Cold Climate Air-Source Heat Pump Demonstration and Analysis

Experimental Study on Cold Temperature Performance

Jon Winkler and Greg Shoukas

National Renewable Energy Laboratory

Produced under direction of Xcel Energy by the National Renewable Energy Laboratory (NREL) under Agreement #TSA-21-17917.

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

Strategic Partnership Project Report
NREL/TP-5500-89413
May 2024

Contract No. DE-AC36-08GO28308

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Suggested Citation
Winkler, Jon, and Greg Shoukas. 2024. *Cold Climate Air-Source Heat Pump Demonstration and Analysis: Experimental Study on Cold Temperature Performance.* Golden, CO: National Renewable Energy Laboratory. NREL/TP-5500-89413.
https://www.nrel.gov/docs/fy24osti/89413.pdf.

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This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Support for the work was also provided by Xcel Energy under Agreement TSA-21-17917. The views expressed herein do not necessarily represent the views of the DOE or the U.S. Government.

Cover Photos by Dennis Schroeder: (clockwise, left to right) NREL 51934, NREL 45897, NREL 42160, NREL 45891, NREL 48097, NREL 46526.

Preface

This project measured the performance of one centrally ducted and one 2-zone multi-split, variable-capacity air-source heat pumps in the National Renewable Energy Laboratory's (NREL) Heating, Ventilating, and Air-Conditioning Laboratory. The work presented in this report does not represent performance of any product relative to regulated minimum efficiency requirements.

The laboratory used for this work is not a certified rating test facility. The conditions and methods under which products were characterized for this work differ from standard rating conditions, as described.

Because the methods and conditions differ, the reported results are not comparable to rated product performance and should only be used to estimate performance under the measured conditions.

Please also note that specific commercial products discussed in this report are used as research examples only—NREL does not endorse or support any particular brand, product, service, or manufacturer.

Acknowledgments

The authors would like to thank Xcel Energy for supporting and funding this research. The authors would also like to Michael Papula at Xcel Energy for his guidance and interest in our work and contribution to managing the project. We would like to acknowledge Bosch for their assistance with understanding the heat pump controls and providing the necessary technical support documentation for this project.

We would like to thank the U.S. Department of Energy Building Technologies Office for funding facility upgrades during this project. The enhanced capabilities allowed heat pump experiments to be conducted at significantly colder temperatures.

This report was prepared by the National Renewable Energy Laboratory (NREL), operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by Xcel Energy under Technical Services Agreement No. TSA-21-17917.

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List of Acronyms

ACCA	Air-Conditioning Contractors of America
ACFM	actual volumetric airflow rates
ASHP	air-source heat pump
ccASHP	cold climate air-source heat pump
CFM	cubic feet per minute
CFR	Code of Federal Regulations
COP	coefficient of performance
EIA	Energy Information Administration
EER	energy efficiency ratio
ECM	electronically commutated motor
EPA	Environmental Protection Agency
ESP	external static pressure
HSPF	heating seasonal performance factor
HVAC	heating, ventilating, and air-conditioning
IDS	Inverter Ducted Split
IDU	indoor unit
MSHP	mini-split heat pump
NEEP	Northeast Energy Efficiency Partnerships
NREL	National Renewable Energy Laboratory
ODU	outdoor unit
RPM	revolutions per minute
SCFM	standard cubic feet per minute
SEER	seasonal energy efficiency ratio

Executive Summary

Space heating energy is the largest end use for U.S. residential buildings, accounting for nearly 45% of residential building energy consumption nationwide, and approximately 51% of space heating energy is consumed on-site by combusting natural gas (EIA 2020a). In Colorado, approximately 53% of the statewide residential building energy consumption goes to space heating, 76% of which is provided by natural gas (EIA 2020a). Heat pumps are an efficient, electric alternative space heating technology and have been proven viable for decades. However, historically air-source heat pumps (ASHPs) have been limited to temperate climates because of (1) subpar performance at extremely cold outdoor air temperatures, (2) the need for air conditioning in summer months, and (3) the availability of natural gas in colder climates. Relatively recent advances to cold climate ASHP technology, which typically relies on inverter-driven, variable-speed compressors and variable-speed fans, have significantly improved low-temperature heat pump performance, enabling the technology to potentially save energy for many homes in cold climates.

The definition of "cold climate heat pump" ranges from a manufacturer marketing term to a specific set of performance targets. Some manufacturers use the term to overcome the stigma of poor low-temperature performance, while others use it to denote the inclusion of particular controls and accessories, such as drain pan heaters, necessary for cold climate operation.

The Northeast Energy Efficiency Partnerships (NEEP) publishes the Cold Climate Air-Source Heat Pump (ccASHP) Specification, which defines a set of performance and reporting requirements for systems to be voluntarily listed as meeting the specification (NEEP 2022). The specification was developed to support the identification of ASHPs well-suited for heating homes in cold climates and applies to air-to-air, variable-speed ducted, and ductless systems. The NEEP specification relies on manufacturer-reported performance data, which can be obtained from either laboratory test results or engineering data sourced from proprietary system models. This project coincided with Xcel Energy, the largest electric utility in Colorado, launching cold climate heat pump rebates for qualified products. To qualify, equipment must receive a quality installation from a participating contractor, be listed in the NEEP ccASHP product list, and meet specific performance criteria (Xcel 2023) (see Section 1.1).

Under Technical Service Agreement TSA-21-17917 with Xcel Energy, NREL conducted laboratory and field research activities to evaluate the performance of current residential ASHP technologies in support of Xcel Energy's carbon-free electricity goals. Results from this research will be used by Xcel Energy to play a role in understanding the impacts that equipment, environment, and installation choices have on field operation and performance of residential ASHPs. This report focuses on the laboratory experiments.

The overall goal of the laboratory evaluation was to measure heat pump performance under a range of real-world heating mode operating conditions. Laboratory characterization was completed on one centrally ducted heat pump and one multi-zone mini-split heat pump (MSHP) (i.e., a multi-split heat pump). Xcel Energy selected and provided the heat pumps for this study.

The selected central heat pump system was the Bosch Inverter Ducted Split (IDS) 2.0 5-ton outdoor unit (ODU) heat pump (BOVA-60HDN1-M20G) with the corresponding 5-ton indoor

air handler unit (BVA-60WN1-M20), which is a non-communicating system with a constant torque, multi-speed electronically commutated motor (ECM) blower designed for two-stage operation.

The selected MSHP was the Bosch Climate 5500 Series 27-kBtu/h ODU heat pump (BMS500-AAM027-1CSXHC). Though the ODU supports up to three connected indoor ductless units (IDUs), the system was characterized with two different capacity wall-mounted, IDUs with a total rated capacity of 27-kBtu/h (BMS500-AAS018-1CSXHB and BMS500-AAS009-1CSXHB). Additional details and specifications on the heat pump systems can be found in Section 1.4.

Specifically, the laboratory study measured:

- Heat pump capacity and coefficient of performance (COP) at cold outdoor temperatures.
- The effect of duct external static pressure (ESP) on the centrally ducted heat pump, which was accomplished by measuring the sensitivity of IDU airflow rate on heat pump performance.
- The impact of Golden, Colorado's elevation above sea level.

