Pacific Northwest
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PNNL-35724

DOE Cold Climate Heat Pump Challenge Field Validation

Data Collection and Analysis Plan

March 2024

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S Rosenberg
K Keene
M Brambley
J Rotondo
J Young (Guidehouse)

U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
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Summary

This document details the data collection, storage, and analysis plan and methodologies for conducting the field validation portion of DOE's Cold Climate Heat Pump (CCHP) Challenge. The study is focused on validating the in-field heating performance of prototypical CCHPs that have successfully demonstrated that they meet or exceed the Challenge specification in a laboratory setting. The units that have passed laboratory testing will be installed in real homes along with sensors and loggers for monitoring performance over an entire heating season. Data collected through monitoring will be cleaned and stored in a secure database. The data will be analyzed for calculating the key metrics defined by the Challenge including heating capacities at low outdoor air temperatures (below 32 ºF), efficiency in terms of the Coefficient of Performance (COP), switchover temperatures and auxiliary heat staging. Demand Response (DR) capabilities will also be tested using specially designed DR events. In most cases, shoulder season and cooling season performance will also be determined and reported.

The first chapter of the document describes the Challenge specifications and provides an overview of the study. The next two chapters describe the field instrumentation and data collection plan, the database schema and privacy controls, and data storage and archiving. The last chapter describes the planned data analysis methodologies for the quantitative data as well as the qualitative data collected through pre- and post-study surveys. The instrumentation plan is included in the Appendix for reference.

Acknowledgments

This report was prepared by the Pacific Northwest National Laboratory (PNNL) for the U.S. Department of Energy Building Technologies Office (DOE-BTO). Members of the Guidehouse team supporting the field testing include Bill Goetzler, Jim Young, Ali Kazmi, and Carolyn Barrera.

Acronyms and Abbreviations

AHRI	Air Conditioning, Heating, & Refrigeration Institute
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CCHP	Cold Climate Heat Pump
COP	Coefficient of Performance
DOE	U.S. Department of Energy
DOE-BTO	U.S. Department of Energy Building Technologies Office
DR	Demand Response
EER	Energy Efficiency Ratio
EERE	Office of Energy Efficiency and Renewable Energy
EPA	Environmental Protection Agency
GWP	Global Warming Potential
HPDB	Heat Pump Database
HSPF	Heating Seasonal Performance Factor
HVAC	Heating, Ventilation and Air Conditioning
M&V	Measurement and Verification
NRCan	Natural Resources Canada
NREL	National Renewable Energy Laboratory
ORNL	Oak Ridge National Laboratory
PNNL	Pacific Northwest National Laboratory
POSIX	Portable Operating System Interface
SEER	Seasonal Energy Efficiency Ratio

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Introduction

As part of the Initiative for Better Energy, Emissions, and Equity (E3 Initiative), the US Department of Energy (DOE) has launched the Residential Cold Climate Heat Pump Technology Challenge (CCHP Challenge) to accelerate the deployment of cold climate heat pumps (CCHPs). The goal of the CCHP Challenge is to advance the performance of CCHP technologies above the performance of best-in-class products available today, while also meeting consumer and stakeholder expectations. The challenge is currently focused on residential, centrally ducted, electric heat pumps, with a nominal cooling capacity (or nominal heating capacity for a heating-only heat pump) greater than or equal to 24,000 Btu/h and less than or equal to 65,000 Btu/h.

Spearheaded by DOE in partnership with the US Environmental Protection Agency (EPA) and Natural Resources Canada (NRCan), the Challenge brings together major heat pump manufacturers and key stakeholders including utilities and state agencies across the country. Figure 1 shows the overall Challenge timeline sourced from a Preliminary Field Demonstration Plan developed by Guidehouse for the DOE Office of Energy Efficiency and Renewable Energy (EERE) in June 2022 (EERE 2022). [1] The project is currently in the laboratory testing stage transitioning towards the first round of field testing in Winter 2022-2023. DOE has funded the Pacific Northwest National Laboratory to oversee the field validation study, with a second round of field testing planned for Winter 2023-2024.

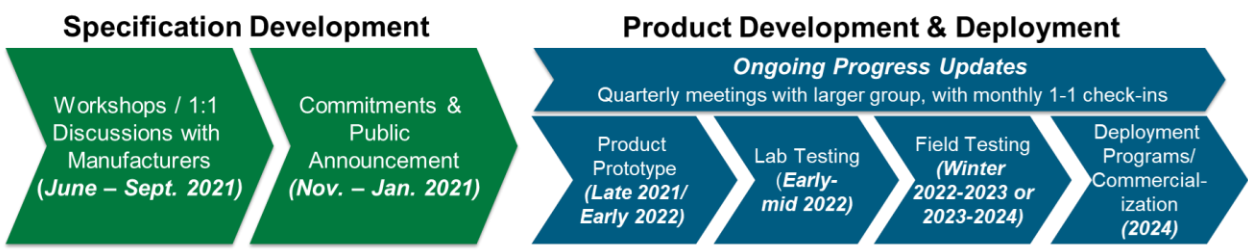

Figure 1. CCHP Technology Challenge Timeline (Source: EERE 2022)

Challenge Specifications

The CCHP Challenge specifications represent a best-in-class heat pump product that provides high-efficiency heating performance in cold climates, employs environmentally friendly low-Global Warming Potential (GWP) refrigerants, and is designed to be grid interactive[2]. The Challenge specifications consist of performance specifications (Table 1), a less than 750 GWP refrigerant requirement, and the *connected product criteria* requirements. The performance specifications were developed based on a review of current CCHP performance data from the Northeast Energy Efficiency Partnerships database[3] and discussions with several manufacturers on technology opportunities and limitations. The Challenge performance specifications represent targets that would exceed current products on the market today and align with a 2024 commercialization timeline.

