
>36,000 and ≤48,000			2.4	100%				
>48,000			2.1	100%				

[1] Capacity for the A2 test of Appendix M1 for a heating/cooling heat pump. Capacity of the $H1_N$ test of Appendix M1 for a heating-only heat pump.

[2] Capacity factor: 1% for every 10% $H1_1/H1_N$ gap. The capacity factor for northern triple capacity HPs is 0.

[3] COP factor: 2% for every 10% excess COP gap between the expected COP reduction and the measured COP reduction from the $H1_1$ verification test and the $H1_1$ regulatory test.

Additional Requirements:

(1) Unit(s) shall comply with electric heat staging requirements as set out in the Challenge specification (reproduced in Table 2 below).

(2) Unit(s) refrigerant shall have a Global Warming Potential (GWP) no greater than 750 (AR4 100-year).

(3) Unit shall comply with Sections 3C, 4B, 4C, and 4D of the ENERGY STAR Central Air-Conditioner and Heat Pump (CACHP) specification.

Table 2. The Challenge Electric Heat Staging Requirement.

Electric Heat (kW)	Minimum Number of Electric Heat Stages
>0 and ≤5	1
>5 and ≤10	2
>10 and ≤15	3
>15	3

Eight manufacturers developed prototype units that successfully demonstrated performance adhering to the Challenge specification at Oak Ridge National Laboratory or a similar third-party laboratory in 2022 and 2023. These prototypical units were installed in the field, along with sensors and loggers to monitor performance, in either winter 2022–2023 (Round 1) or winter 2023–2024 (Round 2). CCHP installation timing was driven by several factors, including the following:

- Date of completion of lab testing (ranged from October 2022 to December 2023)
- Major holidays in November, December, and January, when homeowners preferred not to have major home projects conducted
- Dates of shipments of test units to home sites
- Availability of local heating, ventilation, and air conditioning (HVAC) installer (after successfully submitting an installation quote for the work)
- Date of Natural Resources Canada (NRCan) facilities availability.

1.1 Challenge Participants

Manufacturers that committed to the Challenge by developing prototype units, passed laboratory testing, and successfully completed field validation include Bosch, Carrier, Daikin, Johnson Controls, Lennox, Midea, Rheem, and Trane Technologies. Additionally, nine state agencies[1] and 19 utilities and cooperatives[2] partnered with the Challenge to learn more about the results of the field validation and incorporate findings as appropriate for their locations.

Ultimately, 22 units successfully completed the field validation effort in the United States and Canada. All units installed in the United States were located in occupied homes; units in Canada were installed in a mix of occupied homes and laboratory homes. Data collected through monitoring was cleaned and stored in a secure database. The data was analyzed for calculating the key metrics defined by the Challenge, including delivered heating output at low

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[1] State agencies include the 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, and the Public Service Commission of Wisconsin.

[2] Utility and cooperative partners include 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), and Xcel Energy (CO, MN, and several other states).

outdoor air temperatures (OATs; below 32 °F), efficiency in terms of the COP, switchover temperatures, and auxiliary heat staging. Demand-response (DR) capabilities were also tested using specially designed DR events. Shoulder season and cooling season performance was also collected and evaluated over summer and fall of 2023 and 2024.

Throughout this paper, the phrase "the project team" will be used to describe the efforts of staff from Pacific Northwest National Laboratory (PNNL), Guidehouse, two measurement and verification sub-contractors, and multiple HVAC installation sub-contractors.

1.2 Comparative Review of Field Evaluations of Cold Climate Heat Pumps

The Challenge field validation effort joins a body of work evaluating the performance of heat pumps in the real world. Previous entities have completed field validations for CCHPs, including the Center for Energy and Environment, Eversource, NYSERDA, and others. Table 3 provides a high-level summary of similar studies of ducted, air-source heat pump (ASHP) field validations and key findings on performance (as measured in COP and capacity maintenance). Several of these studies were completed after the Challenge specification had been developed and the prototype units were in the field.

Table 3. Comparison of Air Source and Ducted CCHP Field Demonstrations

Study	Year	Ducted HP Tested	Location	COP (5 °F)	Capacity Maintenance at 5 °F
Cold Climate Air Source Heat Pump (CCASHP) – CARD	2017	4 ducted units	MN	1.75 (site 4, 4 ton)	18,500 Btu/hr (39%) (site 2, 4 ton)
Eversource Air Source Heat Pump Case Study	2024	12 ASHP (ducted and multi-split)	MA	2.2 (ducted)	21,000 Btu/hr (78%) (ducted)
Residential CCASHP Building Electrification Study - CADMUS	2022	11 ducted CCHP	NY and MA	Season COP heating = 2.34	Not evaluated
Technical Study of New York State Heat Pump Performance	2024	72 CCASHP (11 ducted)	NY and MA	SEER 20.79; HSPF 11.65	Not evaluated

Note: HSPF is the Heating Seasonal Performance Factor. SEER is the Seasonal Energy Efficiency Ratio.

2.0 Specification and Laboratory Testing

Before the field validation effort was launched in 2022, DOE worked with Guidehouse, the National Renewable Energy Laboratory (NREL), Oak Ridge National Laboratory, NRCan, and manufacturers to refine the Challenge specification. The Challenge specification included performance targets, testing procedures, and project timelines. Partnerships with state energy agencies, utilities, and industry organizations to collaborate on the specification demonstrated that new generations of heat pump products developed to meet the requirements would help address an unmet market need.

The following list highlights key performance requirements in the Challenge, 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).
- Meets the following criteria in heating mode relating to the Challenge-specified OAT 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) to capacity at 47 °F (8.3 °C)
  - Compressor cut-in at ≤ −5 °F (-21 °C) and cut-out 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 at 47 °F (8.3 °C) ≥ 30%.
- Meets auxiliary electric heating staging requirements.
- Refrigerant must have a Global Warming Potential (GWP) of no more than 750 (100-year).
- Complies with specific connected product installation capability, communications, consumer feedback, and DR requirements set forth by the ENERGY STAR Product Specification for Central Air Conditioner and Heat Pump Version 6.0 (ENERGY STAR 2021). Specifically, the DR 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).

All participating CCHP units needed to validate performance at Oak Ridge National Laboratory or other approved facilities before moving on to field validation in winter 2022 or 2023. Laboratory testing used an enhanced test procedure that supplemented federal regulations (Appendix M1 to Subpart B of Part 430 "Uniform Test Method for Measuring the Energy Consumption of Central Air Conditioners and Heat Pumps"). This procedure evaluated critical cold-climate features, including demand defrost, auxiliary heat staging, and DR capabilities. As part of the laboratory testing (and later during the field validation), NREL simulated utility DR events, requiring systems to reduce power to 70% or 40% of rated load during general and critical curtailment events, respectively.

Key findings from laboratory testing include:

- All prototypes exceeded federal minimum cooling (14.3 SEER2) and heating (8.5 HSPF2 Region V) standards.
- Prototypes delivered ≥100% nominal heating capacity at 5 °F (-15 °C), reducing reliance on backup heating in cold conditions.
- All units maintained COPs above 2.1 or 2.4 at 5 °F (-15 °C), operating at more than double the efficiency of electric resistance heating.
- Several units demonstrated heating capability at -15 °F (-26 °C).
- All prototypes met advanced DR and connected product functionality requirements, utilizing variable-speed capabilities for power modulation during curtailment events.

3.0 Field Testing Methodology

Once each manufacturer's prototype CCHP met the Challenge specification in laboratory testing, the manufacturer was allowed to proceed with the field validation process.

3.1 Field Site Selection Approach

The process of identifying and selecting sites for field installations included several steps and spanned several months. First, each manufacturer identified a list of potential sites. The homeowners[1] at these sites were sent initial recruitment materials and surveys developed by PNNL through the Institutional Review Board process. The materials explained the terms of participating in the field study, along with a discussion of how PNNL would collect and protect the homeowner's Personal Identifiable Information. The materials also explained the expectations of the study and the participants' rights. The surveys collected high-level information about the home and existing heating systems.

The final qualification step included engaging qualified local HVAC contractors to conduct site visits and complete Air Conditioning Contractors of America Manual J, D, and S assessments, as well as electrical and duct assessments, to determine the suitability of the prototype units for installation in the home. Once all steps were complete, a final determination was made on the selection of the site. Where appropriate, project team members developed materials and worked with local building code agencies to finalize the installation preparations before installations were scheduled.

The homes selected for the study were located across the northern United States and Canada. All homes in the study were single-family residences occupied by homeowners. The only exceptions were the NRCan test facilities, which were unoccupied and utilized a simulated occupancy for the purposes of the study. The study sample included homes with varying levels of construction efficiencies. Unfortunately, the study design did not allow adequate time for conducting an evaluation of weatherization improvements or the impact of homeowner education on the performance of the CCHP units. However, the research team recognizes the importance of these elements on the overall optimal performance of the CCHP units and plans to evaluate these elements in Phase II of this research.

3.2 Data Collection Methods and Metrics

Airside measurements conducted during the field validation were used to calculate the COP during heating and cooling operation using the methods described in Mendon et al. (2024).

The heating performance is determined using the indoor unit mass flow rate (m_{air}), the heating capacity ($Q_{heating}$), and the heating COP ($COP_{heating}$)

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[1] The homeowners were employees or affiliates of the companies that manufactured the CCHP installed in their home.

The indoor unit mass flow rate (m_{air}) is given by:

$$\boldsymbol{m_{air} = \rho_{dry} V_{blower}} \tag{1}$$

where

$\boldsymbol{\rho_{dry}}$ is the dry air density (pounds of dry air per unit volume) of the return air

$\boldsymbol{V_{blower}}$ is the blower volumetric air flow rate, determined from an airflow vs. blower power correlation developed from measured data collected during the initial site installation

The heating capacity ($Q_{heating}$) is given by:

$$\boldsymbol{Q_{heating} = m_{air} C_{p,sup} (T_{sup} - T_{ret})} \tag{2}$$

$$\boldsymbol{C_{p,sup} = 0.24 + 0.444 * \omega_{sup}} \tag{3}$$

The latent load resulting from the difference in supply and return air humidity was included in cooling output calculations, whereas for heating it is expected to be negligible. The cooling capacity ($Q_{cooling}$) is given by:

$$\boldsymbol{Q_{cooling} = \ -1 * m_{air} (h_{sup} - h_{ret})} \tag{3}$$

$$\boldsymbol{h_{sup} = [0.24 * T_{sup} + \omega_{sup} * (0.444 * T_{sup} + 1,075)]} \tag{4}$$

$$\boldsymbol{h_{ret} = \ [0.24 * T_{ret} + \omega_{ret} * (0.444 * T_{ret} + 1,075)]} \tag{5}$$

where

$\boldsymbol{m_{air}}$ is the air mass flow rate (lb da/h) from Equation (1)

$\boldsymbol{C_{sup}}$ is the specific heat capacity of the supply air, Btu/(°F-lb)

$\boldsymbol{h_{sup}}$ is the enthalpy of the supply air, Btu/lbm

$\boldsymbol{h_{ret}}$ is the enthalpy of the return air, Btu/lbm

$\boldsymbol{T_{sup}}$ is the temperature of the supply air, °F

$\boldsymbol{T_{ret}}$ is the temperature of the return air, °F

ω_{sup} is the humidity ratio of the supply air, lb of water vapor/lb of dry air

ω_{ret} is the humidity ratio of the return air, lb of water vapor/lb of dry air.

The heating COP is given by:

$$COP_{heating} = \frac{Q_{heating}}{3.412 * P_{total,heating}} \tag{6}$$

where

$Q_{heating}$ is the heating capacity of the unit calculated using Equation (2), Btu/h

$P_{total,heating}$ is the sum of the measured outdoor unit, indoor unit, and auxiliary heater power, W

The COP for cooling can be calculated similarly by substituting $Q_{heating}$ for $Q_{cooling}$:

$$COP_{cooling} = \frac{Q_{cooling}}{3.412 \ * \ P_{total,cooling}} \tag{7}$$

where

$Q_{cooling}$ is the cooling capacity of the heat pump calculated using Equation (3), Btu/h

$P_{total,cooling}$ is the sum of the measured outdoor unit and indoor unit power, W

4.0 Field Testing Results

This section describes the overall trends in field performance across the sites studied. CCHPs were installed at the sites in Winter 1 (between November 2022 and February 2023) or Winter 2 (between October and December 2023). Most Winter 1 sites were monitored through September 2024 with four Winter 2 sites continuing monitoring through early 2025. Data collected through October 31, 2024, is used for analysis described in this report. An update with additional data collected at the remaining four sites will be developed later in 2025.

Table 4 summarizes the amount of data available for each site. For each site, the table shows the installation date (Winter 1 or Winter 2), the number of weeks monitored within the overall study period (December 2022 to October 2024), the hours of usable heating data and cooling data available (excluding data with operational issues and M&V data gaps). The total number of hours of operational issues are noted separately. These include extended periods where the heat pump did not work as intended and the unit relied on supplemental heat to provide the required heating load. These instances often needed manufacturer and HVAC contractor intervention for resolution. The CCHPs installed in this study are pre-commercial units and it is expected that data from the field validation will help manufacturers identify and improve their systems in the final commercialized products. Thus, these periods are excluded from the performance results in this section.

Table 4. Summary of Data Availability for Each Site.

Site ID	Installation Date	Weeks Monitored	Hours of Heating Data	Hours of Cooling Data	Hours of Operational Issues
0734BD	Winter 2	40	3,099	743	-
1145KG	Winter 2	41	2,447	1,027	-
1931ZB[1]	Winter 2	20	1,371	268	-
2089ZA[2]	Winter 2	45	823	313	-
2458CE[1]	Winter 1	10	898	0	-
2563EH	Winter 1	85	1,908	1,604	-
3176UL[3]	Winter 1	46	1,364	836	1,105
3669NT	Winter 2	38	2,417	668	-
4228VB	Winter 1	71	2,553	141	422
4958IQ	Winter 2	47	1,966	1,257	-
5193YW	Winter 2	48	2,964	588	-
5291QJ[1]	Winter 1	18	1,375	0	-
5539NO	Winter 1	83	999	2,078	1,754
5878ZD	Winter 2	40	1,457	528	-
6112OH	Winter 1	78	3,630	714	273
6950NE	Winter 1	91	3,581	1,321	-
7083LM[3]	Winter 1	55	2,699	71	66

Site ID	Installation Date	Weeks Monitored	Hours of Heating Data	Hours of Cooling Data	Hours of Operational Issues
7646TQ	Winter 2	45	2,515	1,145	-
7750UJ	Winter 2	39	2,734	1,233	-
8220XE	Winter 1	91	3,130	2,206	-
8726VB	Winter 1	79	2,219	1,152	-
9944LD	Winter 1	89	2,541	395	3,444

[1] These sites were operated during limited testing windows during the winter only.

[2] The fan power curve for this site does not cover the full range of fan speeds observed in the field due to operational changes made after the fan power test, and so only the times where the fan power is within the range of the testing conditions are included for heating.

[3] These Winter 1 sites experienced delays during install and/or M&V set up and have less data available than the other Winter 1 sites.

Table 5 looks more specifically at HP-only operation for both heating and cooling excluding auxiliary heating and defrost operation. It shows the number of hours of HP-only data available within each outdoor air temperature bin for each site. All sites have a significant amount of HP-only data between 10 °F and 90 °F except for 2458CE, 5291QJ, and 7083LM which do not have summer data available.[1] Many sites experienced somewhat mild winters with only eight of the 22 sites having 10 or more hours of heating data below 0 °F.

Table 5. Summary of Data Availability (in Hours) for HP-only Heating and Cooling by Outdoor Air Temperature Bin.

Site ID	-10 °F and Below	-10 °F to 0 °F	0 °F to 10 °F	10 °F to 20 °F	20 °F to 30 °F	30 °F to 40 °F	40 °F to 50 °F	50 °F to 60 °F	60 °F to 70 °F	70 °F to 80 °F	80 °F to 90 °F	90 °F to 100 °F	100 °F and above
0734BD		17	116	154	758	1,097	671	140	182	407	150	2	
1145KG			40	87	488	1,112	496	178	277	487	239	10	
1931ZB		10	91	343	430	312	35	28	84	87	62	18	
2089ZA			6	43	187	277	116	33	114	128	59	2	
2458CE		1	44	124	285	325	42	6					
2563EH		12	26	152	530	784	373	310	596	411	250	32	
3176UL		17	19	12	95	485	267	125	75	324	425	41	
3669NT		4	56	111	527	1,067	445	127	257	324	64		
4228VB		6	23	133	719	932	358	76	62	46	21	16	5
4958IQ		9	54	104	448	915	317	92	326	630	262	4	
5193YW			35	189	795	1,297	458	150	184	297	105	1	

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[1] 2458CE and 5291QJ were installed at the NRCan test facility which had limited availability beyond winter seasons. The 7083LM site conducted major renovations (unrelated to the study) in summer 2023, thus limiting cooling season data available from that site.

Site ID	-10 °F and Below	-10 °F to 0 °F	0 °F to 10 °F	10 °F to 20 °F	20 °F to 30 °F	30 °F to 40 °F	40 °F to 50 °F	50 °F to 60 °F	60 °F to 70 °F	70 °F to 80 °F	80 °F to 90 °F	90 °F to 100 °F	100 °F and above
5291QJ	30	30	107	256	430	379	31	4					
5539NO				61	283	380	172	106	531	1087	377	2	
5878ZD				23	172	843	271	49	52	292	170	15	
6112OH			12	197	868	1,679	1,059	293	297	263	157	9	
6950NE	22	108	171	262	806	1,194	448	69	121	486	615	88	
7083LM			7	151	582	1,166	415	48	17	8	1		
7646TQ			8	135	465	959	556	266	276	417	293	115	16
7750UJ		2	50	86	345	1,119	754	257	138	571	444	108	
8220XE		91	199	258	582	889	394	301	842	750	467	50	
8726VB			28	224	669	993	512	145	182	493	366	87	26
9944LD	12	17	34	227	526	843	490	89	54	164	134	33	1

4.1 Heating and Cooling Efficiency

Figure 3 shows the range of COP for heating and cooling mode calculated using airside measurements taken in the field. This plot shows data for HP-only heating and cooling (i.e., excluding periods with auxiliary heat or defrost) and each data point used for the plot represents the average COP for one site for one temperature bin. Data points that are based on less than five hours of operation are omitted. The sample size (number of sites with sufficient data) for each boxplot is listed above the boxplot.