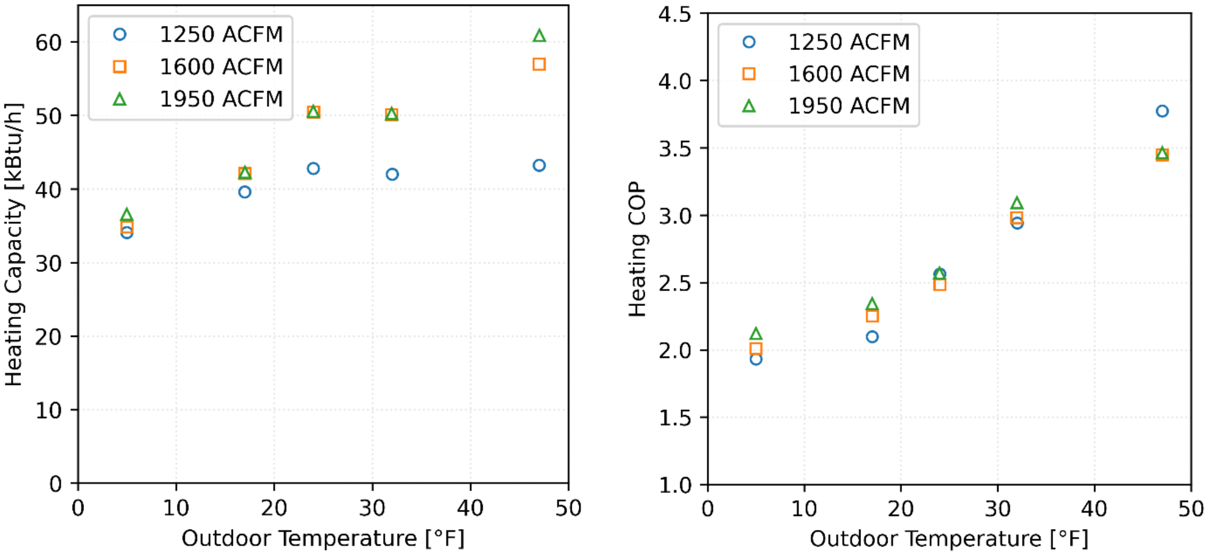
All experiments for this project were conducted at NREL's Thermal Test Facility in the Heating, Ventilating, and Air-Conditioning (HVAC) Laboratory, which is an air psychrometric laboratory that delivers conditioned air to the heat pump using a custom, computer-based measurement and data acquisition system to control and maintain precise air temperature, humidity, pressure, and flow rates. Accurate, real-time measurements were recorded to determine the heat transfer performance and efficiency of both heat pump systems.

The centrally ducted heat pump was evaluated prior to the U.S. Department of Energy funding an upgrade to the laboratory capabilities. Prior to the upgrade, the laboratory could evaluate heat pumps at temperatures 5°F and above. However, after the facility upgrade during this project, the split system test stand evaluated the MSHP at an outdoor air temperature of -25°F.

Central Heat Pump Findings

The goals of the central heat pump laboratory experiments were to measure cold temperature performance, assess the impact of duct ESP, and to estimate the impact of elevation on system performance. The impact of the elevation was estimated by using the laboratory's blowers to force a sea-level equivalent air mass flow rate through both the IDU and ODU. The heat pump was tested at a range of outdoor air temperatures down to 5°F. Prior to the facility upgrade, temperatures below 5°F could not be reliably achieved for this particular heat pump and thus are not reported on.

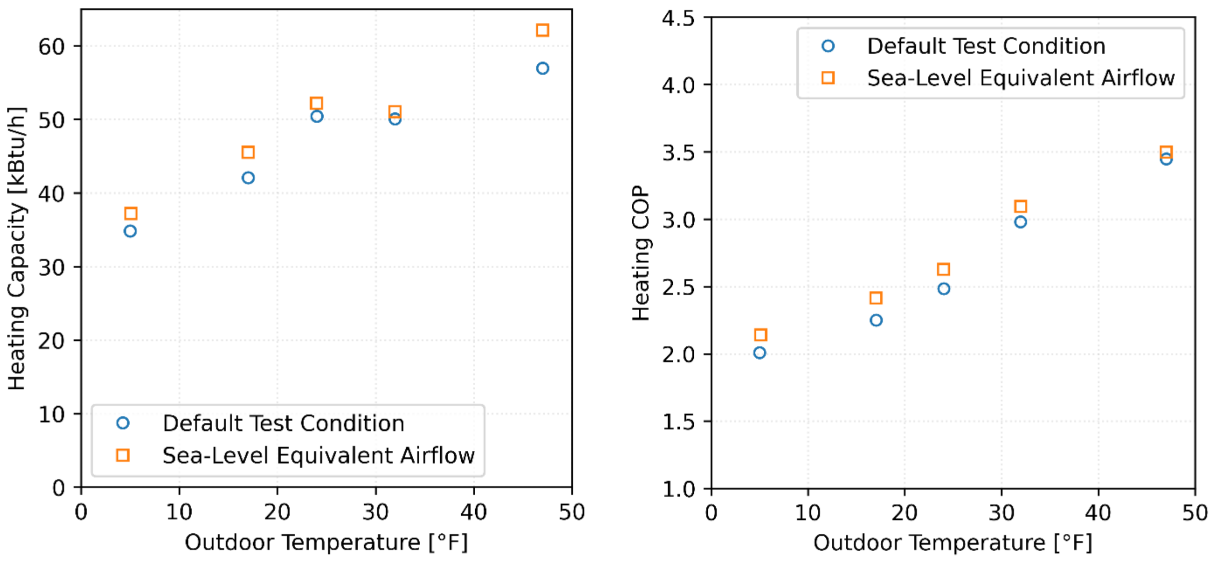
Since the maximum blower motor speed programmed in the motor limited the IDU airflow rate at high ESPs (see Section 4.1.1), we selected three IDU airflow rates to measure the sensitivity of IDU airflow rate on the heat pump's maximum capacity and COP. In Figure ES-1, we see that heating capacity was impacted by the low airflow rate at temperatures warmer than 20°F, because the heat pump's control algorithm limited the maximum compressor speed. However, the heating capacity was not significantly impacted by the airflow rate for the coldest temperature test conditions, i.e., when the outdoor temperature was less than 20°F, because the unit was operating at maximum compressor speed. At cold outdoor air temperatures, the higher IDU airflow rates resulted in higher COP. At 5°F outdoor air temperature, the COP was ~11% higher at the highest tested IDU airflow rate compared to the lowest tested IDU airflow rate. However, at a mild outdoor air temperature the COP was highest when the IDU airflow rate was the lowest due to the compressor speed reduction (see Section 4.1.2.)



(a) (b)

Figure ES-1. Central heat pump (a) heating capacity (Btu/h) and (b) heating COP for the maximum capacity tests

Figure ES-2 compares the heat pump's performance when forcing a sea-level equivalent airflow rate though the IDU and ODU to the series of tests with an indoor airflow rate of 1600 cfm (labeled "Default Test Condition"). As expected, the heating capacity and COP increase when IDU and ODU airflow rates are increased to sea-level equivalent values.



(a) **(b)**

Figure ES-2. Central heat pump (a) heating capacity (Btu/h) and (b) heating COP for tests with a sea-level equivalent airflow rate

Air-Conditioning Contractors of America (ACCA), which publishes standards and guidelines for selecting and sizing air conditioners and heat pumps, states that manufacturer-published ASHP heating capacities values decrease by 8%–10% for systems installed at elevations 5,000–6,000 feet above sea level (ACCA 2023). On average, the capacity decreased by 5.5% and the COP decreased by 4.7% due to the lower barometric pressure at the laboratory's elevation above sea level. The impact on capacity was less than the adjustment recommended by ACCA Manual S, which was approximately 9.7% based on linear interpolation of the Manual S table (see Section 4.1.3).