[1] Prototype development and lab testing timelines will vary for each manufacturer as they prepare for winter 2022-2023 or winter 2023-2024 testing.
[2] CCHP Technology Challenge Specifications. https://www.energy.gov/eere/buildings/cchp-technology-challenge-specifications
[3] https://ashp.neep.org/#!/

The Challenge has two segments: one for a CCHP optimized for 5 °F (-15 °C) operation (“5 °F challenge”) and the other for a CCHP optimized for -15 °F (-26 °C) operation (“-15 °F challenge”). Manufacturers can choose to participate in either one or both segments of the Challenge, although both the 5 ºF (-15 ºC) and -15 °F (-26 °C) requirements must be met for a heat pump participating in the -15 °F (-26 °C) Challenge (DOE 2021). Additionally, the units must employ a refrigerant with a GWP no more than 750 and comply with specific connected product installation capability, communications, consumer feedback and demand response requirements set forth by ENERGY STAR Product Specification for Central Air Conditioner and Heat Pump Version 6.0 (ENERGY STAR 2020).

Table 1 presents a summary of the CCHP Challenge specifications and Table 2 summarizes the electric heat staging requirements. More details are included in the CCHP Challenge specification and supporting documents (DOE 2021).

Table 1. Summary of the DOE CCHP Challenge Specifications

HP nominal capacity (Btu/h)[1]	Seasonal Heating Performance		Heating at 5°F (-15°C)				Heating at -15°F (-26°C) *(optional)*	
	Min HSPF2	**Min. Turndown 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			2.4	100%				
>36,000 and ≤48,000	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)
>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 percent for every 10% $H1_1/H1_N$ gap. The capacity factor for northern triple capacity HPs is 0.
[3] COP factor: 2 percent 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 Table II-1 of the Challenge specification (reproduced in Table 2 below)

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

(3) Unit shall comply with Sections 3C, 4B, 4C, and 4D of the ENERGY STAR CACHP specification

Table 2. DOE CCHP 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

Study Overview

This study focuses on field validation of the CCHP prototypes in real homes. Each prototype unit is expected to meet all CCHP Challenge specifications in laboratory testing before proceeding for installation in selected homes for the field validation. The prototypes will be matched to a specific site based on the heating load requirements of the given home and the unit's capability to serve the load.[1] Sites will be in cold or very cold climates, thereby facilitating the evaluation of the heating performance of the units. Based on early feedback collected from participating manufacturers and key stakeholders, shoulder season and cooling performance will also be monitored.

The field study will collect all data required to calculate the metrics specified by the CCHP Challenge specification over the heating season. The research team will then calculate the metrics, aggregate, and anonymize data as appropriate and report on results. The data will be stored in a secure database maintained by the research team over the period of the project. Manufacturers will only be provided access to data for their respective units during the study period.

The execution of the field validation portion will be divided over a period of two winters. This will accommodate manufacturers progressing on different schedules through the stages of product development and laboratory testing before approval for field installation.

Participating Manufacturers

Overall, eight major HVAC manufacturers are participating in the DOE CCHP Challenge:

- Lennox
- Carrier
- Trane
- Rheem
- Bosch
- Daikin
- Johnsons Controls

[1] Each manufacturer is developing only one heating capacity for laboratory testing, so the team has recruited applicable host sites that would have a heating load that would match the heating capacity for each manufacturer's prototype. It is expected that manufacturers would have a full range of capacities (e.g., 2, 3, 4, and 5 tons) when ready for commercialization.

- Midea

Study Period

The field validation will be conducted over Winter 2022-2023 and Winter 2023-2024 to allow the manufacturers adequate time for completing laboratory testing. As previously discussed, the study primarily focuses on heating season performance to align with the CCHP Challenge specification. However, manufacturers and key stakeholders have expressed an interest in leveraging the deployed units and sensors to evaluate shoulder season data over the spring and cooling season performance over the summer. The research team plans to leave the sensors and equipment in place to collect data over these additional periods and will conduct analysis to report performance metrics subsequently.

Data Measurement and Verification

This section describes the details of the field validation plan, data points along with the measurement frequency, instrumentation details, and design of the demand response (DR) experiment. The research team works closely with selected Measurement and Verification (M&V) subcontractors to execute the data collection plan.

Draft Field Validation Plan

In Spring 2022, Guidehouse developed a draft field validation plan for the DOE CCHP Challenge under funding from DOE (EERE 2022). The draft was reviewed by participating manufacturers and key stakeholders including utility partners as well as the PNNL team and was revised in June 2022 to incorporate feedback provided by the reviewers. This plan lays out details of the metrics to be calculated during the field validation exercise, data points as well as the calculation methodologies.

Data Points and Frequency

Table 3 summarizes the data points to be collected at each site along with the proposed recording intervals.