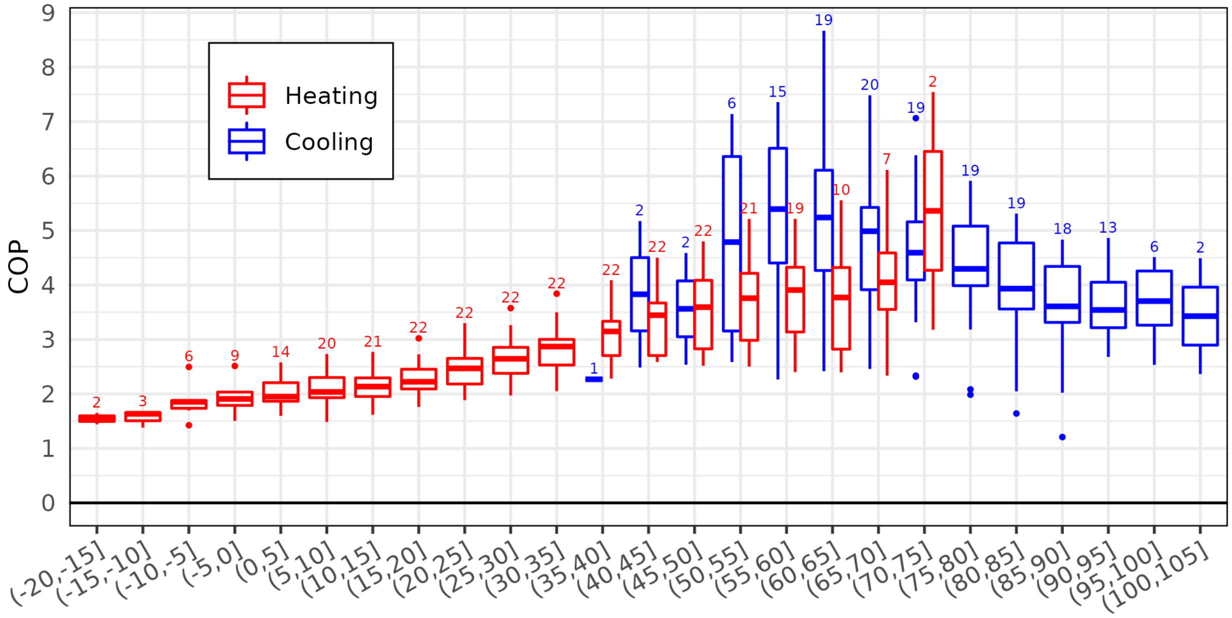

Figure 3. COP for HP-Only Cooling and Heating by Outdoor Air Temperature (OAT) Bin.

Heating COPs were observed to be more tightly clustered at colder temperatures and observed to increase steadily with increasing outdoor air temperature (OAT). The median heating COPs across all sites at cold temperatures (below 30 °F) are in the range of 1.6 to 2.7 with overall median heating COPs ranging from 1.6 to 5.2. Both heating and cooling have a wide range of COPs at moderate OATs (50 - 75 °F). The cooling COPs are overall more disperse than the heating COPs and medians range from, 1.4 to 5.4. Two sites were observed to call for cooling at much cooler OATs below 50 °F and are observed to have low COPs at those temperatures. These were associated with occupant preferences for nighttime cooling. Excluding these temperature bins, the median cooling COP values across all sites and temperature bins range from 3.4 to 5.4.

Figure 4 shows the same HP-only mode heating COP boxplots as the previous figure but has an additional set of boxplots for COP values for times with auxiliary support as well, or the overall system COP. This graph excludes defrost operation and data points that are based on less than five hours of operation are omitted. The sample size (number of sites with sufficient data) is list for each boxplot is listed above the boxplot.

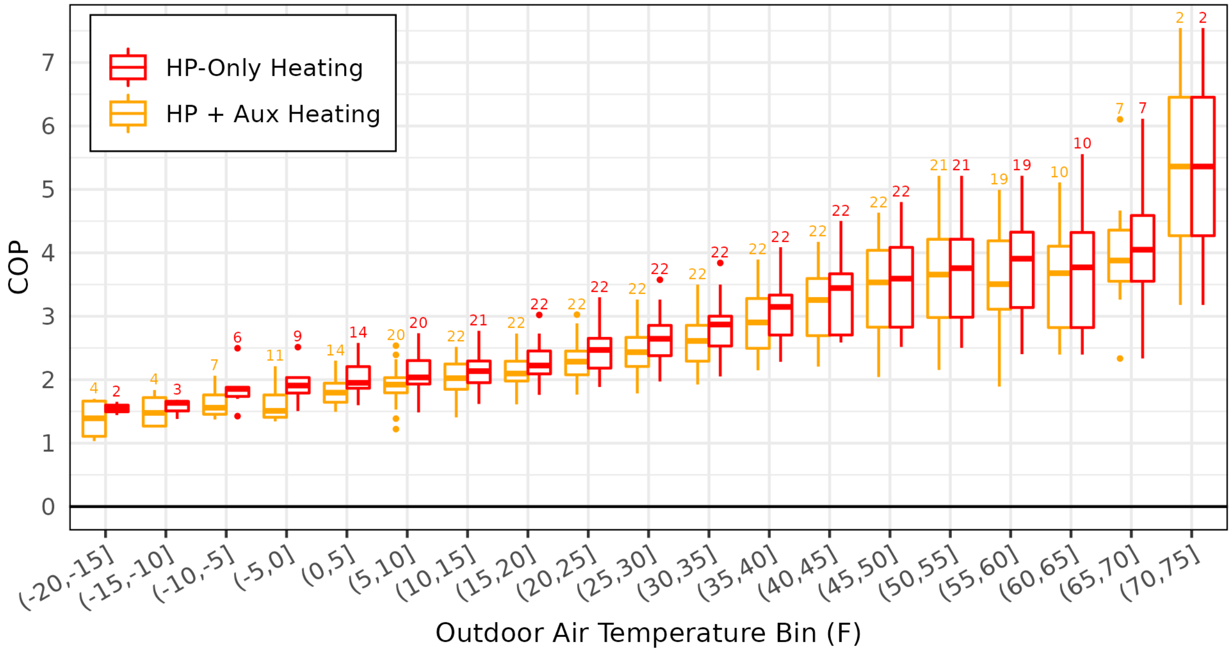

Figure 4. Heating COP for HP Only and With Auxiliary Support by OAT Bin.

The overall system COPs are observed to be lower than the HP-only COPs especially at lower OATs, signifying a higher contribution of auxiliary heat. As OATs become higher, the two boxes align more closely indicating diminishing contribution from auxiliary heat.

The COPs shown in Figure 3 and Figure 4 are calculated based on airside measurements taken during the field study. The supply air temperature was measured using a grid of supply air temperature sensors placed in the supply duct. The average of all readings during the timestep was used in calculations. It was observed that the temperature measurements reported by some supply air temperature sensors were consistently higher from those reported by other supply air temperature sensors in the same duct when the auxiliary heat element was active. Some sites consistently had up to a 20 °F to 30 °F difference. This difference in supply air temperatures between sensors in the same duct was not observed to be prominent when auxiliary heat elements were not active, i.e., the CCHP was operating in HP-only mode. Thus, the difference in temperature readings was potentially due to radiant heat picked by the sensors during periods of auxiliary heat. This difference was more common when placement of the sensors was restricted by the configuration of the ductwork. Averaging the readings taken by all sensors is expected to abate some of the bias in calculations; however, it is noted that averaging would not remove all the bias and thus the COPs calculated for auxiliary heat periods must be considered accordingly.

4.2 Electricity Demand

Figure 5 shows the power draw of the CCHPs at observed OAT bins, normalized by the capacity of the CCHP. Most units installed in the field study were 3 tons with one 4-ton, three 4.5 ton, and one 5-ton units involved. Data for all units are combined in the figure. Each data point is the average value for the data available for that site and OAT bin including defrost, cooling, heating, system idling, and system off. Both boxplots include fan power. Data points based on less than ten hours of available data are removed. The sample size for each boxplot (number of sites with sufficient data) is listed just above each box.

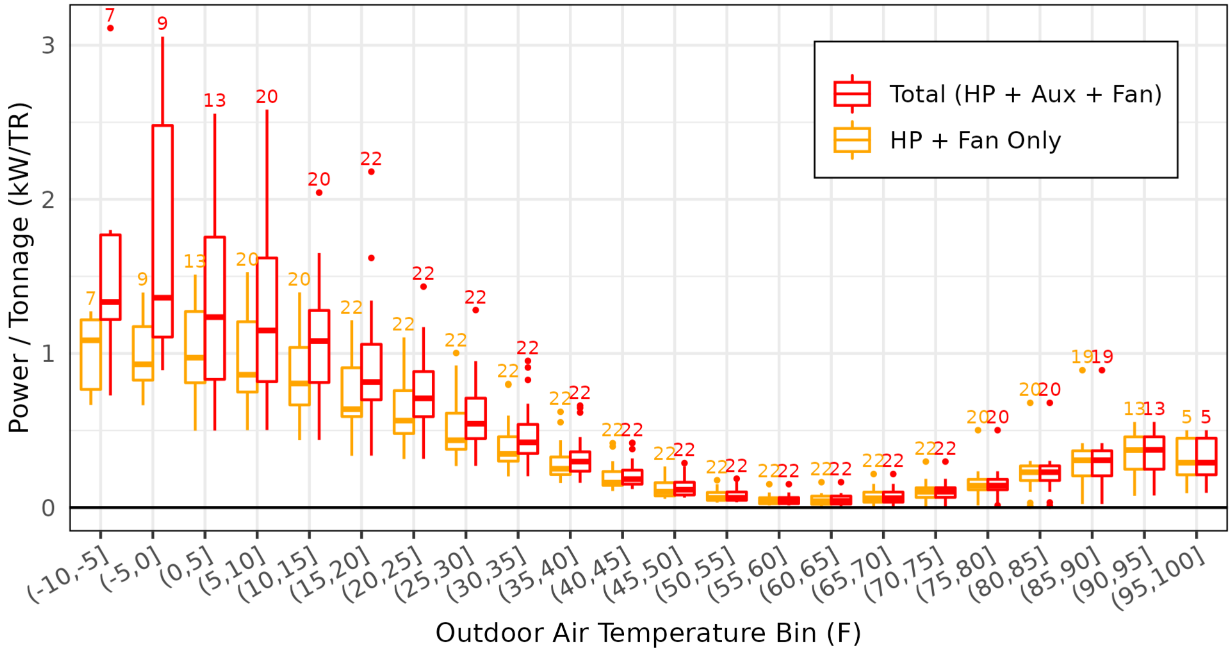

Figure 5. CCHP Input Power per ton by OAT Bin with and without Auxiliary Support.

Over the range of cold OATs (below 30 °F) observed during the analysis period, the median input power across all sites in HP-only mode is in the range of 0.5 to 1.1 kW/TR. This can be compared to a total power draw of 0.6 to 1.4 kW/TR including auxiliary heat. The input power reduces significantly at moderate OATs and then starts increasing again as the units go into cooling mode. The magnitude of values at cooling OATs is overall lower than the values seen in heating mode at cold OATs.

4.3 Heating and Cooling Output

Most of the CCHP prototypes in the study sample were 3-tons (36,000 Btu/hour) in capacity, with one 4-ton unit (48,000 Btu/hour), three 4.5-ton units (54,000 Btu/hour), and one 5-ton unit (60,000 Btu/hour). As described in Chapter 3, load calculations were conducted for all sites using Air Conditioning Contractors of America Manual J to ensure that the CCHP prototypes would adequately provide the required heating and cooling upon installation.

Airside data collected during the monitoring period were used to calculate heating output provided by the CCHPs using supply and return air temperatures and the volumetric airflow based on fan power measured at each timestep. Figure 6 shows the observed heating output, with and without auxiliary heat at very cold temperatures, defined as 0-10 °F, across all sites in the study sample. Only sites with at least five hours of HP-only heating for the HP-only bar and five hours of total heating for the auxiliary plus HP bar in this temperature range are included in this plot. The bars show the mean observed heating output at each site while the black vertical line shows the 10th-90th percentile range of the observed heating output.

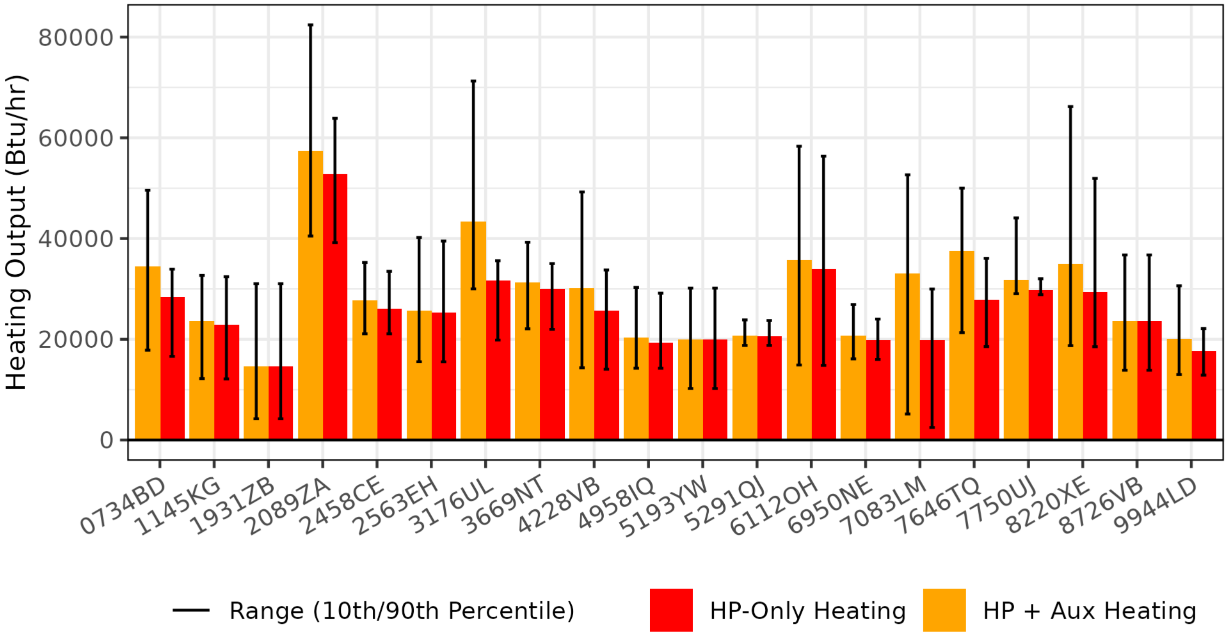

Figure 6. Heating Output Calculated Using Airside Measurements at Temperatures 0 - 10 °F.

Site 7646TQ has a 4-ton unit, sites 2563EH, 6112OH, and 8726VB have 4.5-ton units, site 2089ZA has a 5-ton unit, and the rest of the sites have 3-ton units. Sites 2089ZA and 6112OH have the two highest HP-only average heating output values. The other larger units have average values like the smaller units but have higher 90th percentile values. This means that for most of the operation, these units did not need the additional capacity afforded by the larger CCHP. For many sites, the observed average HP-only heating output was much lower than the maximum capacity of the unit for the shown temperature range. However, the 90th percentile values for HP-only heating were observed to be close to the maximum capacity of the CCHP for most if not all sites. As noted previously, Winter 2 was milder than what usually is typical in many parts of the country. Thus, the CCHPs were not subjected to heating demand as are typical for these locations and data at very cold temperatures was limited for many Round 2 sites.

One site (8220XE) was observed to have much higher heating output values than other comparable units, with 90th percentile values exceeding the capacity of the unit. The research team observed that this unit had higher estimated volumetric airflow rates compared to comparable units which could be the reason for the higher heating output values. The fan power curve was retested at the end of Year 1, but no noticeable differences were found between measurements taken at the beginning of the study. It is likely that the airflows at the site are still being overestimated. However, in absence of better measurements or explanation, the team continued to use the fan curve generated.

Several sites have heat output values (mean value or 90th percentile) including auxiliary heat that are higher than for HP-only at the cold temperatures shown (0 - 10 °F)—0734BD, 2089ZA, 3176UL, 4228VB, 7083LM, 7464TQ, and 8220XE—suggesting a common need for some auxiliary support at low temperatures; however, all sites have a high HP-only output at this temperature range and the additional auxiliary support is a small fraction of the total output. For some sites, some minor auxiliary use has been noted to be triggered by night setbacks or manual setpoint changes by the occupants rather than the ability of the CCHP to meet the thermal demand. This could be contributing to the elevated “HP + Aux” output.

Data was collected through the cooling season was analyzed to evaluate cooling output provided by the CCHPs, and the results at very warm temperatures, defined as 85-95 °F, are shown in Figure 7. Only sites with at least five hours of cooling operation in this temperature range are included in this plot. The bars show the mean observed cooling output at each site in this temperature range while the black vertical line shows the 10th-90th percentile range of the observed cooling output.