Multi-Zone MSHP Findings

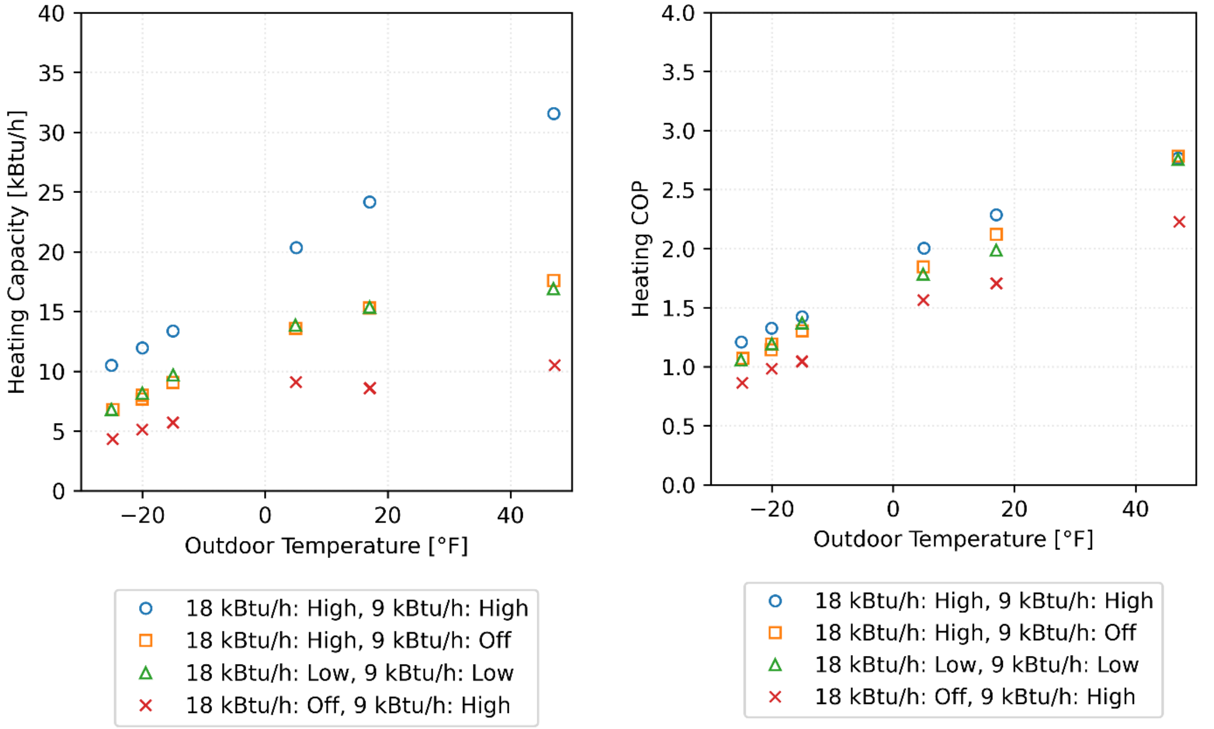
Like the central heat pump system, the main goals of the MSHP laboratory experiments were to measure the cold temperature performance and estimate the impact of elevation on system performance. Since the MSHP had two IDUs with controllable fan settings, we evaluated performance using different combinations of IDU operation and fan speed. Outdoor air temperatures of 5°F, 17°F, and 47°F were selected because these temperatures correspond to typical manufacturer-reported performance values. Because of the interest in cold temperature performance, we also tested the heat pump at outdoor temperatures ranging from -15°F to -25°F in 5°F increments to understand the heat pump controls at cold temperatures.

We noticed that the heat pump generally increases the compressor speed at colder outdoor air temperatures until reaching a maximum compressor speed at temperatures below 5°F. This control feature is unique to variable-speed heat pumps and helps the heat pump maintain heating capacity at cold outdoor temperatures. We also found that the maximum compressor speed is dependent on the IDU fan setting. In other words, the maximum compressor speed with both IDUs set to high was faster than the maximum compressor when both units were set to low (see Figure 17, Section 4.2.1).

Figure ES-3 shows the measured total heating capacity (left) and heating COP (right) of the MSHP. As expected, the measured heating capacity was below the manufacturer-reported capacity due to the tested IDU configuration differing from the manufacturer-reported configuration. It’s likely the maximum compressor speed would have been higher, and the capacity greater, with three 9-kBtu/h IDUs compared to tested configuration. Based on the IDU airflow measurements, the total IDU airflow rate would have been higher with three 9-kBtu/h IDUs compared to a configuration with one 18-kBtu/h IDU and one 9-kBtu/h IDU, which would have resulted in higher heating capacity and COP.

The measured capacity maintenance, defined as the ratio of maximum heating capacity at 5°F to maximum capacity at 47°F, was very close to the manufacturer-reported capacity maintenance. Laboratory results showed a capacity maintenance of 64.6% compared to a reported value of 65.8%.

Similar to heating capacity, the total power consumption of the heat pump was also lower than the manufacturer-reported values. The COP was within the expected range at the outdoor temperatures of 47°F and 17°F, and slightly exceeded the manufacturer-reported COP at 5°F and -22°F (see Figure 18, Figure 19, and Table 9 in Section 4.2.1).

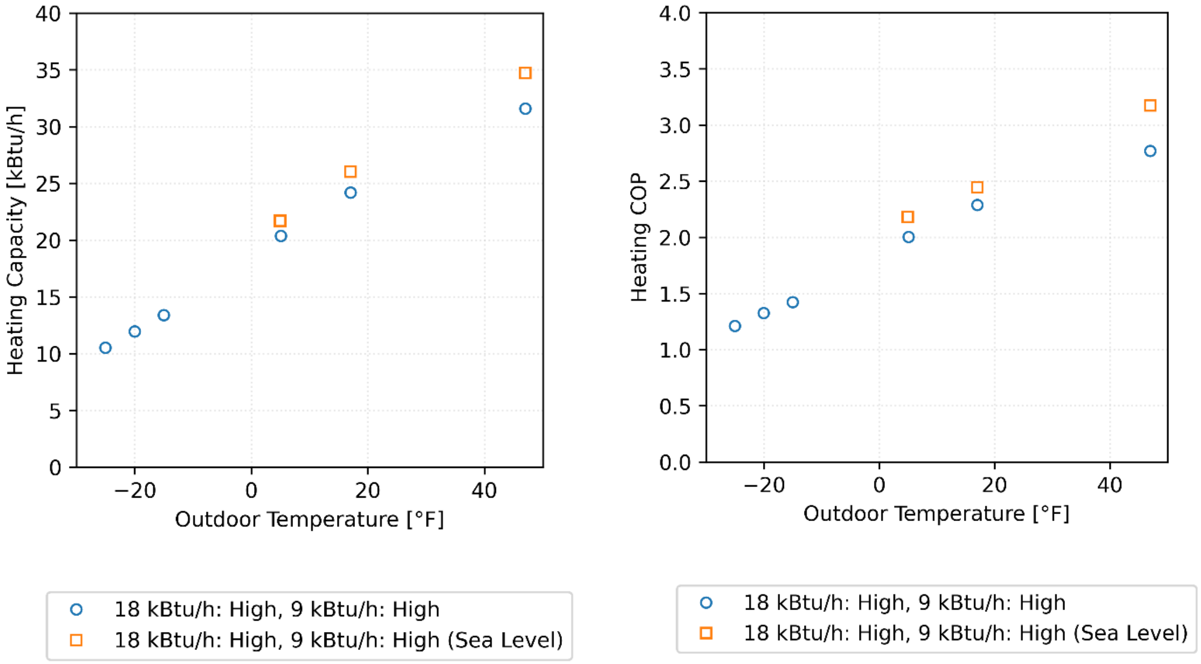


(a) **(b)**

Figure ES-3. MSHP (a) heating capacity and (b) COP for the maximum and part-load capacity tests for different combinations of IDU operation and fan speed settings

The impact of elevation was estimated by running both IDUs in the high fan setting and using the laboratory’s blowers to force more air through the IDUs to match the manufacturer-reported standard volumetric flow rates (standard cubic feet per minute, or SCFM). These tests were conducted at outdoor air temperatures of 5°F, 17°F, and 47°F. Tests were conducted to ensure the compressor speeds matched the maximum capacity test at the given outdoor air temperature.

Figure ES-4 compares the MSHP's performance when forcing a sea-level equivalent airflow rate though the IDUs to the series of tests with both IDUs operating at high fan speed. As expected, the heating capacity and COP increase when the IDU airflow rates are increased to sea-level equivalent values. On average, the capacity decreased by 7.4% ranging from 9% at 47°F to 6.2% at 5°F. COP decreased by 9.1% due to the lower barometric pressure at the laboratory's elevation above sea level. The COP decrease ranged from 6.5% to 12.8% across the temperature range. Similar to the central heat pump, the impact on capacity was less than the value recommended by ACCA Manual S, which was approximately 9.7% (ACCA 2023).



(a) **(b)**

Figure ES-4. MSHP (a) heating capacity (Btu/h) and (b) heating COP for tests with a sea-level equivalent IDU airflow rate

Study Limitations

Key limitations of this study worth considering are listed below.

- This project measured the performance of two variable-capacity, cold climate heat pumps from the same manufacturer—one centrally ducted heat pump and one 2-zone multi-split air-source heat pump. Given the variety in equipment controls and physical characteristics in the cold climate variable-capacity heat pump landscape, conclusions drawn from this study should not be broadly extended to other heat pump systems.
- Experiments were conducted at a limited number of test conditions (i.e., indoor and outdoor temperatures, compressor speeds, and airflow rates). Caution should be taken when using these results to estimate performance at non-tested conditions.