Table 3. Data Points and Recording Frequency

No.	Parameter	Location	Recording Interval
1	Outdoor Unit Power	Outdoor unit circuit	1 second
2	Temperature/Relative Humidity	Outdoor unit inlet	5 minutes
3	Heat / cool / off / defrost on	At reversing valve	1 second
4	Indoor Unit Power	Indoor unit circuit	1 second
5	Fan power	Indoor fan circuit	1 second
6	Temperature/Relative Humidity	Supply Air outlet	1 minute
7	Temperature/Relative Humidity	Return air inlet	1 minute
8	Temperature/Relative Humidity	Indoor Unit Ambient	1 minute
9	Temperature/Relative Humidity	Conditioned Space (at least 3 over the conditioned area)	1 minute
10	Volumetric air flow	Air handler return / filter housing	Upon installation, airflow rate will be correlated with fan power
11	Status on/off	Electric strip	1 second
12	Auxiliary Power	Electric strip	1 second

Demand Response

The DOE CCHP Challenge field trial presents an opportunity to evaluate the new demand response (DR) capabilities of the variable-capacity CCHPs. The Challenge specification requires the prototypes to demonstrate the connectivity and DR capabilities required by ENERGY STAR CAC-HP Specification v6.0 (ENERGY STAR 2020) which bases the connectivity functionality upon *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 2019). Each manufacturer will demonstrate these capabilities through laboratory testing prior to proceeding with field testing.

AHRI 1380 demand response capabilities are new to the utility industry, manufacturers, and other industry stakeholders, with very few lab or field pilots conducted to date. Evaluating the performance and communication capabilities of the CCHP Challenge heat pumps in the field will support greater understanding for how future DR programs can be designed around this standard as more variable-capacity HVAC products enter the market in future years. As part of the laboratory testing, each Challenge prototype is expected to undergo tests to confirm that system communications and heat pump operation are responding correctly to the DR signals. Calling DR events during the field testing will evaluate how well the system communications and heat pump operations perform in a real-world setting under a complete range of heating (and cooling) conditions for each location.

The research team anticipates conducting the following events at each host site:

- Winter:
  - One or more general curtailment event (30% power reduction) near peak winter loads (around 10-20 ºF outdoor air temperature)
  - One critical curtailment event (60% power reduction) at more moderate conditions (around 30-40 ºF outdoor air temperature)
  - One critical curtailment event (60% power reduction) near peak winter loads (around 10-20 ºF outdoor air temperature)
- Summer:
  - One or more general curtailment event (30% power reduction) near peak summer loads (around 90 ºF outdoor air temperature)
  - One critical curtailment event (60% power reduction) at more moderate conditions (around 80-85 ºF outdoor air temperature)
  - One critical curtailment event (60% power reduction) near peak summer loads (around 90 ºF outdoor air temperature)

The DR capability testing will be facilitated by the National Renewable Energy Laboratory (NREL) in coordination with the research team. The simulated DR events will be planned for 4 hours or less during daytime hours (i.e., morning, midday, afternoon, early evening). The research team will monitor the weather forecast, and when the weather is forecasted to be favorable, the team will notify the host site via email and/or phone 4-5 days in advance of the event with the expected time, duration, and DR event type (i.e., general, or critical curtailment). The homeowner can "opt-out" of an event before the event begins, or at any time during the DR event through the smart thermostats installed with the CCHPs. The research team will assess DR responsiveness of the units, the energy savings achieved during the event and the impact on indoor space conditions.

Measured Data Collection and Management

The research will store all data for the CCHP project in the Heat Pump and Heat Pump Water Heater Field Database (HPDB)[1], a database being developed and maintained by PNNL, under funding from DOE with the goal of creating a repository for heat pump and heat pump water heater performance data. Leveraging this existing database provides efficiency to both PNNL and DOE-BTO; rather than developing a new database within PNNL Research Computing, the project team is using a resource that has approved DOE data protections and was developed specifically for this technology. While the HPDB has a public facing website, strict access controls will be implemented to create a secure view only visible by users specific to this project. Additional roles and data access controls will be utilized to allow different users to have different levels of access to the data collected through this project.

This section describes the type of data that will be collected throughout the field validation project, how they will be stored and transferred, how data access controls will be configured, the various groups of users who will have access, and the data sharing and privacy controls that will be incorporated for different groups of users.

De-identification of Personal Identifiable Information

Because this study involves home occupants and thus human subjects, the research team applied to the PNNL Institutional Review Board (IRB) for approval of the study plan. The team received approval in August 2022. The IRB process includes approval of detailed documents pertaining to the informed consent of participants, details about study procedure and equipment installation, protocols for protecting personal identifiable information (PII) of the participants, recruitment emails and pre- and post-study surveys. The research team will utilize these materials for recruiting participants and guiding interactions with the participants. Members of the research team have also completed the Collaborative Institutional Training Initiative (CITI program) training on Social and Behavioral Research in preparation for this study[2].

Once the manufacturer finalizes the sites for installation, the project team will collect the participants' names, home addresses, phone numbers and email addresses for coordination of the installation of the CCHP and the sensors and logging equipment. The project team will de-identify PII including the name and street address by converting them to a unique alphanumeric code. The code will serve as the unique site identifier and will be used to collect and store all data for analysis as well as for conducting pre- and post-study surveys.

The spreadsheet linking the names and addresses with the alphanumeric code will be the only data that will contain PII. This spreadsheet will be stored on the local hard drive of a single PNNL laptop computer. Per PNNL security policies, this computer is kept up to date with IT security patches through regular network updates, is password protected and locked when not in use. In the unlikely event that PII data needs to be copied from this computer to removable media, FIPS 140-2 certification encryption tools such as Entrust will be used to encrypt the data on removable media. Similarly, if sharing PII over email is absolutely necessary, data files containing PII will be encrypted with FIPS 140-2 certified encryption tools, only accessed via secure, encrypted internet connection using TLS 1.1 protocol or newer, and incorporate two-factor authentication for logon access. Passwords for unlocking files will be sent separately from

[1] https://dfeprod01.pnnl.gov/hpdb/

[2] https://about.citiprogram.org/

the encrypted data files. Finally, the project team will make every effort to limit the access and disclosure of participants' personal information, including research study records, to people who have a need to review this information.