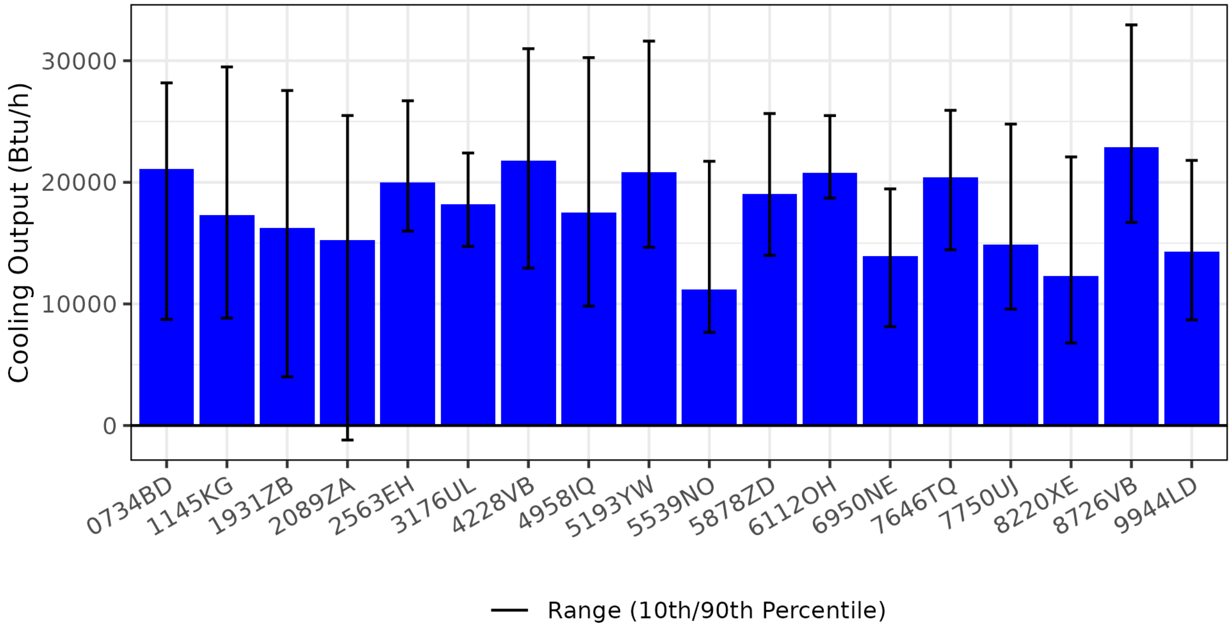

Figure 7. Cooling Output Calculated Using Airside Measurements at Temperatures 85 - 95 °F.

The observed cooling output is between 10,000 and 25,000 Btu/hour across the sites that experienced warm OATs and the peak output ranges from 20,000 to over 30,000 Btu/hour. Site 8726VB is one of the larger units and has the highest average and peak cooling output, but the other large units (2089ZA, 2563EH, 6112OH, and 7464TQ do not have notably larger cooling output values than the smaller 3-ton units. The cooling output values are overall lower than the HP-only heating output values from Figure 6, but some sites have a similar or slightly higher peak cooling output than peak heating output.

4.4 Auxiliary Heat Use

All CCHP prototypes included in the study had at least three, sometimes four, stages of auxiliary electrical heat where each element was controlled separately. The first stage was typically around 5 kW, and the total auxiliary heat capacity was around 15-20 kW for all CCHPs, depending on HP unit size. The staging allowed the CCHPs to optimize the amount of auxiliary heat while minimizing energy use. For example, most CCHPs that used auxiliary heat to maintain supply air temperatures during defrost mode only engaged the first stage of auxiliary heat, around 5 kW. When higher levels of auxiliary heat were required for supplementing the CCHP in meeting heating loads, staged control was utilized as a more efficient method than having one large, single-staged auxiliary element.

Figure 8 shows the contribution of auxiliary heat as a percentage of the total heating energy at various OAT bins. This chart does not include periods of defrost operation because some CCHPs did not utilize auxiliary heat during defrost mode, while some did. Auxiliary heat during defrost is discussed in the subsequent defrost operation section. Data for all sites are pooled together in this chart, obscuring some of the operational differences and variations in control strategies used by the various CCHPs in the study. Only data points that comprise at least five hours of total heating operation are included in the chart. The sample size (number of sites with sufficient data) for each boxplot is listed near the median.

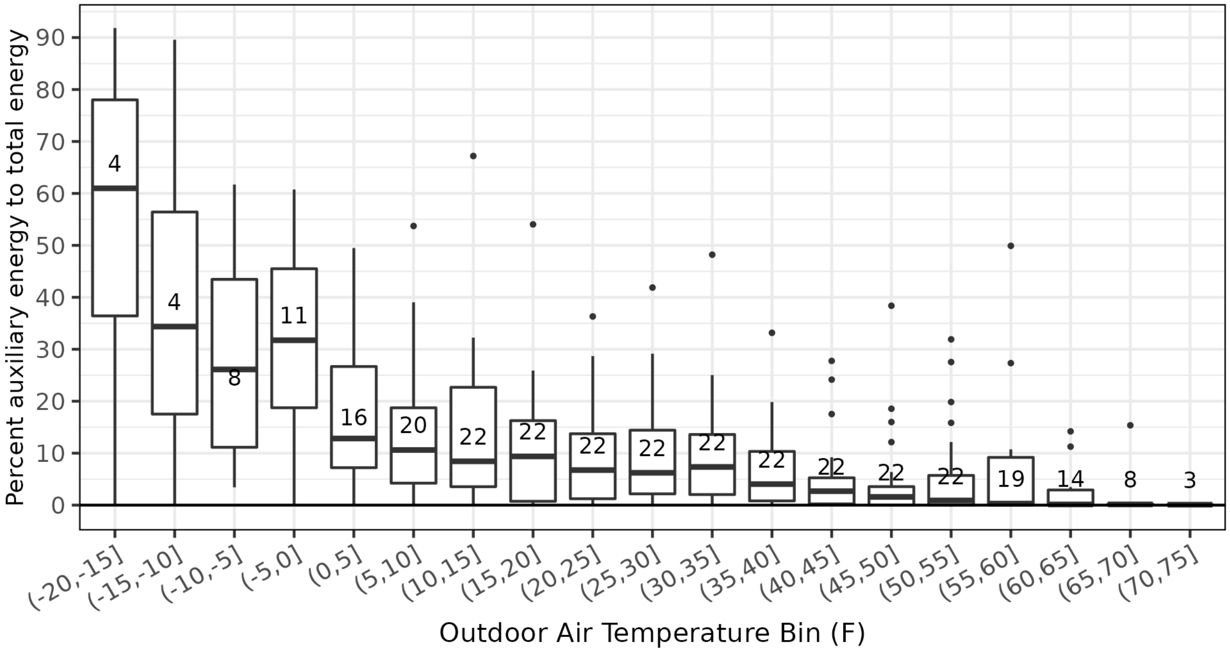

Figure 8. Auxiliary Energy Use (Defrost Excluded) for All Sites by OAT Bin.

For the OAT bins 5 °F and above, the median value decreases from around 11% at 5 °F to 0% at the highest OAT bins that have sufficient heating data to be included. Below 5 °F, the sample sizes (denoted by the number listed near the median) decrease. The data shows that auxiliary energy use increases significantly at these very cold temperatures, however, it is noted that three out of the four sites with data in the two lowest OAT bins had higher auxiliary energy use across all temperature bins compared to the remaining sites, and so it is possible that the sites that do have data at the coldest temperatures are biased to use more auxiliary heat than the average site.

Figure 9 shows the percentage of time each auxiliary stage is activated across the range of OATs observed in the study. Periods of defrost operation as well as periods of system idling or system off are excluded from this chart to only show the impact of auxiliary heat in supplemental mode during heating. Again, data from all sites are pooled together in the chart. To reduce bias, data for an OAT bin is shown only if it has at least 5 sites that each have at least 5 hours of total heating operation. Most units only have three stages of auxiliary heat.

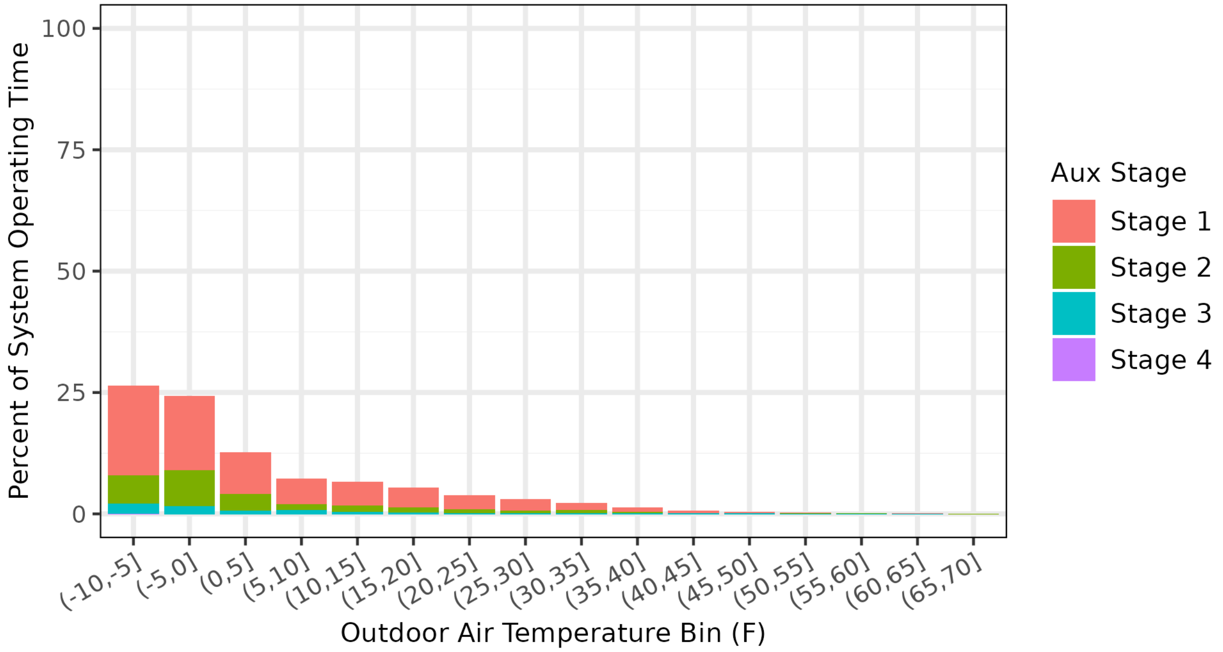

Figure 9. Percent of Time at Each Auxiliary Stage (Defrost Excluded) for All Sites by OAT Bin.

The first stage of auxiliary heat is observed to be the most prominent across all OAT bins, with the higher stages being engaged at the colder temperature bins. The coldest OAT bins (-10 to 0 °F) with sufficient data reach 25% of time across all sites with auxiliary elements engaged. OATs based on less than five sites are removed to reduce bias; however, it is to be noted that the two coldest bins have a sample size of 8 and 11 of the total 22 sites. Stage 4 auxiliary heat operation was observed to be negligible overall (less than 0.001%) and only occurred at the coldest OAT bin.

A more detailed evaluation of auxiliary heat for each site was shared with respective participating manufacturers. However, due to the variations in staging and limited data available at certain OAT bins, disaggregating data further will not allow the de-identification necessary for this report.

4.4.1 Switchover Temperature Trends

Switchover temperature is the outdoor air temperature at which the CCHP goes from operating in HP-only heating mode to needing some supplemental auxiliary heat in addition to the heat provided by the HP. Switchover temperatures are critical to occupants and utilities alike because they impact utility bills for the former and electricity demand planning for the latter.

Typically, the switchover temperature setpoint is programmed into the thermostat and controls the maximum outdoor air temperature below which the CCHP may call for auxiliary heat. Thus, it is based on the capability of the CCHP to provide HP-only heat at cold outdoor air temperatures. Advanced CCHPs such as those developed through the Challenge and evaluated in this field study can continue to extract heat from outdoor air at much colder temperatures than their conventional counterparts, thus extending the efficient HP-only mode operation to much colder temperatures and lowering auxiliary heat use.

Because the research team did not have access to the thermostat information, data collected from the field was used to determine the switchover temperature based on when each unit was observed to switch to auxiliary support. This temperature was observed to be different for different sites, even within the same manufacturer group indicating that there were other variables impacting the switchover temperature, most likely differences in thermostat programming and occupant behaviour driving calls for auxiliary heat at higher outdoor air temperatures than optimal for the CCHP. It was observed at most sites with high switchover temperatures (e.g., above 20 °F), the auxiliary heat tended to be a consistent time in the morning (suggesting that the occupants had implemented early morning temperature setbacks), or for a 20 to 30 minute period at the beginning of a heat cycle (potentially suggesting there was a manual setpoint change by the occupant). Without the availability of continuous setpoint data across sites, it is difficult to confirm these hypotheses.

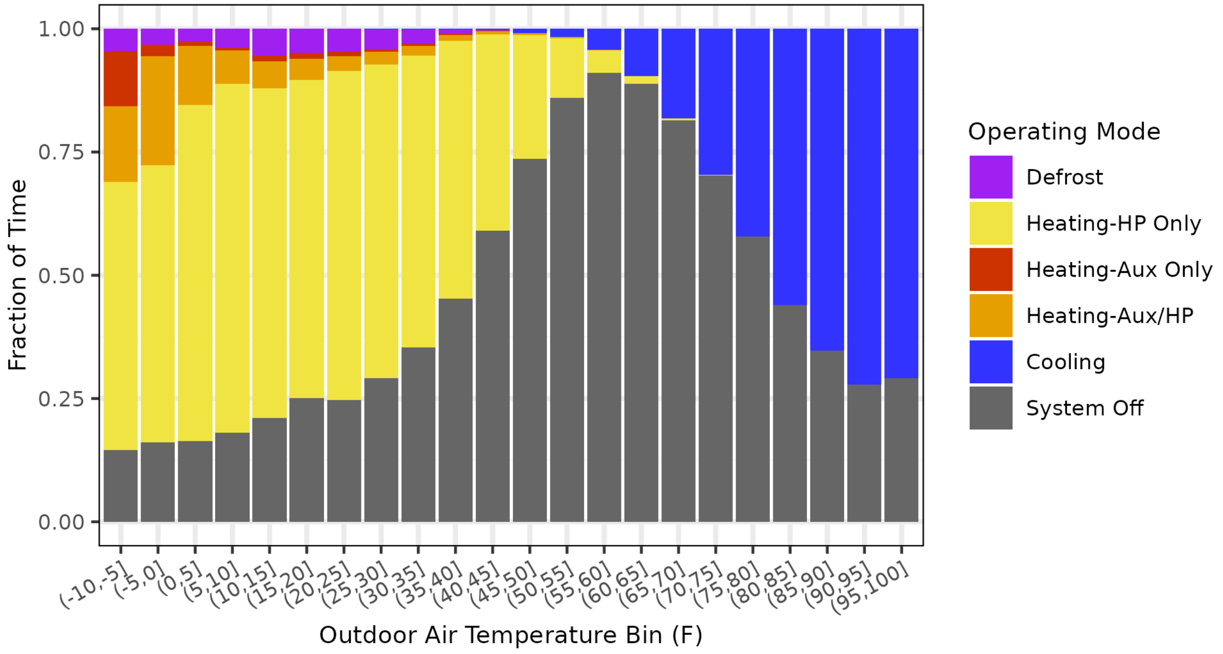

Figure 10. Overall Fraction of Time in Each Operating Mode by OAT Bin Across all Sites.

Figure 10 shows the overall distribution of operating models across all sites by OAT bin. The units are observed to primarily operate in HP-only mode even at the lowest OATs as indicated by the yellow-stacked bars. Overall, switchover temperatures were observed to be around 30-35 °F, indicated by the emergence of the orange-colored stacked bars representing supplemental heat support. However, auxiliary-only operation is observed to be minimal above 0 °F as indicated by the red-colored stacked bars. This means that while some auxiliary heat is needed for OATs between 0-35 °F, it is a small fraction of the heat provided by the unit in HP-only mode. A more typical switchover temperature for these CCHPs without homeowner setpoint interference, or with a static setpoint band, graduated setpoint transitions, or more intelligent setpoint transition controls, would likely be much lower than observed in the study.

4.5 Defrost Operation

When operating in cold climates under humid conditions, frost starts accumulating over time on the outdoor heat exchanger coils of the CCHPs as moisture from outdoor air begins to condense and freeze on the outdoor unit. This results in a loss of effective heat exchange and reduces the CCHP’s capability to extract heat from surrounding air for delivery into the conditioned space. This is typically remedied by reversing the flow of refrigerant through the reversing valve, thereby changing the operation mode of the CCHP to cooling. In this mode, the CCHP effectively rejects heat from the conditioned space to the outdoor air melting off the frost formation. This heat rejection from conditioned space during winter can result in a drop in supply air temperatures resulting in an impact on occupant comfort. To reduce this impact, some manufacturers use auxiliary heat to increase the temperature of the supply air. However, not all manufacturers use this strategy, and some rely on shorter defrost cycles or turning off the supply fan to minimize the impact on the comfort of the occupant.

The most common defrost strategy observed across the sample was to run the fan with the first stage of auxiliary heat. The second most common defrost strategy was running the fan with no auxiliary heat. The third most common strategy was to turn off the fan and not use auxiliary power during defrost. Most sites were observed to predominantly (more than 80% of defrost cycles) employ one of these three strategies throughout the monitoring period, and a few sites were observed to switch between these strategies part way through the study. Two sites were observed to consistently engage higher stages of auxiliary heat along with fan operation during defrost. For at least one of the sites, this behavior of directly engaging higher stages of auxiliary heat was observed during normal operation as well and was noted for the manufacturer team. The manufacturer team indicated that this was a controls problem and not intended operation. The research team anticipates that this issue will be resolved before the units are commercialized.

The impact of defrost on energy is two-fold: One, it temporarily increases the amount of work the CCHP must perform to overcome the induced cooling cycle, and two, it may result in additional auxiliary heat depending on the control strategy implemented by the CCHP. Energy expended during the defrost operation can be significant for CCHPs, especially when auxiliary heat is utilized for maintaining supply air temperatures during the defrost cycle for occupant comfort. Figure 11 shows the defrost energy as a percentage of total energy use for all sites binned by outdoor air temperature as a metric for both defrost prevalence (more time spent in defrost will result in more energy use) and magnitude (more auxiliary elements engaged or greater HP cooling power will result in more energy use). Only data points that comprise at least five hours of total heating operation are included in the chart. The sample size (number of sites with sufficient data) for each boxplot is listed near the median.