- Potential sources of discrepancy need to be considered when comparing the manufacturer-reported data to the laboratory data collected in this study. Potential sources of discrepancy include:
    - Operating conditions: The heat pumps were likely operated at a different indoor airflow rates and return air temperatures than the manufacturer-reported data.
    - Control: The heat pumps were operated using onboard controls during these experiments and thus compressor and fan speeds may have been different than the manufacturer-reported data.
    - Method of test: Though accurate instrumentation and approaches were implemented for this study, there are differences between the approach we implemented and standard test procedures (10 CFR Part 430 2022).
- This study focused on measuring heat pump performance in the laboratory at specific operating conditions. We did not conduct an analysis investigating distribution system losses (i.e., duct losses), heat pump cost-effectiveness, annual heat pump performance, potential carbon emission reductions, or supplemental heating energy use.

Conclusions

In general, the measured performance of both heat pump systems aligned with manufacturer-reported metrics that are typically used to qualify heat pumps for program rebates. Though heat pump performance, system design, and control approaches can vary significantly across the product landscape, the experimental study resulted in the following conclusions:

- The impact of the laboratory's elevation resulted in an average decreased heating capacity of 5.5% for the central heat pump system and 7.4% for the MSHP. The measured impact on capacity for both heat pump systems was lower than industry standard suggested values. However, additional investigation is required for a complete general understanding of elevation impacts on heat pump performance.
- When installing constant-torque ECM blowers at high elevations, it's important for the installer to measure the duct system ESP, take steps to minimize excess ESP that could result in low IDU airflow rates, and measure the indoor airflow rate during heat pump commissioning. For the unit tested, low IDU airflow rates significantly decreased heating capacity at mild outdoor air temperatures and the COP at cold temperatures.
- When installing MSHP systems, installers should understand how the selected IDU configuration will affect the heat pump's performance. For the multi-split system in this study, using three 9-kBtu/h IDUs would likely have resulted in higher heating capacity compared to the chosen configuration with one 18-kBtu/h IDU and one 9-kBtu/h IDU.

Future Work

As previously mentioned, NREL is partnering with Xcel Energy to conduct laboratory and field research to evaluate the performance of residential ASHP technologies in support of Xcel Energy's carbon-free electricity goals. This report focuses on the laboratory experiments. Future work will analyze the data collected on heat pump installed in the field, and where appropriate, make comparisons between the field and laboratory data sets.

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1 Introduction and Technology Description

Space heating energy is the largest end use for U.S. residential buildings, accounting for nearly 45% of residential building energy consumption nationwide, and approximately 51% of space heating energy is consumed on-site by combusting natural gas (EIA 2020a). In Colorado, approximately 53% of the statewide residential building energy consumption goes to space heating, 76% of which is provided by natural gas (EIA 2020a). Heat pumps are an efficient, electric alternative space heating technology and have been proven viable for decades. However, historically air-source heat pumps (ASHPs) have been limited to temperate climates because of (1) subpar performance at extremely cold outdoor air temperatures, (2) the need for air conditioning in summer months, and (3) the availability of natural gas in colder climates. Heat pumps have not seen significant market penetration in regions with access to natural gas (EIA 2020b). Relatively recent advances to cold climate ASHP technology, which typically rely on inverter-driven, variable-speed compressors and variable-speed fans, have significantly improved low-temperature heat pump performance, enabling the technology to potentially save energy for many homes in cold climates. Field studies have shown ASHPs are a viable space heating technology for cold climates (Winkler 2023, Trojanowski 2023, Schoenbauer 2017, Schoenbauer 2016, Davis 2016, Larson 2013).

ASHPs utilize a refrigeration cycle consisting of a compressor, two air-to-refrigerant heat exchangers with fans, and at least one expansion valve. A reversing valve allows the heat pump to switch between cooling and heating modes and control defrost cycles. In heating mode, the outdoor heat exchanger transfers heat from the ambient air flowing over the heat exchanger to the refrigerant and the indoor heat exchanger then releases that heat to an airstream distributed to the living space. There is a diminishing amount of heat available in the outdoor air when temperatures are cold, which can reduce the amount of heating capacity the ASHP can provide to the living space. Additional information on ASHPs can be found on the U.S. Department of Energy’s (DOE) Energy Saver webpage (DOE 2024).

Heat is convectively transferred from the ambient air to the refrigerant by the outdoor unit’s (ODU) constant volume fan. Since air density decreases at higher elevations, the air mass flow rate through the ODU heat exchanger will decrease at elevations above sea level, which will also reduce the amount of heat that can be transferred from the ambient air. Air-Conditioning Contractors of America (ACCA), which publishes standards and guidelines for selecting and sizing air conditions and heat pumps, states that manufacturer-published ASHP heating capacities values should be decreased by 8%–10% for systems installed at elevations 5,000–6,000 feet above sea level (ACCA 2023).

Inverter-driven compressor technology was developed in the 1970s and 1980s for mini-split heat pumps (MSHPs), and nowadays nearly all MSHPs on the market incorporate an inverter-driven compressor. An inverter modulates the compressor speed, thus allowing the heat pump to dynamically adjust the heating and cooling capacity to better match the building load. Inverter-driven heat pumps are more efficient at part loads and have improved cold climate performance because the system can “boost” the compressor speed at low outdoor temperatures, which can overcome the subpar cold temperature performance common in older technology heat pumps.

Inverter-driven compressors are also commonly referred to as variable-speed and variable-capacity.

In the mid-2000s, central split heat pump systems with variable-speed compressors were introduced to the market. Fixed capacity and two-stage central heat pump systems continue to dominate sales; however, manufacturers continue to introduce variable-speed models to the market every year (Salmonsen 2018). Variable-speed, central heat pumps were initially offered by top brands at the highest efficiency levels, but central heat pumps with variable-speed compressors are now offered by nearly every brand at a range of efficiencies.

Additionally, advanced indoor units (IDU) with constant-flow, variable-speed electronically commutated motors (ECM) can control the fan speed to achieve the programmed air mass flow rate, overcoming the reduced IDU air mass flow rate at higher elevations (Shoukas 2022, Winkler 2023).

1.1 Cold Climate Heat Pumps

The definition of "cold climate heat pump" ranges from a manufacturer marketing term to a specific set of performance targets. Some manufacturers use the term to overcome the stigma of poor low-temperature performance, while others use it to denote the inclusion of particular controls and accessories, such as drain pan heaters, necessary for cold climate operation.

The Northeast Energy Efficiency Partnerships (NEEP) publishes the Cold Climate Air-Source Heat Pump (ccASHP) Specification that defines a set of performance and reporting requirements for systems to be voluntary listed as meeting the specification (NEEP 2022). The specification was developed to support the identification of ASHPs well-suited for heating homes in cold climates and applies to air-to-air, variable-speed ducted, and ductless systems (with a minimum of three distinct compressor speeds). Effective January 1, 2023, the key NEEP ccASHP specification requirements include:

- Ducted systems:
    - HSPF2 $\geq$ 7.7 (9 HSPF equivalent)
    - SEER2 $\geq$ 14.3 (15 SEER equivalent)
- Non-ducted systems:
    - HSPF2 $\geq$ 8.5 (10 HSPF equivalent)
    - SEER2 $\geq$ 15 (15 SEER equivalent)
- Coefficient of performance (COP) at 5°F $\geq$ 1.75 at maximum capacity.

Additionally, the NEEP ccASHP specification requires that the unit include a variable-capacity compressor with at least three distinct operating speeds or be continuously variable. The NEEP specification relies on manufacturer-reported performance data, which can be obtained from either laboratory test results or engineering data sourced from proprietary system models. The NEEP ccASHP product list is often used to qualify heat pumps for incentives.

Starting with version 6.1 of the ENERGY STAR® Central Air Conditioner and Heat Pump specification, a cold climate specific designation was created to establish an ENERGY STAR label for cold climate heat pumps (EPA 2022). The requirements include:

- Ducted split systems:
  - HSPF2 ≥ 8.1
  - SEER2 ≥ 15.2
- Non-ducted split systems:
  - HSPF2 ≥ 8.5
  - SEER2 ≥ 15.2
- COP at 5°F ≥ 1.75 at maximum capacity
- Percent of heating capacity at 5°F ≥ 70% of that at 47°F
- A controls verification procedure test is conducted to confirm that the above performance metrics can be achieved using the equipment's onboard native controls.