The selected participants will be sent copies of the informed consent forms and the pre-study survey developed by the research team and approved by IRB via email. Each participant will be asked to return a signed copy of the informed consent form securely via DocuSign[1]. Once the research team receives the signed informed consent forms, the team will begin coordinating the installation process.

Data Collection and Transfer Protocol

The data points described previously will be collected through a set of sensors and loggers at each site. The research team plans to coordinate the installation of these sensors and loggers at the same time as the installation of the CCHPs at participating sites. Table 4 summarizes the measuring equipment proposed for collecting data for each parameter.

Table 4. Proposed Data Points and Measuring Equipment

No.	System	Parameter	Measuring Equipment	Location
1	Outdoor unit	Power	Power meter + current transducer	Outdoor unit circuit
2	Outdoor unit	Temperature/Relative Humidity	Thermocouple, RH sensor, solar shield	Outdoor unit inlet
3	Outdoor unit	Heat / cool / off / defrost on	Relay	At reversing valve
4	Indoor unit	Power	Power meter + current transducer	Indoor unit circuit
5	Indoor unit	Fan power	Power meter + current transducer	Indoor fan circuit
6	Indoor unit	Temperature/ Relative Humidity	Thermocouple (TC) grid /RH sensors	Supply Air outlet
7	Indoor unit	Temperature/ Relative Humidity	Thermocouple (TC) /RH sensor	Return air inlet
8	Indoor unit	Temperature/ Relative Humidity	Thermocouple (TC) /RH sensor	Unit Ambient
9	Conditioned Space	Temperature/ Relative Humidity	(3) Thermocouple (TC) / (3) RH sensor	Conditioned Space (at least 3 over the conditioned area)
10	Indoor unit	Volumetric air flow	Airflow metering plate	Air handler return / filter housing (at installation for initial correlation)
11	Auxiliary Heat	Status on/off	Relay	Electric strip
12	Auxiliary Heat	Power	Current transducer	Electric strip

The data collected by the sensors and loggers deployed in the field will be cleaned by the M&V contractor and uploaded securely to the HPDB by the PNNL team. Depending on the

[1] https://www.docusign.com/

instrumentation plan finalized with the M&V partner, the PNNL team will either directly download data for each site from the portal established by the M&V partner or will be sent periodic data files over PNNL's secure FTP server. The PNNL team will then upload the data to the appropriate manufacturer space on the HPDB, make it accessible to applicable users and conduct analyses.

Database Schema

Table 5 and Table 6 summarize the HPDB schema, as it relates to this field validation effort. Where relevant, comments add more detail about specific fields related to this project.

Table 5. Study Metadata

Field	Data Type / Values / Units	Comments
Study		
Study ID	text box	UID
Study occupancy	occupied, unoccupied	
Study sector	residential, commercial	*residential
Study technology type	heat pump, heat pump water heater	*heat pumps
Study type	performance measurement, load shifting	
Building		
Building type	single-family, multifamily	*single-family
Year of construction	int	
Total Conditioned Square footage	float (ft^2)	Only include space located within the building envelope.
Number of bedrooms	int 0-99	
Number of full bathrooms	int 0-99	
Number of occupants	int 0-99	
Weatherization completed first?	yes or no	
Thermostat locations	text	
Ductwork location	conditioned attic, conditioned basement, conditioned crawlspace, unconditioned attic, unconditioned basement, unconditioned crawlspace	
Ductwork insulation level	R-value	
HVAC		
HP equipment manufacturer	text	
Backup heating system	none, gas, electric, oil, wood	
Description of backup heating	text box	
Backup unit make and model number	text	
Type of heat pump unit		*centrally ducted

Field	Data Type / Values / Units	Comments
Square footage served by this outdoor unit	float (ft^2)	
Rated heating capacity	int Btu/hr	
Rated cooling capacity	int Btu/hr	
Rated Seasonal Energy Efficiency Rating (SEER)	float 0-99	
Rated Heating Seasonal Performance Factor (HSPF)	float 0-99	
Rated Energy Efficiency Ratio (EER)	float 0-99	
Rated Coefficient of Performance (COP)	float 0-99	
Compressor type	single speed, variable speed	*variable speed
Control strategy (setpoints, dead bands, etc.)	text	
Whole-house mechanical ventilation system type	Exhaust, CFIS, inline supply, ERV/HRV	for all specify continuous, intermittent, or uncontrolled

* Indicates the value applicable for this project within the value options available in the database schema

Table 6. Study Time-Series Data

Field	Data Type	Unit	Comments
Study			
Site ID	string		Unique ID
Outdoor unit ID	string		
Timestamp	POSIX (Y-m-d H:M:S)		Local time of field data
Energy Consumption			
HVAC system power	float 0-99	kW	
HVAC outdoor unit power	float 0-99	kW	
HVAC indoor unit power	float 0-99	kW	
Supply fan power	float 0-99	kW	
Supplemental/backup heat power	float 0-99	kW	
Temperature and Relative Humidity			
Outdoor dry-bulb air temperature	float 0-99	deg F	
Outdoor relative humidity	float 0-99	%	
Outdoor wet-bulb temperature	float 0-99	deg F	
Indoor dry-bulb air temperature at thermostat	float 0-99	deg F	