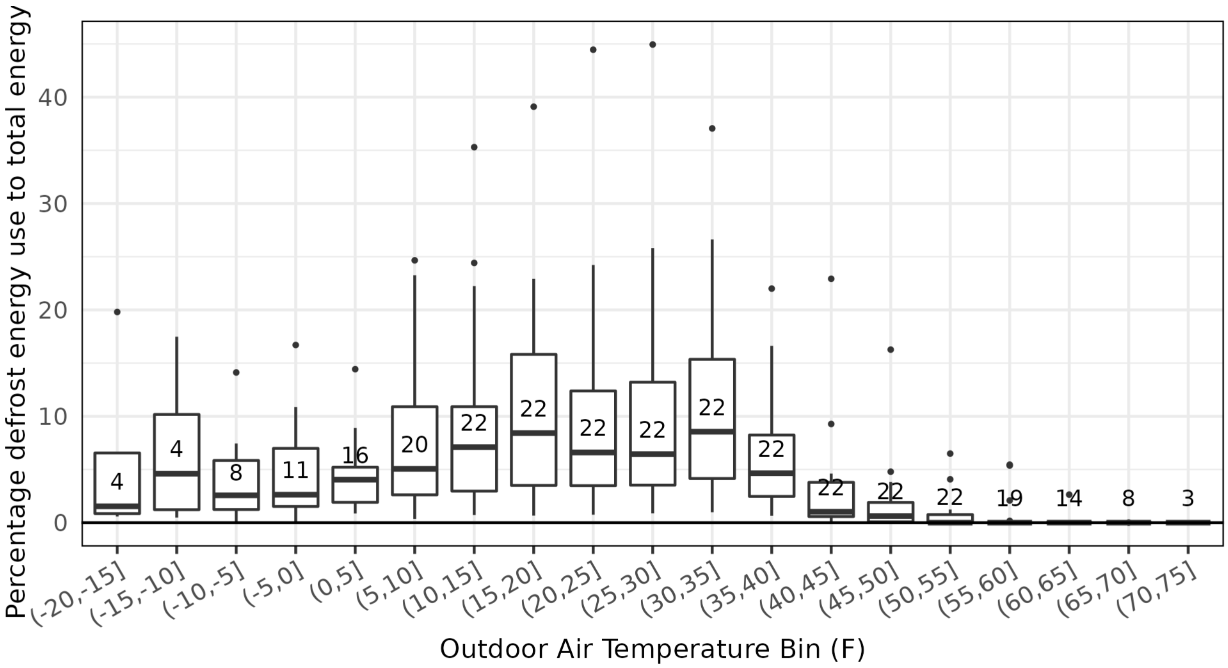

Figure 11. Defrost energy use by Outdoor Air Temperature.

It is noted that energy used during defrost is not a perfect indicator of the energy penalty caused by defrost operation. For example, a unit that is pre-programmed to use auxiliary heat during defrost may supply more heat than cooling impact during defrost, thereby reducing the heating demand in the period directly following defrost. On the other hand, a unit that does not use auxiliary heat will have an additional heat burden following defrost that is difficult to separate from the regular heating load. Under the conditions of this field study where we cannot consistently separate HP heat output from auxiliary heat output and we cannot control defrost operation, it is not possible to have a perfect indicator of defrost energy use.

Across the board, defrost was observed to be more energy intensive at OATs between 5 and 35 °F, and the median percent of energy expended at these OAT bins was between 5% and 8%. This is a small portion of total energy use. Some sites used significantly more energy during defrost than other sites. These were sites that used auxiliary heating during defrost and spent a greater portion of time in defrost mode. All the outliers shown in the figure below 35 °F are from one site. This site spends a large portion of time in defrost mode compared to other sites (16% of time on average under 40 °F compared to the overall average of 5%).

Defrost operation was observed to drop off significantly above 40 °F with the sites that do have defrost operation having defrost energy mostly less than 5% of total energy use. The units that did not use auxiliary heat during defrost and continued supply fan operation were observed to have supply air temperatures that dropped significantly during periods of defrost—on average below 60 °F. It is noted that no occupant complaints were received in this matter from the homeowners who participated in the field study. The units that do not use auxiliary heat and suspended fan use were observed to have a short period following defrost to heat up the ambient indoor unit (IDU) air before turning the supply fan back on and heating the home. These units did not have a significant decrease in supply air temperature during or following defrost.

4.6 Power Modulation

All CCHP prototypes installed in the study were variable speed units. A key characteristic of variable speed CCHPs is their ability to modulate their speed to meet the required heating or cooling load. This ability for modulation allows the CCHPs to have longer cycles and avoids the inefficiencies associated with frequent on/off cycling that is representative of conventional single-speed equipment.

Figure 12 shows the ODU power modulation for each CCHP in the field study. Each data point that the boxplots comprise represents a 5-minute average of ODU power value in heating mode. Most CCHPs in the field study had a capacity of 3 tons; however, there were some units with a capacity of 4, 4.5, or 5 tons. The larger CCHPs are expected to have higher power draws, and so, the power level on the y-axis is normalized based on the size of the unit to provide a more consistent comparison in the chart. Because each boxplots comprises many thousands of 5-minute data points, the outliers are not shown on the chart for clarity. Overall, a range of modulating behavior was observed across the units, with some units being able to achieve a wider range of modulation compared to others.

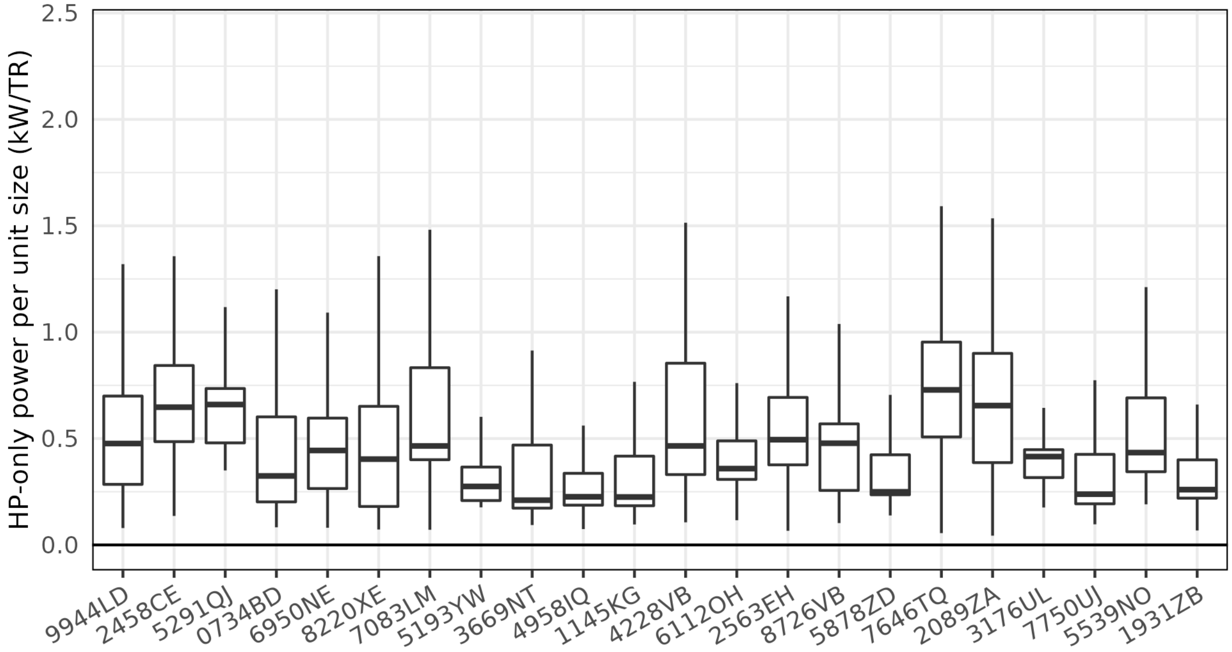

Figure 12. CCHP ODU Power for Each Site Normalized by CCHP Unit Size.

Figure 13 shows the median runtimes for all CCHPs sorted into outdoor air temperature bins. Runtime is calculated based on uninterrupted HP-only heating and cooling operation (i.e., defrost mode, auxiliary support, or idling would interrupt the cycle). Each data point represents the median runtime for one site and for one OAT bin. Only data points that comprise at least five hours of HP-only operation are included in the chart. The sample size (number of sites with sufficient data) for each boxplot is listed above the median.

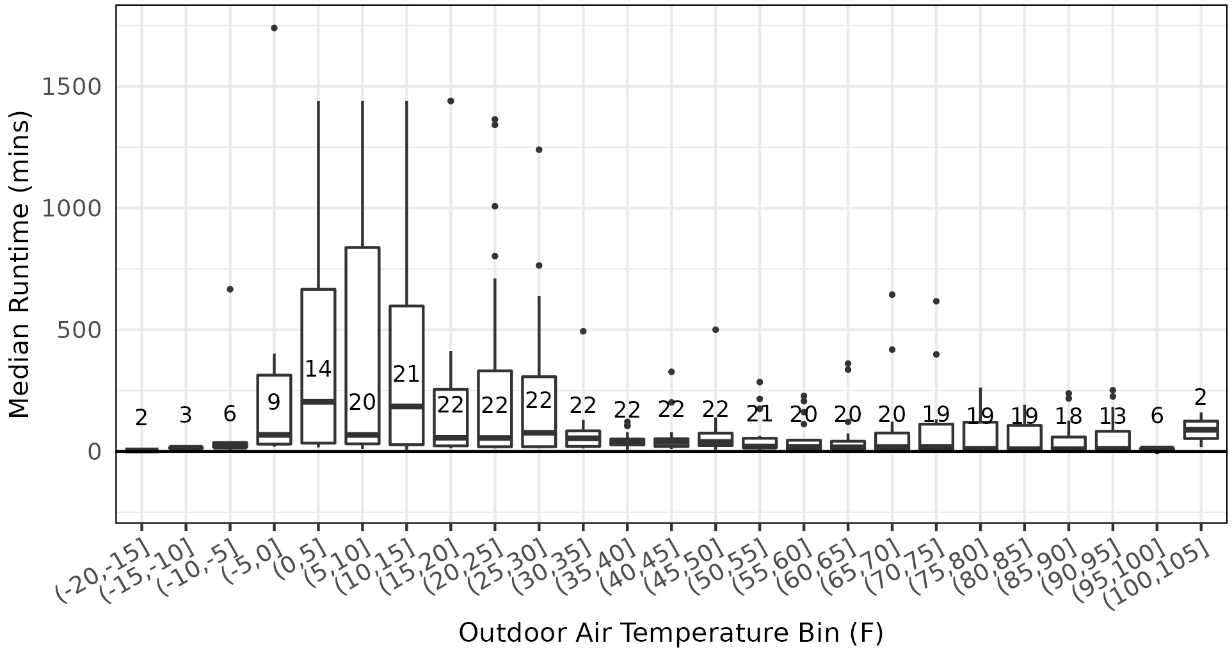

Figure 13. Median Runtime for Heating and Cooling by Outdoor Air Temperature.

A wide variation in runtime was observed across sites with some sites having mostly very short cycles less than 10 minutes and other sites reaching values of almost 1,500 minutes (25 hours) at some OAT bins. Heating cycles between 5 and 30 °F were observed to be longer with median values across all sites in the range of 50 to 200 minutes. The sample sizes for the lowest OAT bins are very small to provide representative information. The runtimes are also short at moderate OATs, which is presumably due to much lower thermal demand. Similarly, the cooling cycle runtimes are observed to be much shorter than the heating ones.

4.7 Demand Response (DR) Performance

The Challenge specification includes requirements for advanced DR capabilities per AHRI 1380 including the capability to curtail power demand for the CCHPs by 30% (general curtailment) and 60% (critical curtailment) with minimal impact on indoor temperatures. The primary objective of conducting DR tests in the winter was to understand the field performance of CCHPs in a curtailed state and to ensure that DR signals were being interpreted adequately. The National Renewable Energy Laboratory (NREL) worked directly with each manufacturer to establish connection with the thermostat at each field site to be able to send DR signals and receive operational information from the unit directly, such as opt-in status, thermostat setpoints, operational state of the CCHP and outdoor air temperature. The PNNL team evaluated the results of the DR tests using the CCHP power data collected through the M&V sensors and loggers.

4.7.1 Overview of DR Events

The DR capability of the CCHPs was tested in the field during summer and winter seasons on pre-selected days that offered optimal weather for these events. NREL used a communication protocol established with the smart thermostats during laboratory testing of the DR capabilities of prototype units to send an appropriate DR signal to the units in the field. The signal specified the start time, duration, and type of each DR event. DR events were 2-4 hours long and were called during early morning hours for the winter DR assessment and late afternoon hours for the summer DR assessment.

The DR signals were supplemented with a specification of a Maximum Indoor Temperature Offset (MITO) which ranged from 4-8 °F.[1] The purpose of the MITO was to ensure indoor comfort for the occupant by setting a limit on how much the indoor temperature setpoint would be allowed to increase (summer DR) or decrease (winter DR). If the MITO was exceeded at any point during the DR event, the DR event would end, and the CCHP would resume normal operation.

The variable-speed capability of CCHPs allowed the units to comfortably maintain temperature setpoints during curtailed states for the duration of most DR events. In some cases, a pre-set thermostat setpoint change occurred during the DR event, resulting in the MITO being exceeded and a termination of the DR event. The occupants were also able to “opt-out” of the DR event when the notification of the planned event was sent to them via email or at any time during the event by selecting the option on the thermostat.[2]

4.7.2 Winter DR Testing and Results

Winter DR testing was conducted in the field at both general and critical curtailment levels, as weather allowed. In most cases, a general curtailment event was scheduled for a weekday with a critical curtailment event scheduled for the very next day. Data collected by the NREL team provided an early indication of whether the units received the signal and responded correctly, or if communication did not go through as expected. When the DR event was successful, these early indications were supplemented with M&V data that allowed the research team to further evaluate the reduction in power draws, impact on indoor air temperatures, and other related effects, including the CCHP performance shortly after the culmination of the DR event and the interaction of the DR event with existing thermostat setbacks programmed by the occupant.

Overall, all participating manufacturers were able to demonstrate DR curtailment in the field. This was confirmed by the data received by the NREL team that related to the opt-in status and operation state during the DR event. Depending on the outdoor weather conditions and the indoor temperature setpoints, some units showed a clear curtailment in CCHP power in the M&V data during the event, while some others did not show a clear impact. When the units did not show a clear curtailment, it was typically due to the CCHP being in idling mode just before the DR event window, or due a low load on the CCHP due to a combination or indoor and outdoor temperature conditions and the heating load profile of the home.

Figure 14 shows an example of a general curtailment event with a clear indication of reduced CCHP power during the event and Figure 15 shows a similar example for a critical curtailment event for one site. The primary Y-axis is the power draw in kW and is shown in the teal-green line on the chart. The secondary Y-axis is the temperature in degrees Fahrenheit and is shown

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[1] The MITO was set at a default value of 4 °F for all events in Winter 1 and updated to 6 °F for all events in Winter 2 to study the impact of a larger MITO on event duration. The NRCan test homes allowed the testing of a more aggressive MITO of 8 °F during critical curtailment periods because occupancy in those homes is simulated.

[2] It was observed that occupants did not opt-out of the DR events while the event was in progress. However, some occupants requested opt-out when the notification email was sent, usually due to personal reasons or planned social events.

by the gray line on the chart. The length of each defrost cycle shown by the purple asterisk also tracks the primary Y-axis and is shown in minutes. The colored bar at the bottom of the chart indicates the operation modes of the unit; red indicates heating mode and blue indicates cooling mode. The DR event is shown by the blue shaded region on the chart and the unit is in normal operation mode before and after the DR event.

As seen in Figure 15, the CCHP power reduces to a higher extent during the critical curtailment event compared to the general curtailment event shown in Figure 14. It is noted that the outdoor temperatures were slightly higher at this site on the day of the critical curtailment event compared to the general curtailment event. It is also noted that at this site, no auxiliary heat operation was observed during or immediately after the DR event. This is an example of an ideal response to a winter DR event. However, in some cases, the conclusion of a winter DR event was observed to immediately correspond with a spike in auxiliary heat, often at higher stages, to overcome the reduction in indoor temperature due to the DR event.

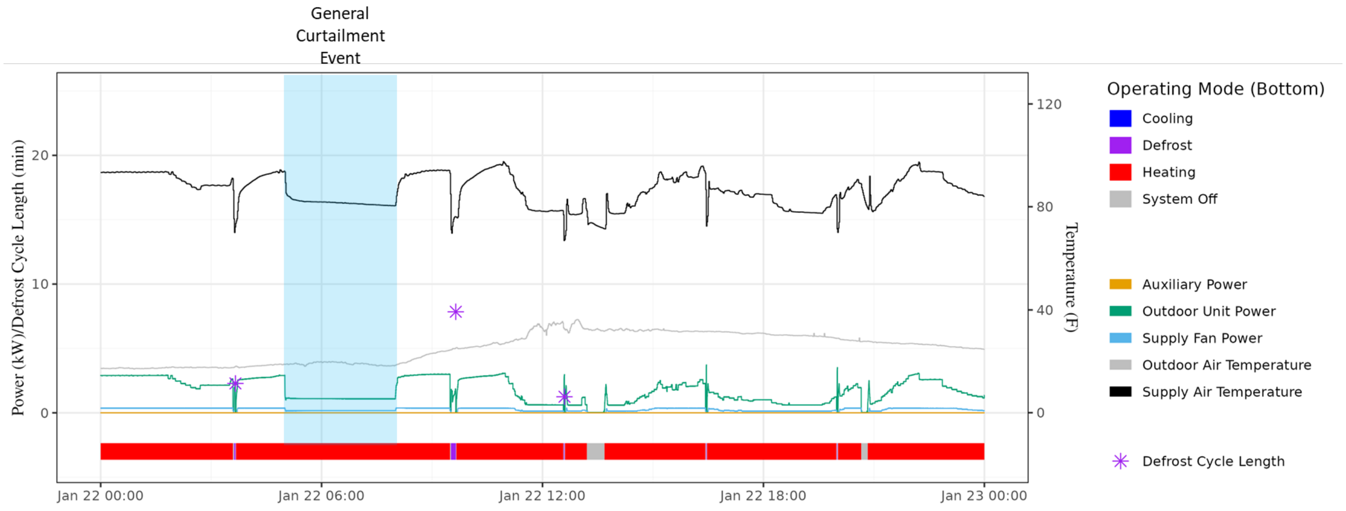

Figure 14. Example of a Winter General Curtailment Event.