Unlike the NEEP ccASHP product list, obtaining an ENERGY STAR label requires the heat pump be tested following U.S. Department of Energy test procedures along with an Environmental Protection Agency (EPA)-developed controls verification procedure (10 CFR Part 430 2022, EPA 2022). Starting with the publication of the final ENERGY STAR specification, required performance values were defined exclusively using the latest metric in Appendix M1 of the Code of Federal Regulations (CFR).

This project coincided with Xcel Energy offering cold climate heat pump rebates for qualifying products. To qualify, equipment must receive a quality installation from a participating contractor, be listed in the NEEP ccASHP product list, and meet the following performance criteria (Xcel 2023):

- Ducted ASHP
  - HSPF2 ≥ 8.1
  - SEER2 ≥ 18
  - EER2 ≥ 11.7
- MSHP
  - HSPF2 ≥ 8.5
  - SEER2 ≥ 18
  - EER2 ≥ 11.5
- COP at 5°F ≥ 1.75 at maximum capacity
- Percent of heating capacity at 5°F ≥ 70% of the 47°F rated heating capacity.

The compressor lockout temperature is typically defined as the minimum outdoor air temperature at which the compressor operates, which can be (1) "hard-coded" within the heat pump controls, (2) an installer setting that can be adjusted using the heat pump's communicating thermostat, and/or (3) an unspecified temperature when the compressor will not operate due to other measured parameters used by the controls to prevent operation that could harm the equipment. The compressor lockout temperature should be considered when selecting a heat pump for a particular application and can often be found within manufacturer engineering literature when it is not an adjustable setting. The NEEP ccASHP specification requires manufacturers to answer the question "Is there a low ambient temperature at which the compressor locks out and the unit switches to electric heat?"; however, the answer to this question could not be found in the product listing database.

Despite established metrics to distinguish cold climate heat pumps, questions remain regarding their installed, real-world performance. Additionally, there are concerns regarding the accuracy of the NEEP ccASHP data since the data is manufacturer-reported and can be obtained from either laboratory test results or engineering data.

1.2 Project Objectives

Under Technical Service Agreement TSA-21-17917 with Xcel Energy, NREL conducted laboratory and field research activities to evaluate the performance of current residential ASHP technologies in support of Xcel Energy's carbon-free electricity goals. Results from this research will be used by Xcel Energy to play a role in understanding the impacts that equipment, environment, and installation choices have on field operation and performance of residential ASHPs. This report focuses on the laboratory experiments.

The overall goal of the laboratory evaluation was to measure heat pump performance under a range of real-world heating mode operating conditions. Laboratory characterization was completed on one centrally ducted heat pump and one multi-zone MSHP (i.e., a multi-split heat pump). Xcel Energy selected and provided the heat pumps for this study.

Specifically, the laboratory study measured:

- Heat pump capacity and COP at cold outdoor temperatures.
- The effect of different duct external static pressures (ESP) on the centrally ducted heat pump.
- The impact of Golden, Colorado's elevation above sea level.

1.3 Approach Overview

All experiments for this project were conducted at NREL's Thermal Test Facility in the Heating, Ventilating, and Air-Conditioning (HVAC) Laboratory. Additional details regarding the experiment setup can be found in Section 2.

NREL's HVAC Laboratory is an air psychrometric laboratory that delivers conditioned air to the heat pump using a custom, computer-based measurement and data acquisition system to control and maintain precise air temperature, humidity, pressure, and flow rates. Accurate, real-time measurements were recorded to determine the heat transfer performance and efficiency of both heat pump systems. The HVAC Laboratory includes a split system test stand that consists of an environmental chamber to house the ODU and supply and exhaust air streams that interface with the IDU using custom-made plenums.

The centrally ducted heat pump was evaluated prior to the U.S. Department of Energy funding an upgrade to the laboratory capabilities. Prior to the upgrade, the laboratory could evaluate heat pumps at temperatures 5°F and above. However, after the facility upgrade that occurred during this project, the split system test stand evaluated the MSHP at an outdoor air temperature of -25°F.

1.4 Heat Pump Specifications and System Information

This study measured the performance of two heat pump systems—a centrally ducted heat pump and a two-zone, non-ducted MSHP. Both heat pump systems were selected and provided by Xcel Energy. The heat pump systems were selected based on their specifications qualifying for Xcel Energy's cold climate heat pump rebates.

1.4.1 Central Heat Pump System

The selected central heat pump system was the Bosch Inverter Ducted Split (IDS) 2.0 5-ton ODU heat pump (BOVA-60HDN1-M20G) with the corresponding 5-ton indoor air handler unit (BVA-60WN1-M20). Table 1 and Table 2 list manufacturer-reported performance data for the 5-ton Bosch IDS 2.0 system, sourced from the NEEP ccASHP database. The system was purchased and tested prior to the transition to the HSPF2 annual efficiency; however, information from the updated product listing is included. The system was characterized without a field-installed electric heater kit.

Table 1. Manufacturer Performance Specifications for the 5-ton Bosch IDS 2.0

	Heating	Cooling
Nominal Capacity (Btu/h)	54,500	56,000
HSPF2 (HSPF) (Region IV)	9.5 (10.5)	-
SEER2 (SEER)	-	18.0 (19.0)
EER2 (EER)	-	11.7 (12.5)
Outdoor Temperature Operating Range (°F)	-4 to 86	

Table 2. Manufacturer Heating Performance Data for the 5-ton Bosch IDS 2.0

Outdoor Temperature (°F)		Minimum	Rated	Maximum
47	Heating Capacity (Btu/h)	22,000	55,000	60,000
	COP	3.93	3.8	3.24
	Power (kW)	1.64	4.24	5.42
17	Heating Capacity (Btu/h)	12,400	43,500	43,500
	COP	2.46	2.4	2.4
	Power (kW)	1.48	5.31	5.31
5	Heating Capacity (Btu/h)	11,400	38,500	38,500
	COP	1.9	2.02	2.02
	Power (kW)	1.76	5.58	5.58
-4	Heating Capacity (Btu/h)	10,300	---	30,400
	COP	1.85	---	1.63
	Power (kW)	1.63	---	5.46

The BVA-60WN1-M20 air handler contains a constant torque, multi-speed ECM blower designed for two-stage operation. Thus, the air handler blower will maintain a constant output torque for each stage and the operational blower speed will be dependent on the ESP. This means the blower will increase the blower speed, up to a maximum value, at higher ESPs to maintain a constant torque. Premium residential air hander units tend to utilize constant flow ECM blowers, which will maintain programmed airflow rates regardless of ESP by adjusting the blower speed until the maximum speed is reached. Constant torque blowers will produce lower air flow rates at high ESPs; however, they are offered at a lower cost compared to constant flow blowers.

The Bosch IDS 2.0 heat pump is a non-communicating system, meaning the thermostat energizes a set of individual wires to control the heat pump. Most premium, variable-speed heat pumps utilize communicating thermostats to control the compressor and blower speeds. A communicating heat pump system utilizes a proprietary serial communication protocol to send and receive operational and performance data to all the components (thermostat, IDU, and ODU) in the system. The Bosch IDS 2.0 heat pump adjusts the compressor speed to maintain a constant high-side refrigerant pressure/saturation temperature rather than feedback from a communicating thermostat. Presumably when the heat pump is installed in a home, as the return air temperature increases during a heating cycle, the compressor speed will decrease to maintain a constant high-side pressure. Even though any two-stage 24 VAC thermostat could have been used for testing, we evaluated the heat pump with Bosch’s premium Wi-Fi-enabled thermostat (model BCC100).

The Bosch IDS 2.0 technical support documentation does not specifically mention a compressor lockout temperature that forces the heat pump to cease operation at a specific cold ambient temperature. However, the heat pump utilizes an “ambient temperature limited protection control and restart” mode that prevents the heat pump from cycling on when the ambient temperature is below -4°F. If the heat pump happens to be running when the ambient temperature falls below -4°F, the heat pump will continue running until the call for heat is satisfied.