Field	Data Type	Unit	Comments
Indoor relative humidity at thermostat	float 0-99	%	
HVAC return dry-bulb air temperature	float 0-99	deg F	
HVAC return relative humidity	float 0-99	%	
HVAC supply dry-bulb air temperature	float 0-99	deg F	
HVAC supply relative humidity	float 0-99	%	
Total duct static pressure differential between supply and return	float 0-99	Inches of WC	
Supply volumetric air flow rate	integer	CFM	
Thermostat set point	float 0-99	Deg. F	
Operating mode	string		
Heating output	float	Btu/h	Calculated upon data input
Heating COP	float		Calculated upon data input
Cooling output	float	Btu/h	Calculated upon data input
Cooling COP	float		Calculated upon data input

Data Sharing and Privacy

The HPDB has several layers of privacy that can be leveraged to ensure that data from this project remains in the private domain and not in the public facing space of the database.-This project will facilitate data sharing and maintain data security by employing two main principles:

Each manufacturer will only have access to data for their respective units. The web framework on which the HPDB is built provides mechanisms for accounts, user roles, user permissions, groups, and content access controls. Using these capabilities, the HPDB can restrict access of content to specific groups of users. Only users with sufficiently elevated roles will have access to all content. Content may also be marked as public and available to any users (including anonymous) if so desired.

PNNL researchers will be assigned the role of an admin which will allow the PNNL team to grant access and assign roles, groups, and permissions view all data, upload, and download data for any other user, and manage access to users. PNNL will be responsible for uploading data collected during field validation from all sites.

Manufacturer accounts will be assigned user roles and will not have permissions to view any private data except for that which is related to their test units. While the manufacturers can download data for their units for their internal review and analysis, the data is PNNL proprietary data bound by conditions laid out in the Non-Disclosure Agreement (NDA) between the manufacturer and PNNL. If multiple accounts associated with the same manufacturer are desired, they will be assigned to a group, which shares permissions to view private data related to the test units from that particular manufacturer. Users who are in a group assigned to one manufacturer will not be able to view private data for a group associated with a different manufacturer.

There will be overarching security measures applicable to the entire database. PNNL hosted servers live behind an enterprise firewall in compartmentalized network enclaves to reduce risk and exposure. The web server runs up-to-date enterprise software patched regularly to address security concerns, and the physical hard drive on the server is encrypted to prevent direct access to the content it stores. Direct access to the physical server requires access to the room in which it lives, requiring a physical access token and specifically granted access to the server room. Access to the website from the internet forces all requests through an encrypted Secure Sockets Layer (SSL) connection from the user browser to the website to encrypt all web traffic and uploads/downloads between the two. Monitoring of the server is automated and designed to alert network staff immediately if any server issues are detected.

The research team proposes the following layers of data sharing controls through a combination of “roles” and “groups” offered by the HPDB. This information is summarized in Table 7.

- **Admin/PNNL Team:** “Admin” role that allows the PNNL team to grant access and assign roles, groups, and permissions to view all data, and upload and download data for any other user and manage access to users. The PNNL team will upload cleaned data collected from the site, conduct analysis, and develop detailed results as well as anonymized aggregated trend-level data for dissemination.
- **Research Team:** In addition to the PNNL team members, the research team will include project partners Guidehouse and the selected M&V contractors. Users in this group will have access to all data from all manufacturers and sites. However, users in this group will not be able to assign groups or roles to other users. All PNNL subcontractors, including Guidehouse and the M&V contractors, will be bound by the provisions of the NDA signed by Battelle with each manufacturer.
- **Manufacturers:** “User” role that allows the manufacturer to view data related to their own test units. If multiple users from the same manufacturer require access, they will be assigned to a “group” so that they may access their own data as a group. A given group will only be able to access data for which the admin has provided access. They will not be able to access data from other groups.
- **Other Research Partners and Key Stakeholders** (with prior DOE permission): Access to aggregated and anonymized data, made available by the admin.

Table 7 summarizes the planned roles and access controls for the groups identified above. PNNL will work closely with the research team and the four manufacturers participating in the Winter 2022-2023 validation period to implement the access controls for the different groups of users.

Table 7. Database Access Controls for Different Groups

Group	Who is in this group?	What can this group do?
Admin	PNNL	Assign individual users to groups, allow or restrict access to data for specific users or groups of users, upload data as their own user or any other user, view all public and private data in HPDB.

Group	Who is in this group?	What can this group do?
Research Team	Guidehouse and M&V contractors	View all public and private data in CCHP project directory of HPDB, but no private data outside of CCHP project directory.
Manufacturer	Each of these manufacturers will have a unique group: - Lennox - Carrier - Trane - Rheem - Bosch - Daikin - Johnsons Controls - LG - Midea - Mitsubishi Electric	Group of users with standard user role for HPDB site users. Each manufacturer will have their own unique group. Any user in a manufacturer group will be able to view data that is specific to the manufacturer and public data in CCHP project directory of HPDB. A user in Manufacturer Group A will not have access to private data for Manufacturer Group B.
Other Research Partners and Stakeholders	- Utility Partners - Program Administrators	View anonymized, aggregated data across multiple manufacturers and multiple sites. Requires prior approval from DOE.

In addition to the data directly collected by the sensors deployed during the installation process, the research team will have access to data collected by the manufacturers through a Wi-Fi enabled smart thermostat which will be installed in all homes during the installation of the CCHPs. This data will be made available to the research team by the manufacturer with approval of the home occupants and could potentially serve as additional points for data validation and redundancy if needed.