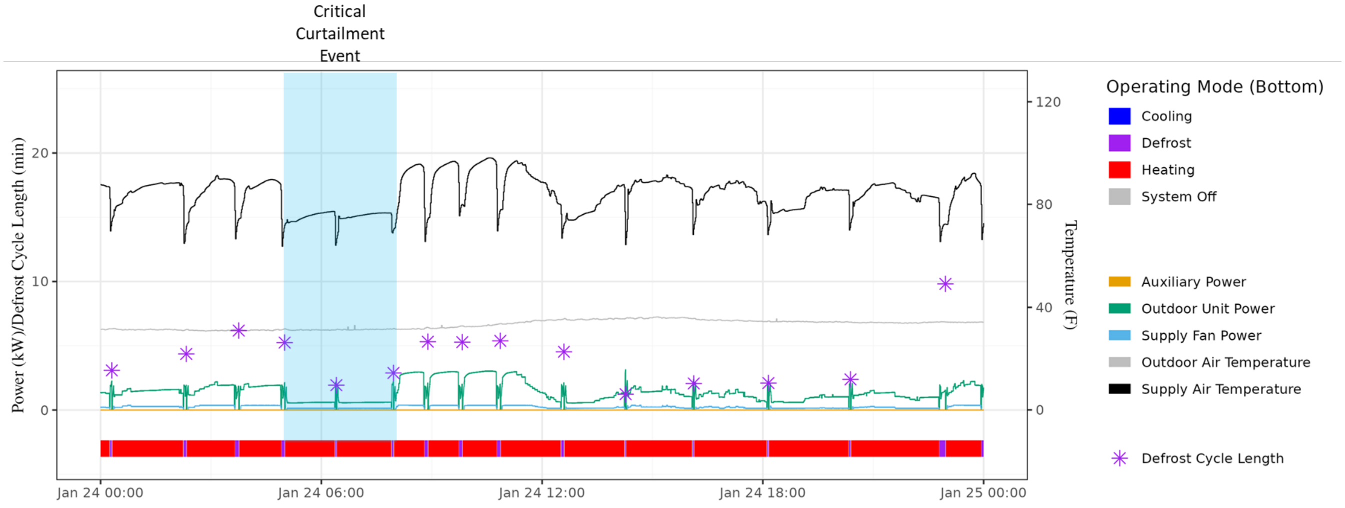

Figure 15. Example of a Winter Critical Curtailment Event.

This “snapback” effect is shown by the region highlighted in yellow in Figure 16. The critical curtailment event was scheduled for 5-8 am local time at this site. As expected, the CCHP power curtails at the beginning of the event at 5 am, staying flat at the reduced level until the event ends at 8 am. However, at 8 am, 15 kW of auxiliary heat is activated and around 10 kW is observed to be continuously engaged for roughly two hours after the event concludes. This increased auxiliary heat usage is likely to negate the benefits of the reduced power draw achieved during the duration of the DR event. By devising rules for delaying the onset of auxiliary heat at the conclusion of a DR event, the negative impact of snapback on energy consumption can potentially be reduced. This area of future research and coordination with AHRI 1380 is discussed further in Section 6.3.2.

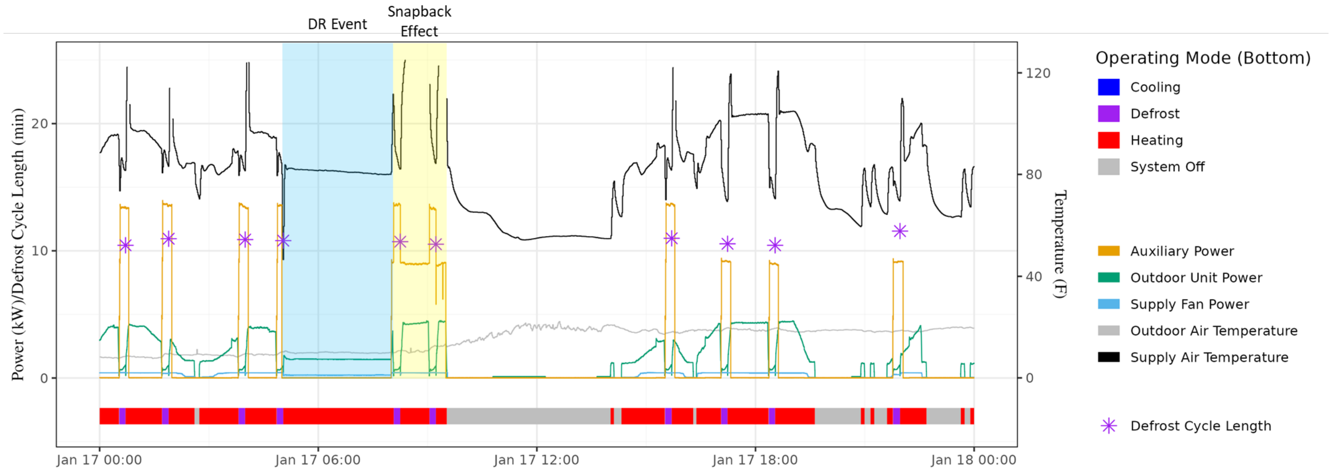

Figure 16. Example of the “Snapback” Effect after a Critical Curtailment Event.

4.7.3 Summer DR Testing and Results

In addition to conducting DR tests during the winter, the research team also conducted general and critical curtailment events during the cooling season to examine the performance of the units. Figure 17 shows an example of a successful summer critical curtailment event at one site.

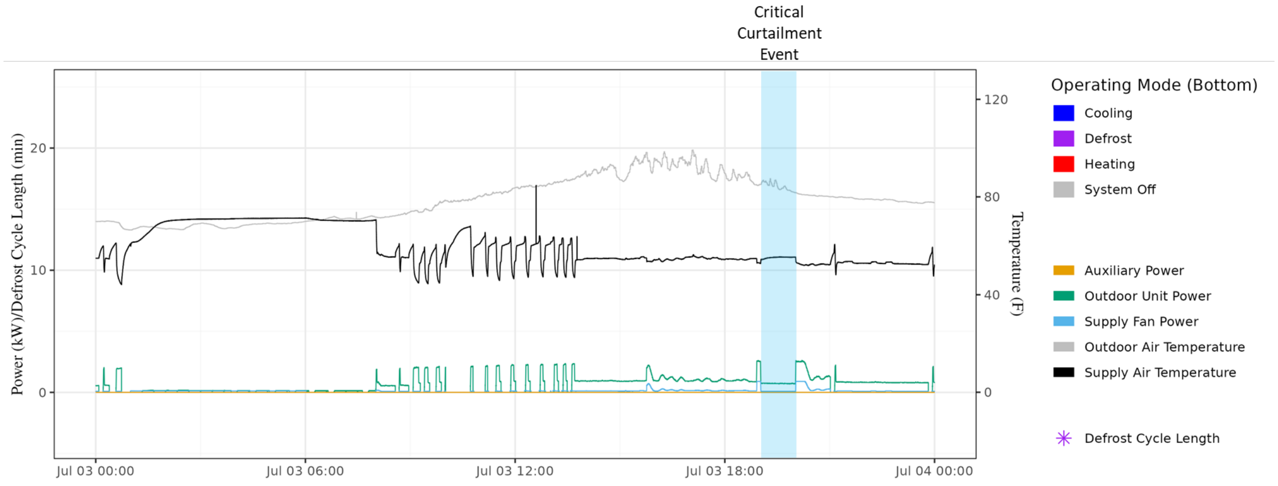

Figure 17. Example of a Summer Critical Curtailment Event with Clear Curtailment.

The curtailment levels in terms of allowable maximum power draw in Watts is determined using the 95 °F peak demand observed in lab testing per AHRI 1380, however, the cooling season power draws rarely exceeded the maximum threshold. As a result, no impact on CCHP power draws was noted for most summer DR tests, even when scheduled at critical curtailment levels. Figure 18 shows an example of cooling season critical curtailment event at one site where the CCHP power draw was below the maximum threshold and no further curtailment was noted. The data reported by the thermostat to the NREL team however confirmed that the DR signal was received by the CCHP, and the unit had indeed entered a curtailed state in response.

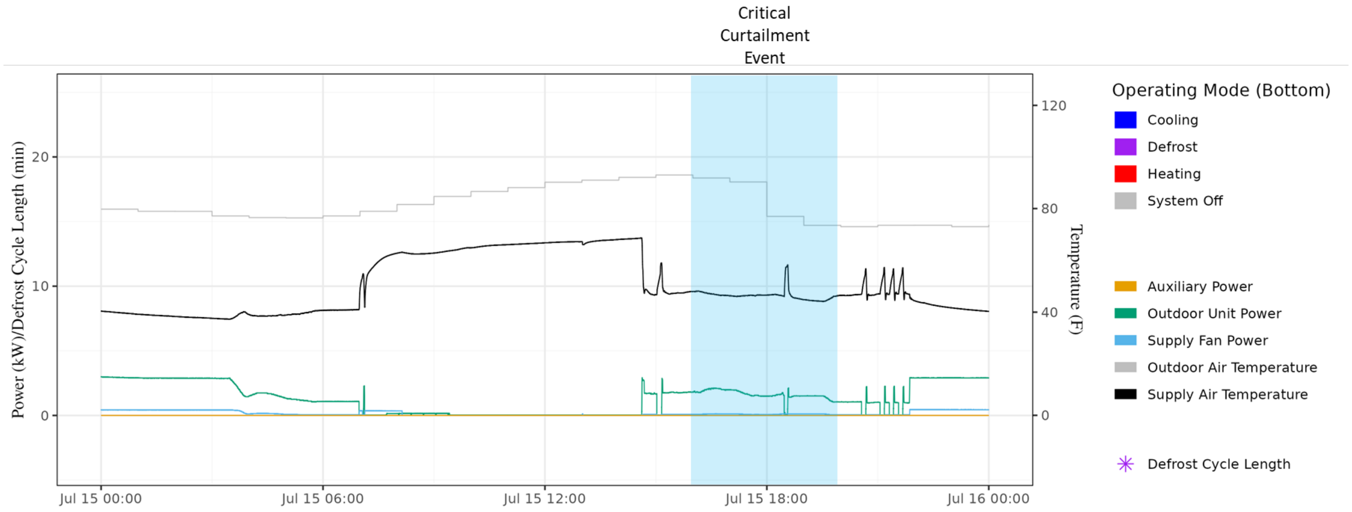

Figure 18. Example of a Summer Critical Curtailment Event with no Curtailment.

4.8 User Behavior Impacts on Energy

The field study design did not include homeowner engagement around user strategies for optimal CCHP performance. However, over the course of the field study, the research team noted several instances where homeowner behaviour resulted in increased energy consumption for the CCHP. For example, some homes utilized thermostat schedules that resulted in increased auxiliary heat usage during early morning periods of the heating season. Figure 19 shows the CCHP power profile for a winter day for a site with a morning thermostat setback that consistently resulted in higher stages of auxiliary heat in the morning hours.

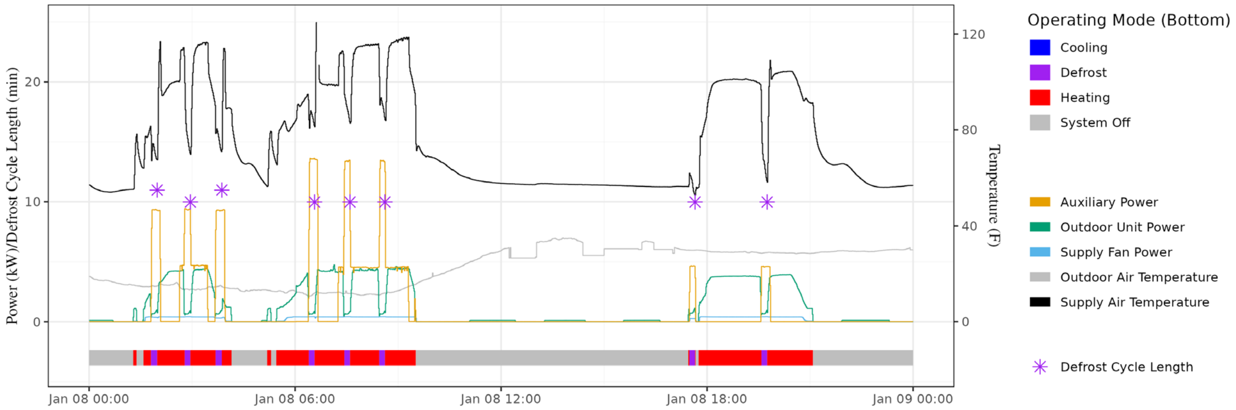

Figure 19. Example of the Impact of Morning Thermostat Setbacks on Auxiliary Heat

At another site, this effect was observed in the late afternoon hours as shown in Figure 20. The thermostat setting would increase by a few degrees around 4 pm and the CCHP would engage higher stages of auxiliary heat to meet the increased heating load. It is plausible that the homeowner saved more energy over the course of the day using this system, however, the impact from the perspective of the grid and potential demand charges could result in higher utility bills.

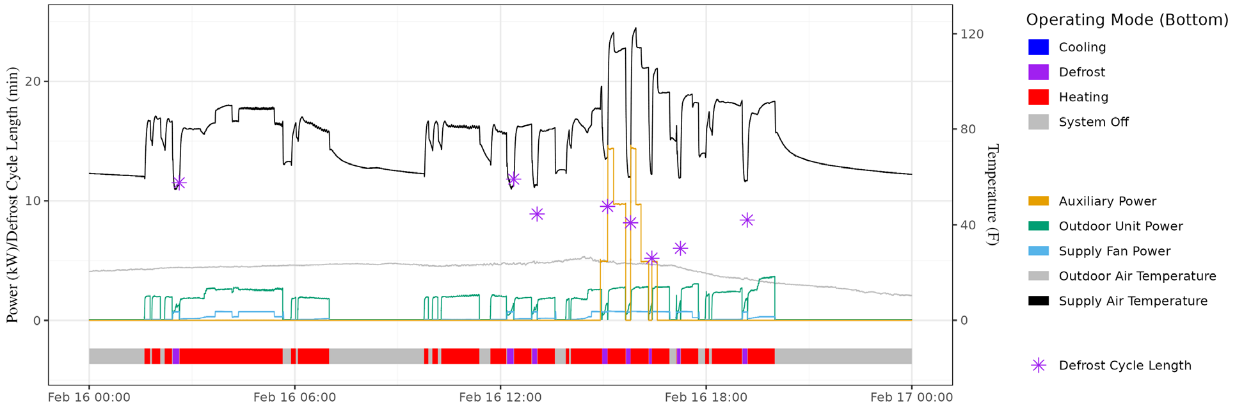

Figure 20. Example of the Impact of Early Evening Thermostat Setbacks on Auxiliary Heat.

This behavior was presumably driven by the homeowners' familiarity with a furnace system. Many sites originally had a furnace as the primary heating system. The furnace was replaced by a CCHP for the field study. Furnaces respond to changing demand in heating load by increasing, or decreasing, the fuel consumption almost immediately. A CCHP by contrast ramps up or down more slowly in response to changing thermostat setpoints. When the CCHP cannot meet the heating demand within a reasonable period, it utilizes auxiliary heat for support. Auxiliary heat is typically less efficient and thus results in higher energy consumption and often higher energy costs.

A solution would be to set the thermostat to a constant temperature and avoid setbacks altogether, or if setbacks are necessary, employing a more gradual setback instead of an instantaneous increase. Homeowner education around this effect would help them operate the CCHPs more efficiently with little impact on comfort and is an important topic for further research in this area.

5.0 Occupant Satisfaction

The research team conducted surveys periodically throughout the monitoring study to understand the occupants' perception of the performance of the CCHPs.

5.1 Participant Satisfaction Surveys

At the beginning of the study, the research team surveyed participating homeowners to solicit feedback on how satisfied they were with the overall performance of their home's current heating and cooling systems, collecting responses from 18 out of 22 participating homeowners.[1] Once cold-climate heat-pump prototypes were installed at each site, the team surveyed homeowners after each heating and cooling season to understand how the performance of CCHP prototypes compared to previous systems and to identify whether CCHP prototypes contributed to performance issues across a range of locations, weather conditions, and home sizes.

Table 6 shows the number of participants that responded to each of the surveys sent out to all 22 homeowners. Over the course of the study, the team received responses from homeowners using CCHP prototypes from all eight participating manufacturers and from several regions in the United States, including Northeast, Midwest, Mountain, and Canada.

Table 6. Total Number of Satisfaction Survey Responses

	Pre-CCHP Heating	Pre-CCHP Cooling	Heating 2022–23	Cooling 2023	Heating 2023–24	Cooling 2024
Number of responses received	18	18	7	7	17	14

5.1.1 Overall Satisfaction Feedback

For each survey, participating homeowners were asked to provide an overall satisfaction rating between 1 and 5, ranging from 1 corresponding to "not satisfied at all" to 5 corresponding to "extremely satisfied." Homeowners were also asked whether they would recommend a CCHP system to a neighbor and if they had any general feedback on their satisfaction that they wanted to provide.

To understand how satisfaction ratings changed over multiple years participating in the study, the team analyzed six sites that participated in the field trial for two years and provided responses to surveys in both years. In general, the two-year participants provided high satisfaction ratings, with five out of six giving a rating of 4 or higher. Of the six sites, three had

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[1] The research team notes that the number of responses to each survey does not show the total number of site installations. There were 23 total test sites, two of which did not participate in the survey because they were lab sites and one of which had two sets of occupants. There were nine sites that provided survey responses in the first year of the study, and 19 that provided survey responses in the second year of the study.

no change in satisfaction between winter 2022–2023 and winter 2023–2024, while two sites reported less satisfaction between winter 2022–2023 and winter 2023–2024 and one site reported increased satisfaction between winter 2022–2023 and winter 2023–2024. The team observed that multiple sites demonstrated higher ratings in cooling than heating, which may correspond to provided comments about higher utility costs in the heating season. None of the six sites reported a satisfaction in heating or cooling season lower than 3.