1.4.2 Multi-Zone MSHP System

The selected MSHP system was the Bosch Climate 5500 Series 27-kBtu/h ODU heat pump (BMS500-AAM027-1CSXHC). Though the ODU supports up to three connected IDUs, the system was characterized with two wall-mounted, ductless IDUs with a total rated capacity of 27-kBtu/h (BMS500-AAS018-1CSXHB and BMS500-AAS009-1CSXHB). Table 3 and Table 4 list system information and manufacturer-specified performance data for the MSHP ODU sourced from the NEEP ccASHP product listing. The performance data provided by Bosch and listed in the NEEP ccASHP product listing is based on a configuration with three 9-kBtu/h wall-mounted IDUs. The Bosch literature states the heat pump operates down to -22°F. Based on Table 4, we see the capacity maintenance (maximum 5°F/ rated 47°F) for this heat pump is expected to be 85%.

Table 3. Manufacturer Performance Specifications for the 27-kBtu/h Bosch Climate 5500

	Heating	Cooling
Nominal Capacity (Btu/h)	28,000	28,000
HSPF(HSPF2) (Region IV)	11.3 (10.6)	-
SEER (SEER2)	-	22.5 (23)
EER (EER2)	-	12.5 (12.5)
Outdoor Temperature Operating Range (°F)	-22 to 86	-22 – 122

Table 4. Manufacturer Heating Performance Data for the 27-kBtu/h Bosch Climate 5500

Outdoor Temperature (°F)		Minimum	Rated	Maximum
47	Heating Capacity (Btu/h)	4,400	28,000	38,000
	COP	4.03	3.66	2.74
	Power (kW)	0.32	2.24	4.07
17	Heating Capacity (Btu/h)	4,600	26,600	26,000
	COP	1.48	2.7	2.08
	Power (kW)	0.91	2.89	3.67
5	Heating Capacity (Btu/h)	4,700	25,000	24,000
	COP	1.2	1.8	1.75
	Power (kW)	1.15	4.07	4.02
-22	Heating Capacity (Btu/h)	2,850	---	13,550
	COP	1.31	---	1.27
	Power (kW)	0.64	---	3.13

2 Experimental Setup and Instrumentation

All experiments for this project were conducted at NREL's Thermal Test Facility in the HVAC Laboratory. Although a similar set of experiments was conducted for the central heat pump system and MSHP system, the experiment setup was slightly different to accommodate the different geometry and configurations.

Experiments to measure the performance of the central heat pump system were conducted during spring 2022. From July 2022 through January 2023, NREL received funding from the U.S. Department of Energy to upgrade the facility, allowing for the laboratory to achieve significantly colder temperatures. The MSHP was tested following the laboratory upgrade in spring 2023.

This section of the report describes the experimental setup and instrumentation used to measure the heat pump performance.

2.1 Setup Overview

For each heat pump system, the ODU was placed in the center of a highly insulated, custom environmental chamber shown in Figure 1. The chamber is subdivided into three plenums using partitions: the inlet plenum, exhaust plenum, and return plenum.

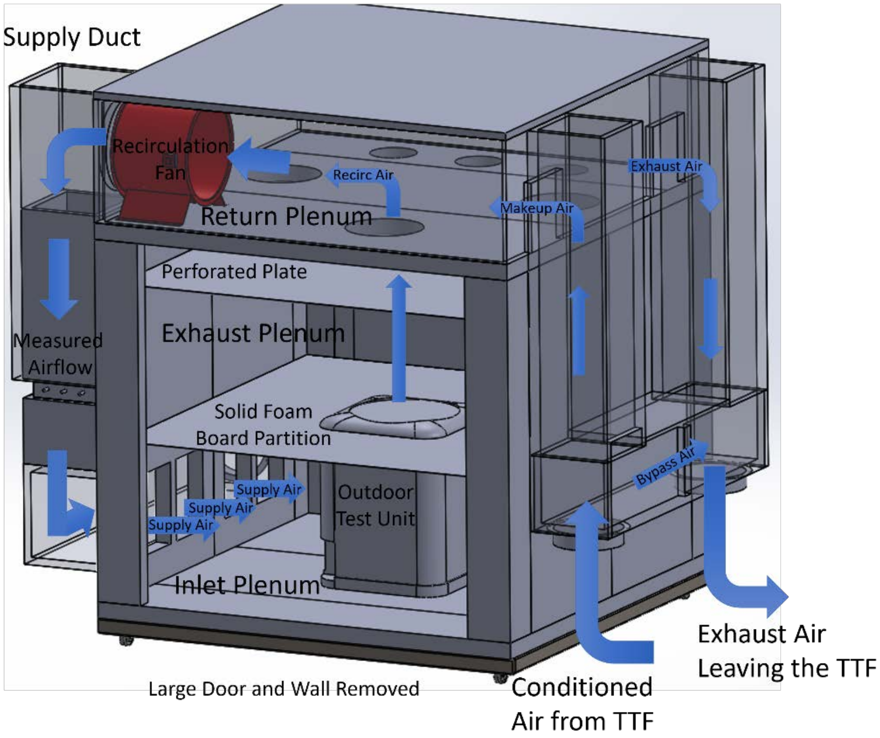

Figure 1. Environmental test chamber to house the ODU and to control the outdoor air temperature (represents configuration prior to the upgrade)

Air conditions supplied to the ODU were controlled by mixing conditioned, makeup air provided by the HVAC Laboratory and recirculation air from the exhaust of the ODU. The mixing takes place in the return plenum of the environmental chamber. In heating mode, recirculating the cold exhaust air from the ODU lowers the temperature inside the chamber and allows it to be cooled down to approximately 0°–5°F depending on the capacity and performance of the heat pump. The DOE-funded upgrade purchased a refrigeration unit, which was placed in the return plenum, to further cool the chamber. With the refrigeration unit installed, the chamber can achieve temperatures down to -25°F. To maintain a constant temperature inside the chamber during heat pump experimentation, the laboratory exhausts a portion of the recirculated air and provides counter-acting warm or cool makeup air. This control strategy maintains a constant inlet temperature during heat pump characterization. Though the configuration changed slightly after the facility upgrade, the principles of the operation remained consistent between the pre- and post-upgrade configurations.

Temperature, humidity, static pressure, and air flow measurements are sampled at various points in the environmental chamber. Characterizing the inlet and exhaust temperature and dew point conditions provides information related to the enthalpy exchange from the ODU. The volumetric air flow rate supplied to the inlet plenum via the booster fan is measured through an averaging pitot tube array.[1] Prior to testing, the pitot tube array measurements were calibrated using the HVAC Laboratory flow nozzles to ensure accuracy in the recirculation air flow values. The static pressures measured in the inlet and outlet plenum allow the laboratory to control the fan speed and air flow rates to the desired experimental conditions.

The solid foam partition board was placed to create the inlet and exhaust plenums and to ensure all the air provided by the booster fan flows through the ODU. This setup is necessary to increase the airflow though the ODU to simulate air mass flow rates at lower elevation.

Custom-made return and supply plenums were constructed to interface the heat pump IDU(s) to the HVAC Laboratory. The HVAC Laboratory air streams were used to control the inlet dry-bulb temperature, total ESP, and airflow rate through the IDU.

The heat pump systems were only evaluated in heating mode, and air-side measurements were used to calculate the heating output (capacity) and COP.

2.2 Central Heat Pump System

Figure 2 and Figure 3 show a schematic of the key measurements for the central heat pump IDU and ODU, respectively. The IDU return and supply air dry-bulb temperature, humidity (dew point temperature), and differential pressure were made in the corresponding air plenum. Blower power and speed was measured to characterize the IDU's fan curves. Current transformers were also placed on the individual blower control wires to directly measure the stage of operation. The secondary capacity calculation was made using refrigerant-side measurements (pressure, temperature, and mass flow rate) within close proximity to the IDU.

In the ODU, the compressor speed was determined by measuring the frequency output from the inverter using a current transformer. The four-way valve was monitored to assist controlling the laboratory during defrost cycles.

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[1] https://www.dwyer-inst.com/Product/AirQuality/FlowSensors/SeriesFLST#literature

Pictures of the experimental setup for the central pump are included in Figure 4.