Storage and Archives

All PII will be stored digitally on a local hard drive on a single PNNL laptop with encrypted storage and a printed copy will be stored in a locked cabinet per IRB guidelines. All study data will be de-identified and scrubbed of PII before uploading to the HPDB. Study data will be stored on physical encrypted drives owned by PNNL, and in the HPDB. The de-identified survey and home energy data will be retained according to PNNL record retention policy. The Excel spreadsheet and printed copy of alphanumerical identifiers linked to names and addresses will be destroyed once the study is completed. However, a list of the alphanumerical identifiers linked to the CCHP model (and manufacturer name) and the location (city, state only) will be maintained on PNNL-password protected computers and will be archived according to PNNL records policy and procedure.

Data Analysis

This section describes the data analysis methodologies associated with calculating the quantitative metrics included in the Challenge specifications as well as the qualitative metrics that will be determined based on the pre- and post-study surveys of the participants.

Challenge Metrics and Calculations

The following are key metrics that will be used to evaluate heat pump performance.

- **Heating Capacity**: Delivered heating capacity will be evaluated for various outdoor temperature bins. Heating capacity (Btu/h), turndown ratio[1], and the ratio of heating capacity at 5 °F compared with the heating capacity at 47° F[2] will be determined. Furthermore, the team will track the heating capacity over the entire operating range, including to -15 °F and below, where applicable. Heating capacity calculations are described in the section below.
    - A similar calculation for cooling capacity will be performed with a possible wet-bulb temperature adjustment. The cooling capacity will be reported at an outdoor air temperature of 95 ºF and tracked over the entire operating range. This calculation is described further below.
- **Coefficient of Performance (COP)**: COP will be calculated at each timestep and evaluated for various outdoor temperature bins and at 47 °F and 5 °F and will be used in determining seasonal performance for comparison with Heating Seasonal Performance Factor (HSPF) ratings. This can be compared with a calculation for ideal COP with auxiliary heating elements not engaged. COP calculations are described in the section below.
    - Cooling performance metrics (COP, Energy Efficiency Ratio (EER), Seasonal Energy Efficiency Rating (SEER)) have not been explicitly included in the Challenge specification; however, feedback received suggests that manufacturers and key stakeholders are interested in evaluating cooling performance metrics. The research team plans to collect data for the cooling season. A calculation for the cooling efficiency (i.e., EER) will be performed, calculated at an outdoor air temperature of 95 °F, indoor air temperature of 80 °F, and 50% relative humidity.
- **Cycle Runtimes**: Heating and cooling cycle start and stop times will be used to diagnose and characterize system performance. Runtime information will help identify best practices for CCHP system sizing with variable-speed systems. Calculated metrics will include average runtime and cycle frequency grouped by outdoor air temperature bins. If frequent, short cycles are observed, that signifies that the system cannot sufficiently modulate down to meet lower heating and cooling loads. Time periods with multiple, short runtimes can be automatically flagged and individually evaluated to assess the behavior of the equipment for short cycling.

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[1]Turndown ratio refers to the ratio of the heating maximum and minimum capacities for specific outdoor ambient temperature or other test point.
[2]The CCHP Challenge requires lab demonstrated performance of 100% capacity ratio of 5 °F to 47 °F.

- **Defrost Runtimes**: The average frequency and length of the defrost mode, grouped by outdoor air temperature bins will be used to evaluate defrost events. The power consumed over defrost events at various temperatures will be used to evaluate the energy demand of defrost cycles. Defrost events will be identified in the measured data and evaluated to check for patterns in conditions.

- **Switchover Temperature**: Switchover outdoor air temperature will be evaluated based on the onset of auxiliary heating to serve the required heating load. The metric will be the outdoor air temperature below which auxiliary heat is first engaged. The initiation of the auxiliary system will be recorded in the sensor data and the outdoor temperature at the onset of that event will be noted as the switchover temperature The outdoor air temperature below which the heat pump turns off and the unit operates purely in auxiliary heating mode will also be noted.

- **Auxiliary Heat Staging**: Auxiliary heat staging will be evaluated using the power consumption of auxiliary heaters at various outdoor air temperatures. Ideally, the system will run at low stages for most of the time and occasionally modulate to a higher stage to meet high thermal loads. The auxiliary heat staging will be evaluated by the average duration of time in each stage and the frequency of stage modulation during an auxiliary heating event grouped by outdoor air temperature bins. The researchers will confirm whether the staging performance meets the specifications defined by the Challenge.

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

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

$$\boldsymbol{m_{air} = \rho_{dry} V_{blower}} \quad (1)$$

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:

$$\boldsymbol{Q_{heating} = m_{air} C_{p,sup} (T_{sup} - T_{ret})} \quad (1)$$

and the cooling capacity ($Q_{cooling}$) is given by:

$$\boldsymbol{Q_{cooling} = m_{air} (h_{sup} - h_{ret})} \quad (2)$$

$$\boldsymbol{h_{sup} = [0.24 * T_{sup} + \omega_{sup} * (0.444 * T_{sup} + 1075)]} \quad (3)$$

$$h_{ret} = [0.24 * T_{ret} + \omega_{ret} * (0.444 * T_{ret} + 1075)] \qquad (4)$$

where

m_{air} is the air mass flow rate (lb da/h) from equation (1)

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

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

T_{sup} is the temperature of the supply air, ºF

T_{ret} is the temperature of the return air, ºF

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:

$$COP_{heating} = \frac{Q_{heating}}{3.412 * P_{total,heating}} \qquad (3)$$

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

An extrapolation approach can be used to calculate heating capacity at temperatures that were not recorded or are lacking sample points, if needed.