In the second year of the study, 10 additional sites provided survey responses compared to the first year. In this larger sample of participants, satisfaction increased for both heating and cooling compared to pre-CCHP surveys, with roughly 75% of homeowners increasing or maintaining their satisfaction ratings for both heating and cooling. For heating, the average satisfaction rating increased from 3.61 to 3.88. For cooling, the average satisfaction rating increased from 3.61 in the pre-installation survey to 3.86 in the 2024 cooling survey. Between the 2023–2024 heating season and 2024 cooling season, 13 out of 14 homeowners maintained or increased their satisfaction, suggesting that there were no widespread issues with CCHPs during the cooling season that decreased participants' overall satisfaction with their systems. Figure 21, below, shows how the average satisfaction rating differed in the pre-CCHP surveys, the year 1 surveys, and the year 2 surveys.

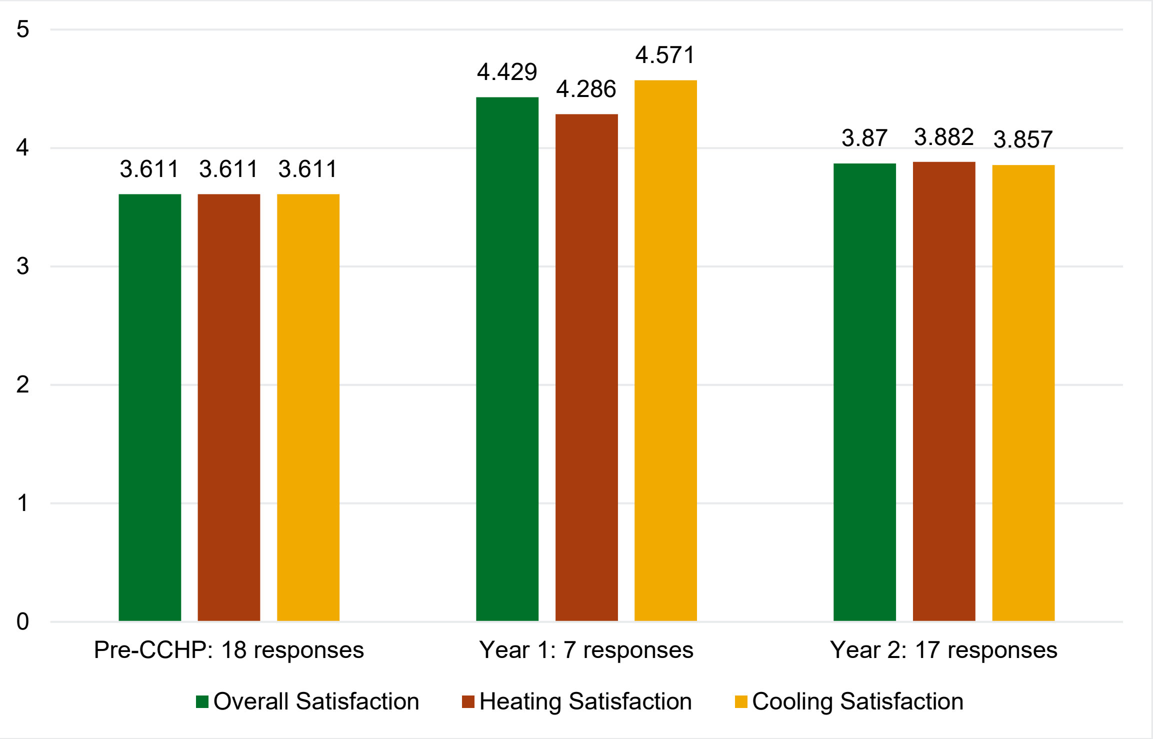

Figure 21. Customer Satisfaction Survey: Average Satisfaction Ratings.

Figure 22 shows the breakdown of responses to the question of recommending CCHPs to a neighbor, and whether they changed or remained consistent over the course of the survey. The team notes that this table includes the 20 homeowners who participated in at least one of the four post-installation satisfaction surveys. The survey results showed that:

- There were 14 (70%) participants whose final response was “Yes” to whether they would recommend a CCHP to a neighbor.

- There were six (30%) participants whose final response was “No” to whether they would recommend a CCHP to a neighbor.
- There were two (10%) participants who changed their responses from from “No” to “Yes.” They both described that the better performance of their units during the cooling season prompted them to change their responses.
- There were two (10%) participants who changed their responses from “Yes” to “No.” They cited dissatisfaction with increased utility bills in the heating season, which aligns with the feedback provided by the four other participants who would not recommend a CCHP to a neighbor.
- Of the six participants that said “No,” two specific participants shared additional feedback justifying their rating.
  - One of them stated that they did so because even though a high utility bill was expected in the winter, it was not anticipated in the cooling season. The team notes that this participant was also experiencing issues with their thermostat and temperature control, which could explain the relatively inflated utility bill in the cooling season.
  - The other participant stated that even though they are happy with a CCHP, they would not recommend it to neighbours who have a natural gas line because of high utility costs.

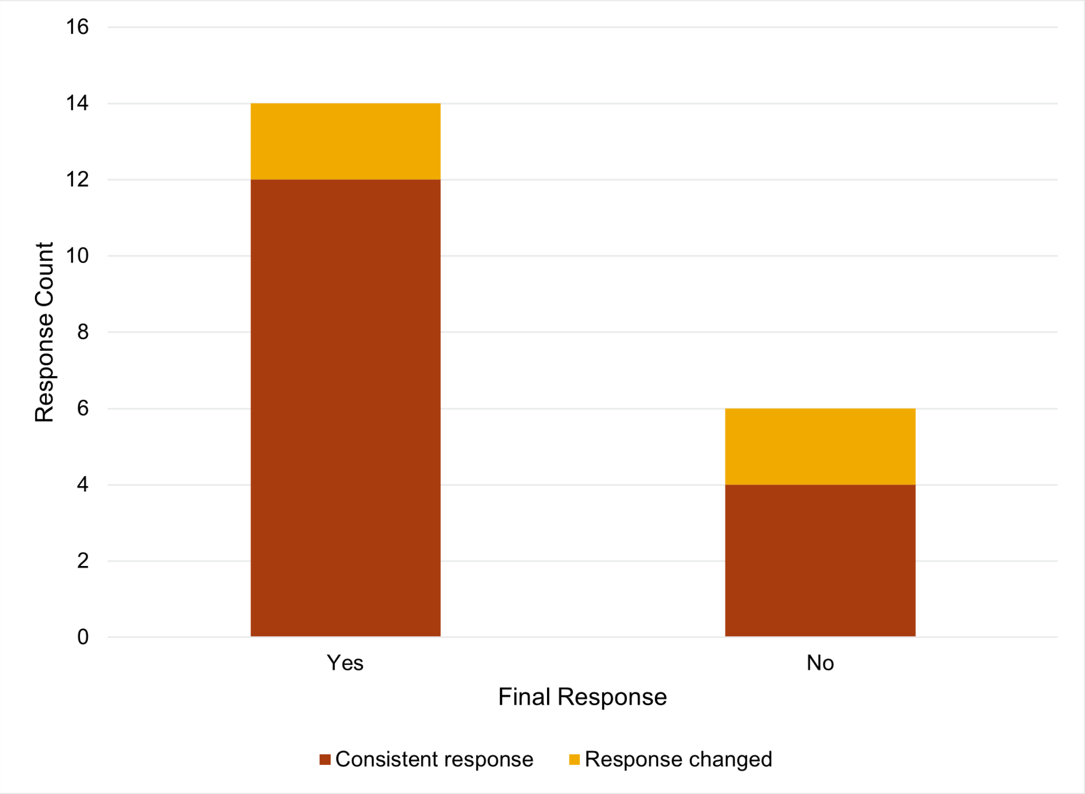

Figure 22. Customer satisfaction survey: Would you recommend a CCHP to a neighbor?

While high utility bills were clearly the main factor contributing to negative satisfaction for those two respondents, the overall survey responses demonstrate that it was not an issue for most participants. Regions with multiple installations by the same contractor with the same legacy heating system type showed both “Yes” and “No” responses to the recommendation question, suggesting that customer experiences with CCHP products will vary even in similar circumstances. Further, some homes in regions with delivered fuels or electric heating did show high satisfaction and would recommend a CCHP to neighbor, suggesting that their utility bills likely decreased or remained on par with the heating system previously installed in the home. Ultimately, the survey results suggest that at least some customers who adopt a CCHP will experience and express dissatisfaction with higher utility costs.

Interestingly, one homeowner commented that their utility bills decreased after replacing their existing system (a heat pump paired with a natural gas furnace backup) with the CCHP. This homeowner also stated they appreciated that the prototype kept their home comfortable throughout the day. Another homeowner cited improved satisfaction with the upgraded controls scheme associated with the CCHP prototype, though this may not be inherent to CCHPs only.

5.1.2 Feedback on Performance Quality and Reliability

The team also asked participants to report on four common performance-related issues that homeowners experience with their central AC and heating system, including (1) temperature control, (2) noise issues, (3) comfort in the home, and (4) the need for technical support from an HVAC contractor. In asking about these issues, the team sought to identify whether the CCHP prototypes had any widespread quality or reliability problems and the root cause of any problems that did occur. As demonstrated below, the team observed that there were no widespread issues with any of the four topics and that the number of instances that occurred were at a rate that was expected for prototype field testing.

5.1.2.1 Temperature Control

Table 7 shows the responses to the question of whether the pre-CCHP system or the new prototype was “able to maintain the desired temperature consistently and reliably?” At the pre-CCHP stage, there were two participants that reported temperature control issues with both their heating and cooling system. When asked to describe their temperature control issues during the pre-CCHP survey, most participants stated that their system would overshoot the set point by multiple degrees and that the system may not be sized properly. When CCHPs were installed, every site that had previously experienced temperature control issues no longer had any issues. The team assumes that the pre-CCHP temperature control issues were fixed by the manufacturer installing prototypes that were sized properly and using better control systems.

The three sites that reported temperature-control issues during the study did not report any temperature-control issues during the pre-CCHP survey or during other heating or cooling seasons. Both sites that cited issues during the 2023–2024 heating season stated that their heating systems were frequently turning on and off to maintain the set temperature, therefore over- and undershooting the target. The site that reported temperature-control issues during the 2024 cooling season experienced a thermostat calibration issue for which the manufacturer found a thermostat setting solution. As of this writing, the homeowner has not elected to incorporate the solution and recorded survey responses that expressed dissatisfaction with the overall system as a result.

Table 7. Reporting for Temperature-Control Issues.

Did the system maintain temperature?	Pre-CCHP Heating	Pre-CCHP Cooling	Heating 2022–23	Cooling 2023	Heating 2023–24	Cooling 2024
Yes	16	13	7	7	15	13
No	2	5	0	0	2	1

5.1.2.2 Noise

Table 8 shows the responses to the question, “Do you experience any noise issues with the indoor or outdoor unit?” on the pre-CCHP and prototype systems. The team included this question in the survey because most sites originally used combustion furnaces as their home-heating system, which are quieter because of their lower airflow rate than heat pumps. In the pre-CCHP survey, one site noted that their outdoor unit was noisy during the cooling season and another participant experienced noise issues with their electric furnace during the heating season. Figure 23, below, summarizes the comments provided in the survey that explain the cause of each noise issue and whether the issue occurred during heating or cooling. As the team expected, the most common noise issue was reported to be louder indoor airflow. Regardless, the team observed that noise issues were never mentioned as affecting the overall satisfaction for participants, and therefore it is likely considered a minor factor in overall satisfaction by system users.

Table 8. Reporting for Noise Issues.

Did you experience noise issues?	Pre-CCHP Heating	Pre-CCHP Cooling	Heating 2022–23	Cooling 2023	Heating 2023–24	Cooling 2024
No	17	17	3	5	14	11
Yes	1	1	4	2	3	3

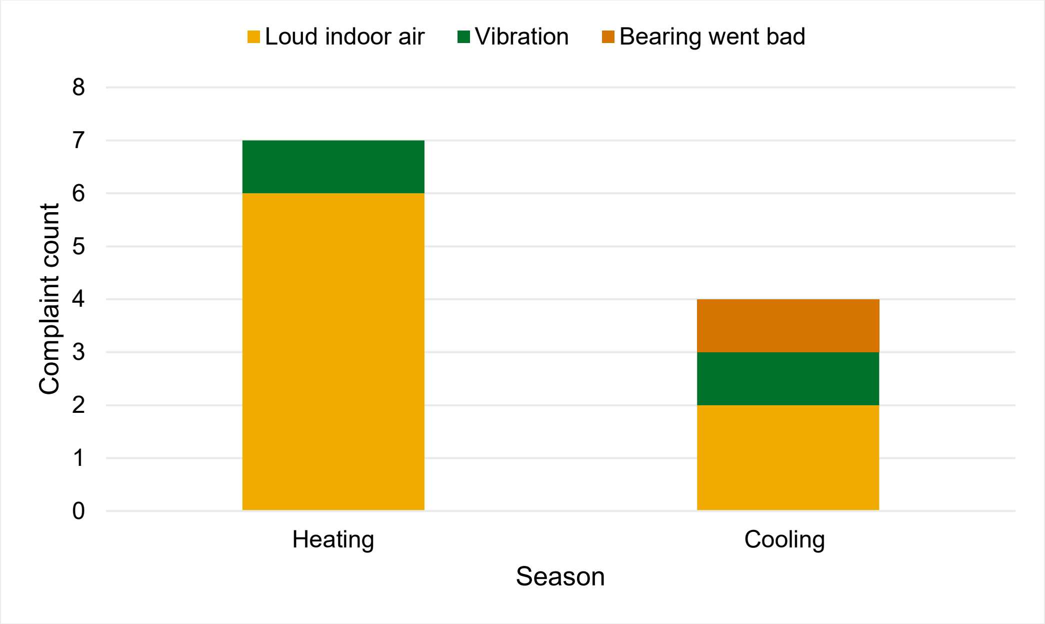

Figure 23. Reported Noise Issues by Season.

5.1.2.3 Comfort

Table 9 shows the responses to the question of whether participants "experienced any comfort issues" with either their pre-CCHP system or CCHP prototype. The team left the definition open-ended regarding what constituted a comfort issue to allow participants the freedom to interpret as they preferred. As a result, some respondents grouped temperature control issues as also being comfort issues. Participants also reported extreme humidity levels, high or low, and poor performance in extreme conditions as a comfort issue.

Over the course of the entire study, there were seven homeowners who experienced comfort issues, only one of which experienced issues during more than one season. During the 2022–2023 heating season, one participant reported a comfort issue because of poor temperature control during defrost mode. In the 2023 cooling season, a different participant reported their CCHP prototype performed poorly in extreme heat conditions. In the 2023–2024 heating season, there were two participants who reported discomfort with humidity levels that were too low and one participant who reported a temperature control issue as affecting their comfort. In the 2024 cooling season, two participants reported issues with humidity levels being too high, and the participant from the previous heating season reported the same temperature control referenced earlier. Based on how homeowners responded to questions about general satisfaction, comfort issues appear to have affected overall satisfaction ratings for only a few homeowners.

Table 9. Reporting for Comfort Issues.

Did you experience comfort issues?	Pre-CCHP Heating	Pre-CCHP Cooling	Heating 2022-23	Cooling 2023	Heating 2023-24	Cooling 2024
No	15	14	6	6	14	11
Yes	3	4	1	1	3	3

5.1.2.4 HVAC Contractor Support

In total, there were seven homeowners who needed support from an HVAC contractor to perform repairs on their CCHP prototypes. According to comments from the participants, the visits from HVAC contractors were prompted by an assortment of issues that were either routine maintenance issues (i.e., condensate pan overflow) or control/sensor issues that would be mitigated as CCHP prototypes are refined to be brought to market. Table 10 shows further details on the survey responses concerning why HVAC contractor support was needed for the CCHP prototypes, and when it was first reported in the surveys. All issues but one were considered minor and solved after a single visit from an HVAC contractor. One site experienced a fault in the refrigerant leakage mitigation system, which was difficult to diagnose as separate from a normal leak event and required several visits to assess and remedy the issue.[1] By comparing survey responses from before (see Figure 24) and after the CCHPs were installed, the team determined that the need for HVAC contractors during the study was not atypical in comparison to needs in the past and did not affect overall satisfaction ratings.

Table 10. HVAC Support for CCHP Prototypes.

Issue Described	Heating 2022–23	Cooling 2023	Heating 2023–24	Cooling 2024	Additional Context
Insulation/sealing issue where the line set entered the home	-	1	-	-	Issue was only resolved after multiple visits. Likely fixed with better insultation/sealing on the line set
Sensor issues/replacement	-	-	3	-	Two of these were minor issues that the team anticipates would be fixed on a commercially available product. One was the faulty refrigerant leak sensor mentioned above
Control issues, leading to recalibration and replacement	-	-	2	-	Minor issue that the team anticipates would be fixed on a commercially available product
Variable frequency drive (VFD) replaced	-	-	1	-	The manufacturer discovered an issue with their VFDs that could impact CCHP operation and proactively updated the VFDs at several sites.
Condensate pan overflow	-	-	-	1	Routine maintenance issue caused by a clogged drainpipe

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[1] Manufacturers developed and tested their prototypes using A2L refrigerant sensors and mitigation systems available in 2021. Several manufacturers indicated they will commercialize with improved and more robust leak mitigation systems.

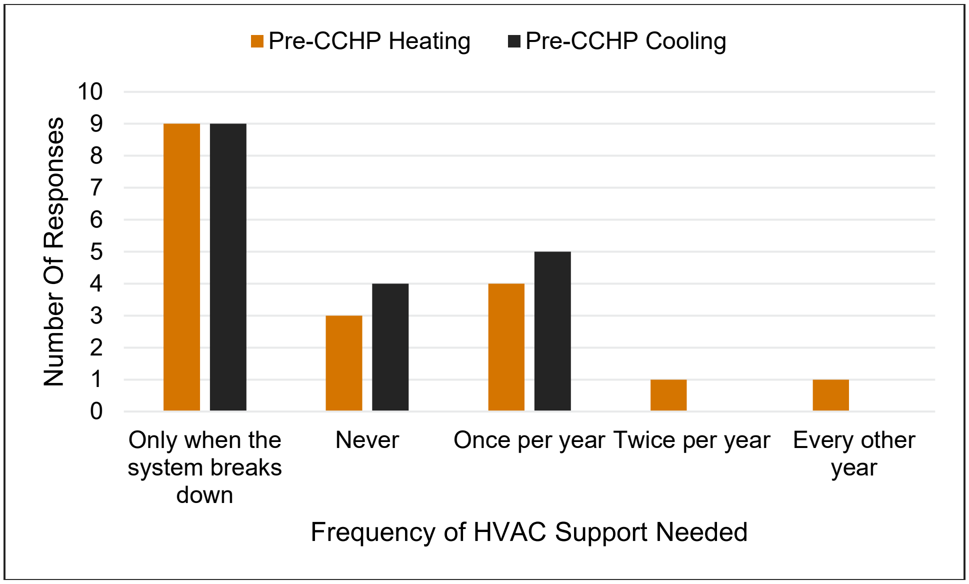

Figure 24. Pre-CCHP Survey: Need for HVAC Support.