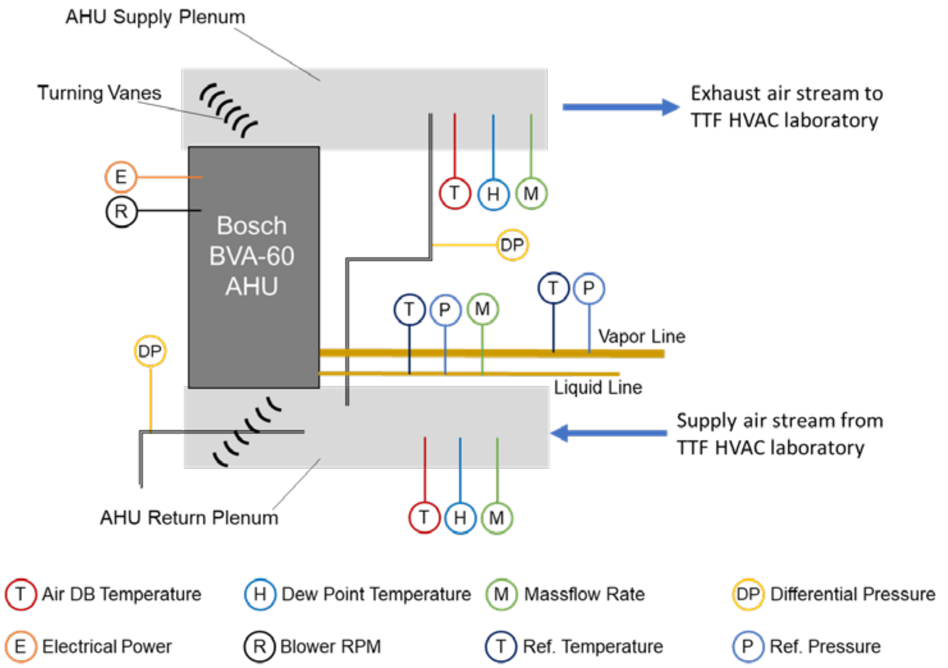


Figure 2. Schematic of key measurements for the central heat pump IDU

Note: TTF stands for Thermal Test Facility

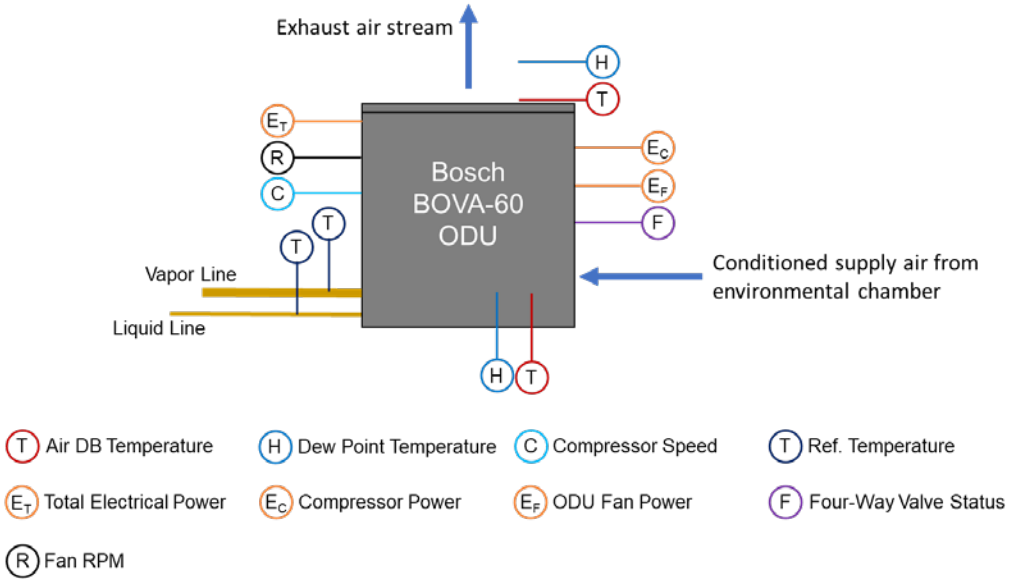


Figure 3. Schematic of key measurements for the central heat pump ODU

Note: DB stands for dry bulb

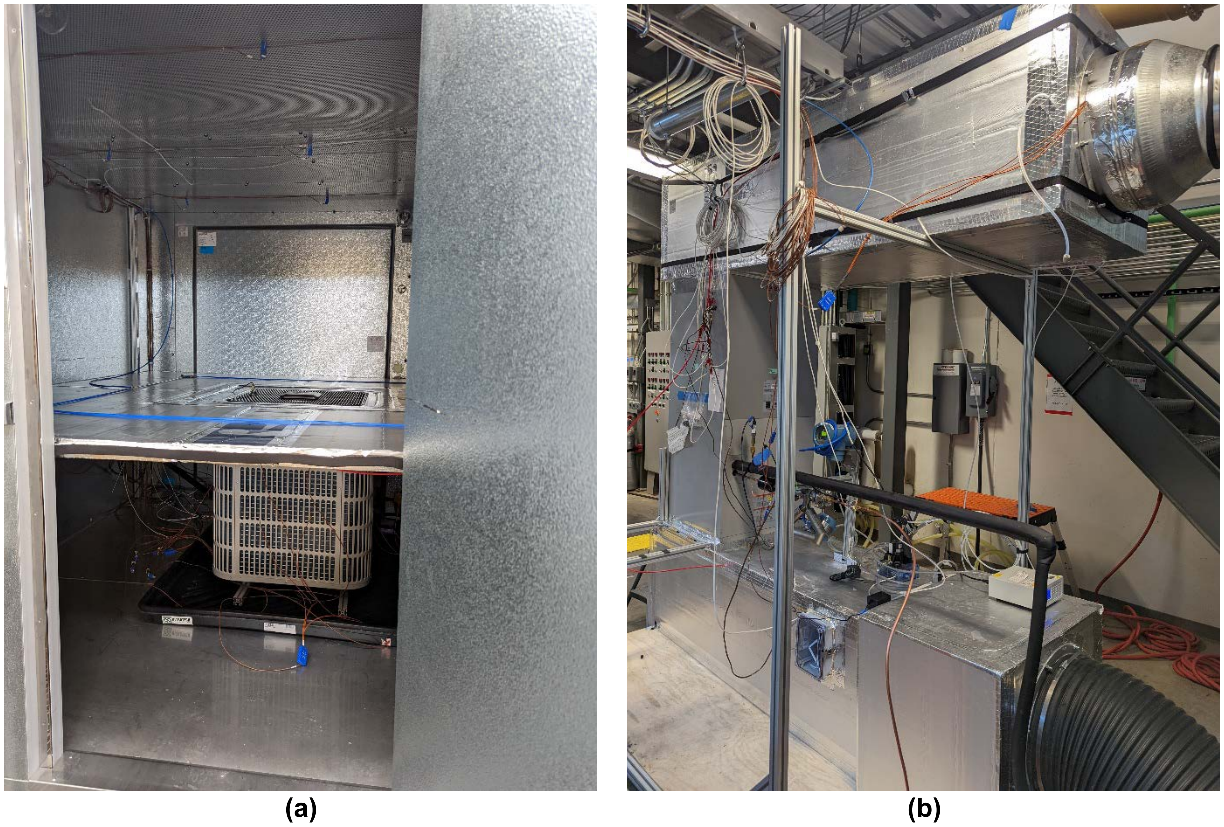

(a) (b)

Figure 4. Photographs of the central heat pump (a) ODU and (b) IDU installed in the laboratory

Photos by Greg Shoukas, NREL

2.3 Multi-Zone MSHP System

Figure 5 and Figure 6 show a schematic of the key measurements for the MSHP IDUs and ODU, respectively. The two IDUs were ducted to a single return plenum and single supply plenum since the laboratory only had a single set of nozzles to measure return and supply airflow rates. Thus, the supply air streams from the individual IDUs were mixed prior to measuring the air conditions. Blower speed (RPM) and electrical power were measured for each IDU individually. A removable partition was included in the return air duct to prevent air from passing through one of the IDUs if the current test point called for the IDU to be turned off.