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

$$COP_{cooling} = \frac{Q_{cooling}}{3.412 * P_{total,cooling}} \qquad (4)$$

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

The EER in units of kBtu of cooling per kWh of input power is a metric that will be used to evaluate cooling performance and is given by

$$EER = \frac{Q_{cooling}}{P_{total,cooling}} \quad (5)$$

Typically, the EER is calculated at an outdoor air temperature of 95 ºF, indoor air temperature of 80 ºF, and 50% relative humidity. The season equivalent, SEER, is calculated similarly but over the entire cooling season.

In addition to the key metrics identified above, the following supplemental data will also be collected in this study:

- **Thermal Comfort**: Measured outdoor ambient, supply and return air dry-bulb temperatures and relative humidity values collected from the field measurements can be used to determine the Predicted Mean Vote (PMV) as defined by ASHRAE Standard 55: Thermal Environmental Conditions for Human Occupancy (ASHRAE 2020). Metrics can include the percentage of time within the general comfort range. Box-and-whisker plots will be used to show the distribution of data for each parameter. Note that thermal comfort will also be evaluated as a qualitative metric based on the post-study survey data. The qualitative and quantitative evaluations will be conducted separately.

- **Weather Data**: Local weather data will be acquired to generally confirm the primary outdoor temperature and humidity measurements and fill in missing datapoints (such as outdoor barometric pressure for the dry air density used to calculate mass flow rate). Heat pump performance at other geographical locations can be estimated based on the difference in heating degree days (HDD) and hourly temperatures.

Data Review and Quality Analysis

The M&V team will conduct a preliminary data review and quality analysis on the data collected from the field before passing it on to the research team. The research team will account for the following considerations related to data quality and analysis:

- The timestamps for each sensor will be converted to a POSIX (Portable Operating System Interface) measure for standardization of the time zone, daylight savings time, and timestamp format. The process of identifying the time zone and raw timestamp format will be done for each sensor as a step during data processing.

- The unit of measure for each parameter will be confirmed at the beginning of data collection and verified by confirming that collected data values fall within the pre-defined expected range. Extreme outliers, if present, will be evaluated to understand the source.

- Data may be aggregated, such as minute averages or hourly averages during data processing to make graphs more legible or to improve processing speed. This will only be done if the first pass at the analysis shows that it would be beneficial for each specific parameter.

- Scatter plots will be included in the data analysis for each parameter and will be used for an initial quality check and to identify any overarching trends. Multiple parameters can be compared on a secondary axis, such as heating capacity and outdoor temperature to help to understand general relationships.

- Summary statistics in the form of graphs and tables can be used to compare locations or compare data within a location by a secondary variable, such as month of the year, hour of the day, day of the week, outdoor temperature range, outdoor humidity range, climate zone, etc.

- The data analysis process can incorporate flags for what will be considered interesting by the research team, such as a certain number of defrost events in a day or outdoor temperature going below a certain threshold, and diagnostic graphs can be created automatically for those events to help provide insights.

Manufacturers can work with the project team to connect their own on-board or add-on monitoring devices to measure additional data (especially refrigerant side measurements), provided that these devices do not interfere with the collection of the primary data as implemented by the research team. Having on-board and field-installed sensors can help troubleshoot data anomalies or explain unexpected observed performance and serve as additional datapoints if necessary.

Survey Data and Qualitative Metrics

In addition to the key performance metrics described in the previous section, the research team will also capture key qualitative data and insights related to non-energy impacts, customer feedback, and project observations. The qualitative information will help the project team understand the overall success of the field demonstration and future CCHP deployment planning by examining more subjective metrics (e.g., comfort, noise, reliability, satisfaction) and the potential installation costs and complexity for conversion to CCHP products. Comfort, reliability, satisfaction with the technology, and lower energy bills are critical factors for the long-term success of the technology. The team will gather this qualitative information through the following means:

- Conducting pre- and post-study surveys with the host site participants.

- Reviewing the HVAC installer quotes for installation cost, list of materials, and key activities (Note that the product cost of the CCHPs will not be considered in this analysis).

- Detailing key activities during installation, including quantitative details regarding the need for any duct, electrical, and other upgrades, as well as an installer survey or interview. Understanding the need for additional maintenance is another important component to ensure the success of the technology.

- Recording reported CCHP reliability and maintenance issues over the study period.

- Documenting key concerns and questions raised by installers, homeowners, code officials, and other stakeholders involved in the projects.

- Estimating annual operating cost based on the observed CCHP performance metrics and the local utility and fuel rates for the CCHP and equivalent baseline systems. A range of energy prices can be used to evaluate other locations and potential future scenarios.

Table 8 outlines the key qualitative metrics of interest for the field study. Within the final report, the team will present the results from the pre- and post-surveys, installer quotes, upgrade needs, and other findings for each of the host sites, by manufacturer, and an overall average, where appropriate. The team will also highlight findings and trends of interest, especially if they may relate to the quantitative performance metrics observed in the field testing. The small sample for this study limits the ability to draw conclusions with statistical significance, but the qualitative insights will still provide significant value for DOE and manufacturer, state, and utility partners as they develop their CCHP deployment strategies.