6.0 Discussion

Field validation allows the research team to understand how units perform outside controlled laboratory testing environments. This section explores qualitative lessons learned from the experience.

6.1 Installation Types, Upgrades, and Costs

When organizing and observing site installations, the team gathered information on the types of upgrades and associated costs that would be required to install CCHPs at each site. Consequently, the team summarized this data to evaluate how installation upgrades varied by region and by which type of system (i.e., natural gas or electric furnace) was being replaced.

Out of the 23 CCHPs installed over the course of the two-year study, the team was able to gather information for 21 sites, not including the NRCan facilities. The team first compiled data on the original systems that were replaced at each site to provide context for the electrical and ducting upgrades that would be needed for the CCHP installs. Two-thirds of the original heating systems were natural gas-fired furnaces, ranging from 66 to 100 kBtu/hr. The remaining sites originally used heating system options including propane-fired furnaces, “dual fuel” systems, and electric furnaces ranging from 36 to 58 kBtu/hr.

Because gas furnaces tend to be oversized for a home’s heating needs, natural gas-fired furnaces were replaced with CCHP prototypes that had a much lower heating capacity. Appendix B.1 demonstrates how the heating capacities of original site heating systems that were furnaces and CCHP prototypes matched up with their Manual J heating load.

Table 11 below shows the different types of upgrades that were required by sites to install CCHP prototypes. The team gathered this data using invoices provided by the different HVAC contractors used at all 21 sites, as well as our observations during installation.

Table 11. Summary of Upgrades Needed for Installation.

Upgrades Required?	**Electrical Upgrades**				**Duct Upgrades**	
	New Panel	New Breakers	New Wiring for Aux. Heat	Service Line Upgrade	Any Duct Upgrades	Major Duct Upgrades
Yes (% of all participants)	38%	90%	55%	24%	76%	29%
No (% of all participants)	62%	10%	45%	76%	24%	71%

Data on installation costs were also collected from the invoice totals for all participating sites. A wide range was observed in installation costs, likely due to variations in the region and the complexity of installations required for each site. Most sites needed minor ductwork upgrades, but major ductwork upgrades were correlated with a significant price hike. The total costs for electrical upgrades were observed to vary between $3,750 and $8,970. When both electrical and mechanical upgrades were needed, the total costs were observed to vary between $3,258 and $18,400. These costs are only for labor and materials and do not include the cost of the CCHP prototype itself.

6.2 Challenges

The field validation effort, as discussed in earlier sections, involved prototypical units. In some cases, the unit that was installed in the field was the unit that had previously gone through laboratory testing in the previous stage gate, while others were purpose-built for the field validation effort. It is anticipated that participating manufacturers will leverage performance data and homeowner feedback to make modifications to their production units that will become commercially available. The degree to which the performance on the commercially available units will differ from the prototypical units observed in this study is unknown as of this publication.

Additionally, the CCHP prototypes were installed in 2022 and 2023, a time of great change in the codes landscape as it relates to A2L refrigerants. In the first round of installations, several potential sites had to be excluded from the sample because the local code officials were unable to approve units with A2L refrigerants. However, industry is increasingly moving to use A2L refrigerants to better comply with the American Innovation and Manufacturing Act (AIM) of 2020 and the U.S. Environmental Protection Agency's Technology Transition Rule. It is anticipated that state and local code bodies will continue to update their requirements to allow for this class of refrigerants. Within the study, all HVAC contractors who installed the test units were able to do so successfully, including safely handling and adding refrigerants.

Finally, due to the highly granular data collection plan, the team encountered several challenges that should be noted by others looking to conduct similar field validation efforts. First, while sensors and data loggers have continued to evolve over the years, batteries were still required for several sensors. With those sensors installed in the outdoor units, the initial data collection frequency of 1-minute temperature data was found to deplete the batteries faster than originally anticipated—going from an anticipated 1-year lifespan to approximately six to nine months. To reduce contractor trips back to the field sites (and reduce homeowner burden), the team changed to a 5-minute data collection frequency. Secondly, due to PNNL's research plan approved by the Institutional Review Board, PNNL had to collect all data via SIM cards to avoid encroaching on the homeowner's Wi-Fi and personal information. Several of the locations in the sample were in remote areas, where cellular signal was unreliable. In several instances over the course of the study, cellular signal that had previously been functional changed because of weather and cellular tower availability. In those instances, the team tried combinations of refreshing the SIM card in coordination with the vendor, changing carriers, and using antennas to boost the cellular signal. In one instance when none of the interventions worked, the research team worked with PNNL's Institutional Review Board to modify the homeowner agreement to leverage the homeowner's Wi-Fi. Finally, the highly granular data collection plan also required significant storage space for the data.

6.3 Areas for Further Research

The field validation effort described in this report encountered several key areas that could benefit from further research, specifically relating to refrigerants, demand response, controls (including homeowner interaction with controls), and weatherization. This section describes take-aways from the research team with a description of outstanding research questions that may benefit from further exploration.

6.3.1 Low GWP Refrigerants

The Challenge prototypes were some of the first centrally ducted HVAC products in the United States to use the lower GWP refrigerants R-32 and R-454B in real-world field installations, and often were the first such products being installed in that state. The research team and partner manufacturers worked with the local installers and code officials to ensure everyone felt comfortable with the product's safety measures and installation procedures. Overall, installers were successfully able to install the prototype CCHPs efficiently and were able to work with next-generation, low-GWP refrigerants as well as the CCHP's leak detection and mitigation systems.

Low-GWP HVAC products are expected to achieve wide adoption beginning in 2025 due to federal regulations restricting the sale of new products with high-GWP refrigerants. In late 2023, the U.S. Environmental Protection Agency finalized its sector-specific restrictions on the use of high-GWP refrigerants for Heating, Ventilation, Air-Conditioning, and Refrigeration (HVAC&R) applications under subsection i of the 2020 AIM Act. The sector specific HFC restrictions outline GWP limits and dates for each major HVAC&R subsector, with the regulations primarily targeting new systems for new construction and major retrofit only. Most HVAC product categories, including residential CCHP products, will have a 700 GWP limit for products manufactured starting 1/1/2025.[1] In a subsequent amendment, EPA clarified that new HVAC systems with a GWP above 700 can be installed until January 1, 2026, so long as all components are manufactured or imported before January 1, 2025. Commercial variable refrigerant flow systems were granted an extra two years to 1/1/2027 during a June 2024 update.[2]

Supporting the national rollout of low-GWP refrigerant CCHP technologies will require a coordinated effort by federal, state, and local leaders representing manufacturers, building code officials, distributors, contractors, and other stakeholders to raise awareness of the required installation, maintenance, and handling practices as well as the unique safety features that will be on-board these systems. For the last several years, HVAC&R industry stakeholders have supported widespread education and training for key parties to enable this transition, but this support will need to continue over the next several years to ensure that all parties are trained and comfortable working with these newer technologies. Furthermore, this education should be extended to homeowners and the public to address potential safety questions and concerns and provide guidance on what to do should a leak occur.

While the 2025 transition occurs, the HVAC&R industry is also considering the potential impacts of further state and federal regulation to transition to ultra-low GWP refrigerants (<10, <150, or <300 GWP depending on the definition). The AIM Act has a national goal of hydrofluorocarbon (HFC) production and consumption by 70% in 2029, 80% in 2034, and 85% in 2036 against a calculated baseline. California and New York State have announced goals to transition to ultra-low GWP refrigerants in the mid-2030s. In December 2024, New York State's updated Part 494 HFC regulations established a 20-year GWP target of 10[3] for residential and light-commercial

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[1] EPA. 2023. Technology Transitions HFC Restrictions by Sector. https://www.epa.gov/climate-hfcs-reduction/technology-transitions-hfc-restrictions-sector

[2] https://www.epa.gov/climate-hfcs-reduction/regulatory-actions-technology-transitions

[3] While 100-year and 20-year GWP values for fluorinated refrigerants differ substantially, ultra-low GWP refrigerants have essentially the same GWP values under both 100-year and 20-year metrics.

air conditioning and heat pump systems beginning in 2034.[1] As of this writing, similar regulations in California have not been proposed yet. Should federal and state regulations move toward ultra-low GWP refrigerants, such as carbon dioxide (R-744), propane (R-290), ammonia (R-717), or certain hydrofluoroolefins,[2] the HVAC&R industry would need to again assess the potential performance, efficiency, cost, safety, and other impacts of future CCHP products.

6.3.2 AHRI 1380 Demand Response

The Challenge prototypes each successfully demonstrated advanced demand response functionality to 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). Each system was first tested for both general curtailment (30% power demand decrease) and critical curtailment (60% power demand decrease) in laboratory testing of space heating operation. During field testing, each system was tested for general and critical curtailment events during a range of space heating and space cooling conditions. While each prototype was successful in demonstrating AHRI 1380 capabilities in the field, the testing revealed several areas for further development and discussion.

Traditional demand response programs either a) send a radio signal to a disconnect switch that cuts power to the outdoor unit for a set period of time (e.g., AC cycling programs), b) adjust the thermostat setpoints by several degrees to reduce system runtimes (e.g., smart thermostat programs), or c) send a message to the occupants to reduce their consumption (e.g., behavioral programs). AHRI 1380 was designed to utilize the advanced control capabilities of variable-speed HVAC systems paired with smart thermostats. In this strategy, the heat pump's compressor and fan speeds are reduced, but the heat pump is still allowed to operate and provide at least some heating/cooling capacity to maintain comfort in the space. The overall strategy is to drive a predicable demand reduction while maintaining comfort so that there are minimal impacts on occupants, resulting in greater participation and fewer event opt-outs.

Although AHRI 1380 was originally published in 2019, the standard has seen limited field testing or program adoption by manufacturers, utilities, and distributed energy resource management system (DERMS) providers.[3] The Challenge field testing represents a significant advance in demonstration of the standard with a large field test sample to support future utility program developments and manufacturer product capabilities. The team is also aware of additional AHRI 1380 field testing underway with partner manufacturers and utilities. Nevertheless, for the AHRI 1380 standard to become a common form of utility demand response, several developments would need to occur:

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[1] New York State Department of Environmental Conservation. Part 494, Hydrofluorocarbon Standards and Reporting. December 2024. https://dec.ny.gov/sites/default/files/2024-12/part494expressterms.pdf

[2] In addition to concerns around the GWP of HFC refrigerants, European stakeholders are also evaluating the potential environmental and health impacts caused by chemicals known as per- and poly-fluoroalkyl substances (PFAS). PFAS include thousands of different chemical compounds and are often referred to as "forever chemicals" due to their very long lifetimes before degrading in the environment. Stakeholders in Europe and other regions have concerns around certain HFC and hydrofluoroolefin refrigerants, most notably R-1234yf, that break down in the atmosphere to trifluoroacetic acid, which is a form of PFAS. Haggerty, J. 2024. PFAS Regulations. Anthesis Group. https://www.anthesisgroup.com/regulations-hub/pfas/

[3] As described in Section 4.7, NREL served as the "utility" to establish a communication link with each of the field prototypes and call the demand response events.

- A greater share of the residential HVAC market would need to have variable-speed capabilities. Many ductless products are variable speed, but most centrally ducted products are single or two stage and could not provide the full set of capabilities within AHRI 1380.
- Utilities would need to see the impacts and benefits of this demand response strategy compared to the more traditional options (e.g., smart thermostat setpoint adjustments).
- Utilities would need to see a near-term risk of peak demand issues during the winter heating season due to increased heat pump adoption and building electrification in their regions. Today, the vast majority of utility programs focus on summer cooling peak demand. Discussed below, our field testing identified some issues during summer cooling events.
- DERMS providers would need to develop the communication and controls capabilities to call such events. At this time, we are not aware of major DERMS providers offering AHRI 1380 capabilities.
- Manufacturers would need to standardize the number, type, and frequency of reporting channels to better support utility program implementation and impact evaluation. Our testing found that each manufacturer had its own reporting approach, which creates integration challenges for utility programs that are designed to be brand agnostic.

To support further industry and market adoption of the AHRI 1380 standard, the research team identified the following activities:

- Evaluating the comparative impacts, benefits, and challenges of AHRI 1380 vs. traditional demand response methods in a laboratory and/or a future field study.
- Sharing the findings from Challenge field testing with the AHRI 1380 committee members and partner manufacturers to collectively discuss how to address certain challenges experienced in the field related to the following:
  - How to consider the maximum indoor temperature offset (MITO) in situations where the thermostat temperature schedule changes by several degrees coming out of nighttime setback, which could end a demand response event prematurely (e.g., event begins with a thermostat setpoint of 62 °F with 4 °F MITO, and then the thermostat schedule raises the setpoint to 68 °F 30 minutes later).
  - Whether to require a delay in auxiliary heat usage at the conclusion of an event that did not end due to exceeding the MITO to allow the heat pump a chance to recover the lost heat by only using mechanical heating, and not switching on the auxiliary heaters. Some manufacturers showed a large snapback of electric resistance heating at the end of events as the thermostat activated the auxiliary heating when recognizing a multi-degree difference between the room temperature and thermostat setpoint.
  - How to address summer cooling curtailment functionality for events that are not called during extreme heat >95 °F conditions. The target curtailment percentage for summer AHRI 1380 events is measured relative to the 95 °F peak demand observed in lab testing. In the field, the team observed situations during 85–95 °F conditions where the heat pump's power demand was already lower than the defined AHRI 1380 peak, so the heat pump did not provide much if any further curtailment.
- Sharing findings with leading utility program managers and their DERMS providers to support their future field testing and pilot programs with AHRI 1380 compatible products in their regions.

6.3.3 Auxiliary Heat, Controls, and Homeowner Engagement

Section 5.0 of this report discussed auxiliary energy usage across OAT bins and noted that auxiliary energy use increases significantly at very cold temperatures, but that the small sample size limited the team's ability to make more certain conclusions. Further research with increased data on cold temperature performance can identify if further research into the staging of auxiliary heat may provide increased performance benefits.

Additionally, the report discussed trends from analysis of switchover temperature, noting that there was a wide range of switchover temperatures used to determine when to switch to auxiliary support. The research team imputed that these differences were likely due to a combination of thermostat programming or from occupant behavior. The study design did not include any homeowner education on how to operate these units most efficiently, and the research team observed several sites with programmed or manual setpoints that led to a need for auxiliary heat that might not otherwise be required. If this observed behavior becomes widespread, winter peaks for electricity could result in the need for major grid infrastructure projects. Further research into enhancing the controls strategy for switchover temperature and homeowner education about the impacts of large set-points on the energy consumption of heat pumps (compared to traditional heating systems) may help reduce energy usage. Understanding the potential reduction of each strategy will be key to utility programs looking to deploy this technology class within their service territories.

6.3.4 Weatherization

The field sites in this study did not undergo any weatherization measures before installation of the CCHP prototype unit. Best practice for existing homeowners looking to replace a traditional furnace with a heat pump is to weatherize their home before installation to ensure optimal cost savings and comfort. The homes in the study were all located in cold climates but differed in terms of vintage, insulation levels and air tightness. Research in the future should evaluate the impact of weatherization measures on the sizing of the cold climate heat pump (potentially reducing costs to the homeowner if a smaller unit can provide the new required heating load), homeowner comfort, and utility bill savings.

6.3.5 Commercialization Status

As of this writing, four out of the eight participating manufacturers—Carrier[1], Lennox, Bosch[2], and Trane[3]—had made public announcements related to the commercialization of the Challenge units by early 2025. The remaining manufacturers are expected to make similar plans in the coming year.

Participating manufacturers worked closely with DOE and the National Laboratories throughout the development, laboratory testing, and field-testing portions of the Challenge. They noted the critical value of DOE and industry collaboration for revolutionizing energy-efficient home heating and cooling through the Challenge.[4] This collaboration between government and industry

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[1] https://www.prnewswire.com/news-releases/carrier-completes-department-of-energys-cold-climate-heat-pump-challenge-transformative-innovation-set-for-2024-commercial-rollout-302245339.html

[2] https://www.bosch-homecomfort.com/us/en/ocs/residential/ids-ultra-inverter-ducted-split-cold-climate-heat-pump-20831889-p/

[3] https://www.trane.com/residential/en/resources/blog/cold-climate-heat-pump-challenge/

[4] https://www.energy.gov/eere/buildings/partners

helped to address a persistent gap in the market by providing a common set of performance requirements for which Challenge partners were able to quickly develop high-performance heat pumps prototypes and test performance in both the laboratory and real-world setting. Manufacturers noted that the Challenge has helped increase public awareness and accessibility of these new products, which feature cutting-edge technologies that deliver consistently high efficiencies in colder climates while maintaining occupant comfort. Manufacturers noted that the partnership between industry, DOE, and the National Laboratories not only helped overcome technological barriers that have traditionally slowed the introduction of new technologies to the market, but also provided stakeholders with performance information needed to drive broader industry and consumer adoption.

6.4 Incentive and Deployment Programs

Energy-efficient technologies are often incentivized through programs funded by utilities and other sources, including private entities and federal and state governments. These programs aim to reduce the adoption cost of beneficial technologies, thereby encouraging their widespread use. Products developed under the Challenge will naturally align with or expand these programs. For effective integration into incentive programs, administrators must be able to identify qualifying products, assess their performance across varying outdoor conditions, and access accurate equipment cost data. The approach to recognizing Challenge-compliant products may differ between programs. Some programs may develop entirely new measures for these products, while others may incorporate them into existing frameworks. Regardless of the approach, robust product identification, performance evaluation, and cost analysis are fundamental.

Many utility incentive programs rely on Technical Resource Manuals (TRMs) to guide the development of measures and programs. TRMs are designed to provide standardized performance ratings, energy savings potential, cost information, and other criteria for selected technologies and are crucial for justifying the benefit of a specific technology over a baseline.

Most TRMs nationwide already include measure packages for heat pumps, but these measures vary widely in scope and detail. For instance, some TRMs distinguish between ducted and ductless configurations, some categorize measures based on performance ratings such as SEER2, EER2, HSPF2, or COP, and some employ unique methods of grouping or binning products. Regardless of the method used, it is critical for TRMs to effectively identify and evaluate the performance of products developed under the Challenge. This ensures that the technologies are both recognized and appropriately incentivized.

To identify products meeting the Challenge specification, programs may reference performance indicators outlined in Table 1. Primarily, programs may choose to utilize the minimum COP set by the Challenge specification. The minimum HSPF2 value can be calculated as defined in Equation 8 (DOE 2021) as:

$$HSPF2 = 8.5 \times (1 + \text{Capacity Factor}) \times (1 + \text{COP Factor}) \tag{8}$$

where:

Capacity factor = 1% for every 10% $H1_1/H1_N$ *gap. The capacity factor for northern triple capacity HPs is 0.*

COP factor = 2% for every 10% excess COP gap between the expected COP reduction and the measured COP reduction from the $H1_1$ verification test and the $H1_1$ regulatory test

To quantify the energy savings of products meeting Challenge specification, TRMs and programs may conduct energy modeling or similar analyses to establish baseline comparisons and develop savings assumptions. The data provided in this report will support such efforts, with Tables Table 1, Table 3, Table 5, and Table 7 offering necessary information for energy modeling and the creation of characteristic profiles for these products.

However, while these resources provide valuable insights, additional in situ research is necessary to fully understand the performance of these technologies as they are seen in the market. Such research will ensure that TRMs and incentive programs accurately reflect how these products perform under actual operating conditions. Some additional field research is planned for Phase II of this effort to better understand the impact of weatherization and homeowner education on the performance of CCHPs.

Incorporating Challenge-specification-compliant products into incentive programs and TRMs presents a valuable opportunity to realize the benefits of these highly efficient technologies. By leveraging standardized performance metrics, conducting robust modeling analyses, and continuing to refine TRM measures, stakeholders can maximize the adoption of these products while ensuring their performance aligns with expectations. Continued research and collaboration with utilities, TRMs, and other stakeholders will be essential to fully realize the benefits of these technologies in the market.

7.0 References

DOE 2021. Residential Cold Climate Heat Pump Technology Challenge Specification and Supporting Documents Version 1.2. Available at https://www.energy.gov/sites/default/files/2021-10/bto-cchp-tech-challenge-spec-102521.pdf

Mendon V, S Rosenberg, K Keene, M Brambley, J Rotondo, and J Young. 2024. DOE Cold Climate Heat Pump Challenge Field Validation: Data Collection and Analysis Plan. Pacific Northwest National Laboratory, Richland, Washington.

Appendix A Additional Occupant Satisfaction Results

A.1 Site Information Considered for Occupant Satisfaction Results

Site Code	OEM	Site Region	Install Year	Extended Period of Operational Issues?	Same Metro Area?
2089ZA	G	Northeast	Winter 2	-	No
7646TQ	G	Northeast	Winter 2	-	No
2563EH	D	Northeast	Winter 1	-	Yes - Area D3
6112OH	D	Northeast	Winter 1	Yes	Yes - Area D3
8726VB	D	Northeast	Winter 1	-	Yes - Area D3
0734BD	F	Midwest	Winter 2	-	No
1931ZB	F	Canada	Winter 2	-	No
5193YW	F	Midwest	Winter 2	-	No
5878ZD	H	Midwest	Winter 2	-	No
6950NE	A	Midwest	Winter 1	-	Yes - Area A2
8220XE	A	Midwest	Winter 1	-	Yes - Area A2
9944LD	A	Mountain	Winter 1	Yes	No
1145KG	E	Midwest	Winter 2	-	No
3669NT	E	Midwest	Winter 2	-	Yes - Area E4
4958IQ	E	Midwest	Winter 2	-	Yes - Area E4
7750UJ	E	Midwest	Winter 2	-	Yes - Area E4
3176UL	C	Midwest	Winter 1	Yes	Yes - Area E4
5539NO	C	Northeast	Winter 1	Yes	No
7083LM	C	Northeast	Winter 1	-	No
4228VB	B	Mountain	Winter 1	Yes	No

A.2 Survey Responses for Temperature Control

The following table displays how sites responded at each phase of the study to the questions related to whether occupants experienced temperature control issues. “YES”, in green, indicates that the system was able to maintain temperature consistently, while sites that had issues with maintaining temperature control are either indicated by “NO” or by the reported cause of the issue if it was provided.

Did the system consistently maintain temperature? If no, please describe.

Site Code	Pre-CCHP Heating	Pre-CCHP Cooling	Winter 1	Summer 1	Winter 2	Summer 2
2089ZA	YES	YES	-	-	YES	-
7646TQ	YES	YES	-	-	YES	YES
2563EH	YES	YES	YES	YES	YES	YES
6112OH	YES	YES	YES	YES	-	-
8726VB	NO	NO	YES	YES	YES	YES
0734BD	YES	YES	-	-	YES	YES
1931ZB	-	-	-	-	-	YES
5193YW	-	-	-	-	-	YES
5878ZD	YES	YES	-	-	YES	YES
6950NE	YES	YES	-	-	YES	-
8220XE	YES	YES	YES	-	YES	-
9944LD	YES	NO	-	YES	YES	YES
1145KG	YES	YES	-	-	YES	Cooled by 2 to 5 degrees below setpoint
3669NT	YES	NO	-	-	YES	YES
4958IQ	YES	NO	-	-	YES	YES
7750UJ	YES	YES	-	-	Continuously running, falls behind temp setpoint	YES
3176UL	YES	YES	-	YES	YES	YES
5539NO	NO	NO	YES	YES	YES	-
7083LM	YES	YES	YES	-	Cycling on and off too often	YES
4228VB	YES	YES	YES	YES	YES	-

A.3 Survey Responses for Noise Issues

The following table displays how sites responded at each phase of the study to the questions related to whether occupants experienced noise issues. “NO”, in green, indicates that the system did not experience noise issues, while sites that did experience noise issues are either indicated by “YES” or by the reported cause of the issue if it was provided.

Did the system cause any noise issues? If yes, please describe.

Site Code	Pre-CCHP Heating	Pre-CCHP Cooling	Winter 1	Summer 1	Winter 2	Summer 2
2089ZA	NO	NO	-	-	NO	-
7646TQ	NO	NO	-	-	NO	NO
2563EH	NO	NO	Outdoor Unit Vibration	Outdoor Unit Vibration	NO	Loud Indoor Air
6112OH	NO	NO	Loud Indoor Air	Loud Indoor Air	-	-
8726VB	NO	NO	Loud Indoor Air	NO	Loud Indoor Air	NO
0734BD	NO	NO	-	-	NO	NO
1931ZB	-	-	-	-	-	NO
5193YW	-	-	-	-	-	NO
5878ZD	NO	NO	-	-	NO	NO
6950NE	NO	NO	-	-	NO	-
8220XE	NO	NO	Loud Indoor Air	-	NO	-
9944LD	YES	NO	-	NO	NO	NO
1145KG	NO	NO	-	-	NO	NO
3669NT	NO	YES	-	-	Loud Indoor Air	NO
4958IQ	NO	NO	-	-	NO	NO
7750UJ	NO	NO	-	-	NO	Bad Bearing
3176UL	NO	NO	-	NO	Loud Indoor Air	Loud Indoor Air
5539NO	NO	NO	NO	NO	NO	-
7083LM	NO	NO	NO	-	NO	NO
4228VB	NO	NO	NO	NO	NO	-

A.4 Survey Responses for Comfort Issues

The following table displays how sites responded at each phase of the study to the questions related to whether occupants experienced comfort issues. “NO”, in green, indicates that occupants did not experience comfort issues, while sites that did experience comfort are either indicated by “YES” or by the reported cause of the issue if it was provided.

Did the system cause any comfort issues? If yes, please explain.

Site Code	Pre-CCHP Heating	Pre-CCHP Cooling	Winter 1	Summer 1	Winter 2	Summer 2
2089ZA	NO	NO	-	-	NO	

Site Code	Pre-CCHP Heating	Pre-CCHP Cooling	Winter 1	Summer 1	Winter 2	Summer 2
7646TQ	NO	NO	-	-	NO	NO
2563EH	NO	NO	NO	NO	NO	NO
6112OH	NO	NO	NO	NO	-	-
8726VB	Undersized	Undersized - temp diff. by floor	NO	NO	NO	NO
0734BD	NO	NO	-	-	NO	NO
1931ZB	-	-	-	-	-	NO
5193YW	-	-	-	-	-	NO
5878ZD	NO	NO	-	-	NO	NO
6950NE	NO	NO	-	-	NO	-
8220XE	NO	NO	NO	-	YES	-
9944LD	Undersized and Leaky	Undersized	-	Temp Control in High Heat	NO	NO
1145KG	NO	NO	NO	NO	NO	Temp Control
3669NT	NO	Undersized - temp diff. by floor	-	-	NO	Higher than Typical Humidity Levels
4958IQ	NO	Undersized	-	-	Lower than Typical Humidity Levels	Higher than Typical Humidity Levels
7750UJ	NO	NO	-	-	Temperature Control	NO
3176UL	NO	NO	-	NO	NO	NO
5539NO	Temp Control	NO	NO	NO	NO	-
7083LM	NO	NO	NO	NO	NO	NO
4228VB	NO	NO	Cold in Defrost Mode	NO	NO	-

A.5 Survey Responses for HVAC Support

The following table displays how sites responded at each phase of the study to the questions related to whether occupants experienced comfort issues. “NO”, in green, indicates that occupants did not experience comfort issues, while sites that did experience comfort are either indicated by “YES” or by the reported cause of the issue if it was provided.

Prior to the study, how frequently did you require HVAC support? At any point during the study, did you require HVAC support? If so, when, and why?

Site Code	Pre-CCHP Heating	Pre-CCHP Cooling	Needed any HVAC Support?	If Yes, When?	If Yes, Why?
2089ZA	Only when the system breaks down	Only when the system breaks down	NO	-	NO
7646TQ	Never	Never	NO	-	NO
2563EH	Only when the system breaks down	Only when the system breaks down	YES	Summer 1	Condensation on the line set causing water damage
6112OH	Never	Never	NO	-	-
8726VB	Only when the system breaks down	Only when the system breaks down	YES	Summer 2	Condensate Pan Overflow
0734BD	Never	Never	NO	-	-
1931ZB	-	-	NO	-	-
5193YW	-	-	NO	-	-
5878ZD	Only when the system breaks down	Only when the system breaks down	NO	-	-
6950NE	Once per year	Once per year	NO	-	-
8220XE	Twice per year	Once per year	NO	-	-
9944LD	Only when the system breaks down	Never	YES	Winter 2	Bad Leak Detection Sensor
1145KG	Only when the system breaks down	Only when the system breaks down	NO	-	-
3669NT	Every other year	Only when the system breaks down	YES	Winter 2	Sensor Fault
4958IQ	Only when the system breaks down	Only when the system breaks down	NO	-	-
7750UJ	Only when the system breaks down	Only when the system breaks down	YES	Winter 2	Outdoor control board, line set, and sensor replaced
3176UL	Only when the system breaks down	Only when the system breaks down	YES	Winter 2	Control issues with aux. heat setting
5539NO	Once per year	Once per year	YES	Winter 2	Parts replaced
7083LM	Once per year	Once per year	NO	-	
4228VB	Once per year	Once per year	NO	-	-

A.6 Survey Responses for Overall Satisfaction Rating

The following table displays how sites responded at each phase of the study to the questions related to overall satisfaction ratings. Ratings were provided on one to five scale, from lowest to highest satisfaction, respectively.

Rate your overall satisfaction with the system on a 1 to 5 scale, with 5 being the highest.

Site Code	Pre-CCHP Heating	Pre-CCHP Cooling	Winter 1	Summer 1	Winter 2	Summer 2
2089ZA	3	5	-	-	5	-
7646TQ	4	4	-	-	4	5
2563EH	5	5	4	4	4	4
6112OH	4	4	4	4	-	-
8726VB	2	3	4	5	4	4
0734BD	4	4	-	-	4	4
1931ZB	-	-	-	-	-	4
5193YW	-	-	-	-	-	5
5878ZD	4	4	-	-	4	4
6950NE	4	4	-	-	4	-
8220XE	4	4	5	-	4	-
9944LD	2	2	-	4	3	3
1145KG	3	3	-	-	4	2
3669NT	5	3	-	-	4	4
4958IQ	3	2	-	-	4	5
7750UJ	4	4	-	-	3	3
3176UL	3	3	-	5	3	4
5539NO	4	4	4	5	5	-
4	4	5	-	3	3	
4228VB	3	3	4	5	4	-

A.7 Survey Responses for Recommending a CCHP to a Neighbor

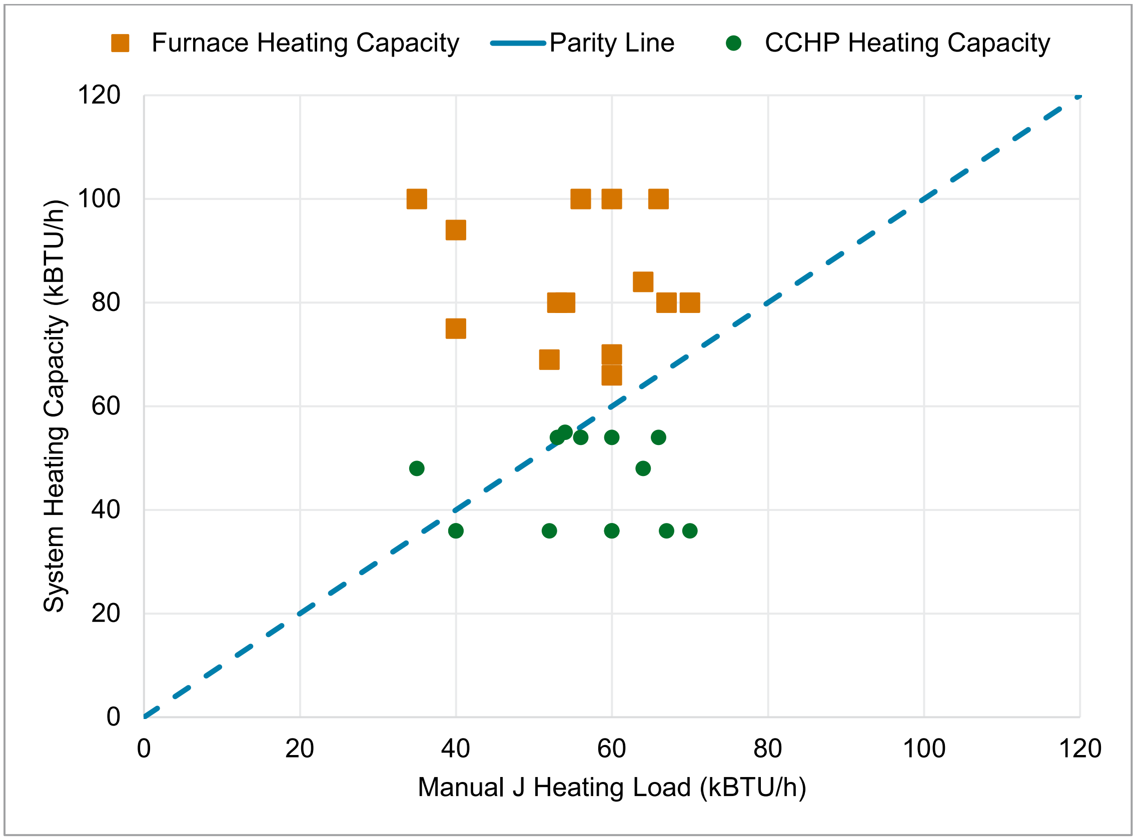
The following table displays how sites responded at each phase of the study to the questions related to whether they would recommend a CCHP to a neighbor. “YES”, in green, indicates that occupants would recommend a CCHP to a neighbor, while “NO”, in red, indicates sites with occupants that would not recommend a CCHP to a neighbor. The team also included any comments or reasoning provided by occupants.

Site Code	Winter 1	Summer 1	Winter 2	Summer 2	Reasoning/Comments
2089ZA	-	-	YES	-	High operational efficiency, low noise output in defrost mode.
7646TQ	-	-	YES	YES	-
2563EH	NO	NO	NO	NO	Higher utility bills
6112OH	YES	YES	-		-
8726VB	YES	YES	YES	YES	-
0734BD	-	-	YES	NO	Higher utility bills compared to natural gas, but better option than other heating systems (elec, propane)
1931ZB	-	-	-	YES	
5193YW	-	-	-	YES	Lower utilitiy bills, higher comfort than previous system
5878ZD	-	-	NO	NO	Higher utility bills compared to natural gas, but better option than other heating systems (elec, propane)
6950NE	-	-	YES	-	-
8220XE	YES	-	YES	-	Noted that potential users should be aware of how the defrost cycle causes temporary periods of low temperatures, but wasn't an issue that decreased overall satisfaction
9944LD	-	NO	NO	NO	Higher utility bills compared to natural gas, but better option than other heating systems (elec, propane)
1145KG	-	-	YES	NO	Higher utility bills and some temperature control issues
3669NT	-	-	YES	YES	-
4958IQ	-	-	NO	YES	-
7750UJ	-	-	NO	NO	Higher utility bills
3176UL	-	YES	NO	YES	-
5539NO	YES	YES	YES		-
7083LM	YES	-	YES	YES	-
4228VB	YES	YES	YES	-	-

Appendix B Additional Installation Types, Upgrades, and Costs Data

B.1 Heating System Sizing vs. Manual J Heating Load

The following chart demonstrates the tendency for furnaces to be oversized for a home's required heating load. The heating capacity for the CCHP prototypes tended to be much closer to the Manual J heating load for sites which originally had a natural gas or propane-fired furnace. An auxiliary electric heater is used to make up the difference between the CCHP heating capacity and the peak heating load.



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