Table 8. Qualitative Metrics of Interest

Metric	Definition
Thermal Comfort	Occupant thermal comfort will be evaluated through 1) pre/post occupant survey to understand how well the delivered space conditions (temperature, humidity, airflow) meet the desired space conditions of the occupants, and 2) the use frequency of supplemental/backup space heating systems (e.g., fireplace, electric baseboard, portable heater).
Noise	Satisfaction and dissatisfaction with noise will be evaluated through pre/post occupant survey to understand how disruptive the sound produced by the indoor and/or outdoor units, especially during defrost cycles and start/stop operation, is perceived by occupants.
Satisfaction	Homeowner satisfaction will be evaluated through pre/post occupant survey to understand how satisfied the homeowner was with their original system and the new CCHP, as well as if they would recommend the new CCHP to a friend or neighbor.
Reliability	Reliability will be evaluated based on a combination of: how often the unit requires servicing / maintenance, consistency of operation based on similar outdoor temperatures and expected performance envelope for each unit (i.e., does the unit behave consistently in similar conditions?), consistency of operation for each unit compared with other field test units of the same manufacturer (i.e., does the unit behave consistently with other units of the same model).
Ease of Installation	Ease of installation (including time to install) will be evaluated through an installer survey to understand how the installation of the CCHP Challenge products compares with the typical installations of AC, HP, and heating systems.
Operating Cost	Operating cost will be calculated based on local utility and fuel rates for the CCHP and equivalent baseline systems.
Installation Cost	Installation cost will be evaluated based on both the standard installation of a typical centrally ducted HVAC system and any upgrades to the home's ducts, wiring, etc. *This would not consider the cost of the equipment itself.*

Expected Results and Supplemental Information

The research team will work with each manufacturer to evaluate the field performance of each unit installed in the field. The research team will use the data collected by the sensors deployed in the field to generate results for each site and aggregate them into a unique report for each manufacturer. The reports will include the quantitative metrics described in this section as well as potentially supplementary information and analysis. It is expected that during the data analysis process there will be additional trends and metrics that could become useful for evaluating a site or a performance characteristic. The research team will evaluate these trends and metrics for inclusion in the project report as appropriate.

High-level findings and overall trends observed from aggregating collected data across all sites will be used for developing public-facing technical reports, after anonymizing results. The intent of publishing these results will be to support the development of deployment and incentive programs for CCHP technologies and to showcase the overall capabilities and challenges of CCHP products. The qualitative data collected through the pre- and post-study surveys will be used to determine the qualitative metrics described in this section. The qualitative metrics will help supplement the quantitative data analysis and provide the participants' perspectives on the performance of the CCHPs in the field.

References

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Appendix A – Instrumentation Details

- Weatherproof enclosure with eGauge EG4015, Monnit Wireless Sensor Receiver, and Pepwave cellular router will be installed outside, near the heat pump unit.
  - The monitoring equipment in the enclosure will be powered from the heat pump circuit.
  - Split-core current transformers will measure the amperage provided to the heat pump outdoor unit. Coupled with voltage readings, the eGauge will also measure power and power factor at up to 1-second intervals.
  - If the heat pump reversing valve solenoid operates on AC power (most common), a voltage adapter will allow the eGauge meter to monitor the heating/cooling mode of the valve. If the reversing valve solenoid operates on DC power (less common), a DC Relay with eGauge analog input sensor will allow the eGauge meter to monitor the state of the heat pump reversing valve.
- Enclosure with eGauge EG4015 and TP-Link N300 Wi-Fi adapter will be installed inside the home, near the air handler for the heat pump system.
  - TP-Link N300 Wi-Fi adapter will wirelessly connect to the Wi-Fi signal of the Pepwave cellular router (installed in the enclosure outside the home), providing internet connectivity for the eGauge installed near the air handler.
  - eGauge will be powered from the circuit powering the air handler. Electrician to assist with wiring.
  - Split-core current transformers will be installed within the air handler cabinet to monitor the amperage going to the air handler, the amperage going to the blower fan motor, and the amperage going to each supplemental heat circuit. Coupled with voltage readings taken by the eGauge, power and power factor measurements will also be taken, at up to 1-second intervals.
  - A voltage adapter (such as Magnelab SPT-0375-300) will be installed to monitor the energized/de-energized state of the auxiliary heat circuit(s) with the eGauge. Alternatively, 240V AC relay(s) coupled with eGauge analog input sensors will allow the eGauge meter to monitor the on/off state of the heat circuit(s). Readings can be taken at up to 1-second intervals.
- Monnit wireless temperature/humidity sensors will be installed to measure at 5 second intervals.
  - Monnit sensors will be placed at the following locations:
    - Heat pump outdoor unit inlet air conditions – just before heat exchanger & fan.
    - Heat pump ducted system return air conditions – at the point where the return air enters the air handler cabinet.

        - Ambient air conditions – near the air handler cabinet.
        - A minimum of 3 locations throughout the home, to measure space conditions.
        - A grid of four sensors to monitor the supply air temperature & humidity profile just after the air handler cabinet.
    - Monnit sensors will transmit readings back to the Monnit Gateway Receiver every five seconds. Readings are read from the Gateway Receiver by the eGauge via a RS485 USB adapter.
    - Monnit wireless sensors are powered by internal batteries and will have a battery life of 10-12 months at a 5-second sampling interval.
- The Energy Conservatory (TEC) Digital TrueFlow Meter will be used with a DG-8 digital manometer to measure heat pump system airflow rates and duct static pressures at each fan speed, and corresponding air handler fan amperage/power measurements will be recorded from the eGauge, to develop a profile relating airflow to fan amperage/power. If possible, airflow readings will be taken with the system in heating mode and in cooling mode.

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