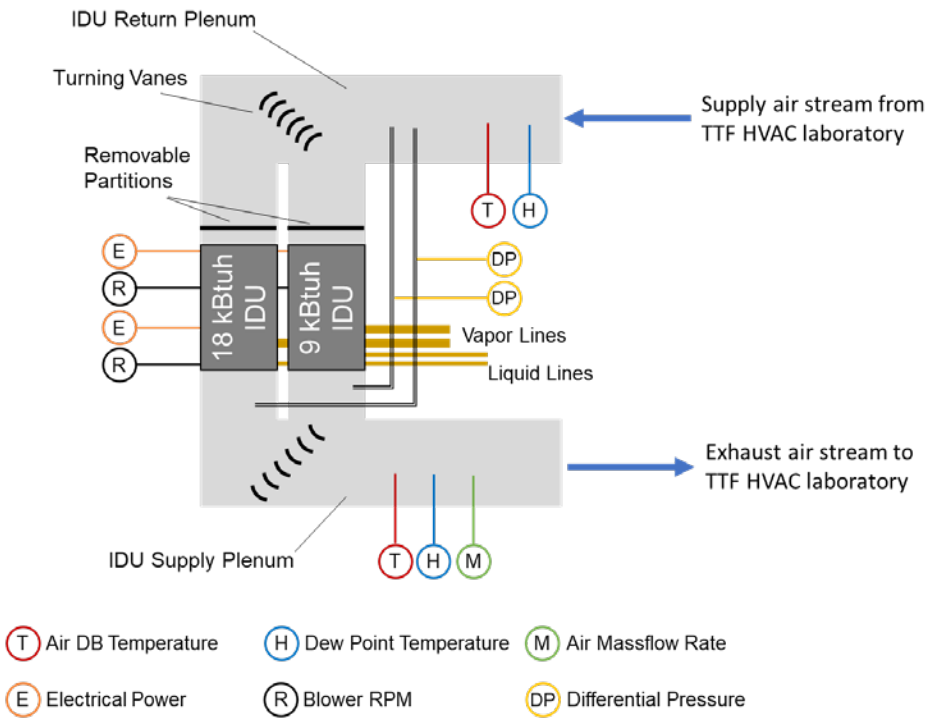


Figure 5. Schematic of key measurements for the MSHP IDUs

Similar to the central heat pump, compressor speed was determined by measuring the voltage frequency output from the inverter using a current transformer. The four-way valve was monitored to assist controlling the laboratory during defrost cycles. Since the heat pump's expansion valves are in the ODU, a secondary capacity measurement using refrigerant-side measurements was not made.

Pictures of the experimental setup for the MSHP are included in Figure 7.

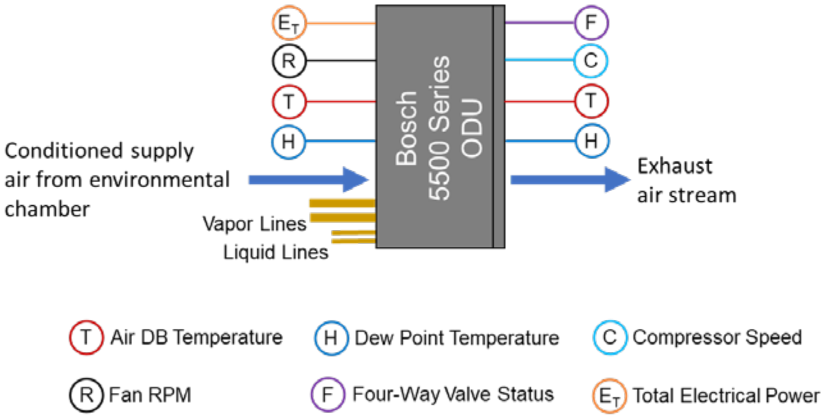


Figure 6. Schematic of key measurements for the MSHP ODU


(a) (b)

Figure 7. Photographs of the MSHP (a) ODU and (b) IDUs installed in the laboratory

Photos by Greg Shoukas, NREL

3 Experiments and Operating Conditions

This section of the report describes the experimental operating conditions imposed on the heat pump systems. Although a similar set of experiments was conducted for the central heat pump system and the two-zone MSHP, the experimental test matrix was slightly different to accommodate the different available settings and laboratory capability during the time of testing.

3.1 Central Heat Pump Experiment Test Matrix

The goals of the central heat pump laboratory experiments were to measure cold temperature performance, assess the impact of duct ESP on heat pump performance, and to estimate the impact of elevation on system performance. Table 5 lists the experimental test matrix for the central heat pump system. Outdoor air temperatures of 5°F, 17°F, and 47°F were selected because these temperatures correspond to values reported in the NEEP ccASHP product listing (see Table 2). Prior to the facility upgrade, temperatures below 5°F could not be reliably achieved for this particular heat pump and thus are not reported on. The IDU inlet temperature was 68°F, which was determined to be a representative heating setpoint for the region. The outdoor humidity was not controlled to a specific target value; however, the outdoor humidity was representative of the region since testing occurred during dry, winter months.

According to the Bosch technical support documentation, the ODU boosts the maximum compressor speed in heating mode, from 80 Hz to 94 Hz when the outdoor temperature is colder than 28.4°F (-2.0°C). Thus, the 32°F and 24°F test conditions were added for granularity around the temperature when the maximum compressor speed changes.

The approach for determining the high, medium, and low airflow rate values is discussed in Section 4.1.1.

Table 5. Experiment Test Matrix for the Central Heat Pump Maximum Capacity Tests

Test Type	IDU Inlet Temperature (°F)	Outdoor Air Temperature (°F)	IDU Airflow Rate [ACFM]		
			High	Medium	Low
Maximum Capacity	68	47	1,950	1,600	1,250
		32			
		24			
		17			
		5			
Altitude Impact	68	47	Not Tested	1,975	Not Tested
		32			
		24			
		17			
		5			

The impact of the elevation was estimated by using the laboratory's blowers to force a sea-level equivalent air mass flow rate through both the IDU and ODU. Since the laboratory is located approximately 5,860 feet above sea level with a standard barometric pressure of 11.9 psi, the airflow rates through the IDU and ODU were increased by approximately 23%. These tests were conducted for the medium airflow condition listed in Table 5.

The Bosch IDS 2.0 ODU contains a dip switch (SW4-4) that enables an “Accelerated Heating” mode to boost the capacity. The default position of SW4-4 disables the accelerated heating mode, and the tests listed in Table 5 kept the dip switch in the default position. However, a limited number of tests were conducted with the SW4-4 dip switch enabled to investigate the impact on performance, which are discussed in Section 4.1.4.

3.2 Multi-Zone MSHP Experiment Test Matrix

Like the central heat pump system, the main goals of the MSHP laboratory experiments were to measure the cold temperature performance and estimate the impact of elevation on system performance. Since the MSHP had two IDUs with controllable fan settings, we evaluated performance using different combinations of IDU operation and fan speed.

Table 6 lists the experimental test matrix for the MSHP system. Outdoor air temperatures of 5°F, 17°F, and 47°F were selected because these temperatures correspond to values reported in the NEEP ccASHP product listing (see Table 4). Because of the interest in cold temperature performance, we also tested the heat pump at outdoor temperatures ranging from -15°F to -25°F in 5°F increments to understand the heat pump controls at cold temperatures. Similar to the central heat pump, the IDU inlet temperature was held constant for all test points at 68°F, and ODU inlet humidity was not controlled.

The tests labeled “maximum capacity” were conducted by setting both IDU fans to the highest possible fan speed. Tests labeled “part-load” were conducted using different fan setting configurations to evaluate the impact of fan setting on heat pump performance.

The heat pump was operated using the equipment’s onboard, native controls and by setting the IDU thermostat to the maximum possible value (if it was scheduled to operate for the given test point). This approach ensured the heat pump operated at compressor maximum speed for the given IDU fan configuration. Return air was provided by the laboratory at 68°F for all tests. The laboratory fans were controlled such that the differential pressure measured between the return and supply sides of the IDU was zero unless the test point called for a prescribed IDU air mass flow rate.

The impact of the elevation was estimated by running both IDUs in the high fan setting and using the laboratory’s blowers to pull more air through the IDUs to match the manufacturer-reported SCFM. These tests were conducted at outdoor air temperatures of 5°F, 17°F, and 47°F. Due to laboratory constraints, sea-level airflow adjustments were not made to the ODU. Ramifications of this limitation are discussed in the Section 4.2.2. Tests were conducted to ensure the compressor speeds matched the maximum capacity test at the given outdoor air temperature.

Table 6. Experiment Test Matrix for the MSHP

Test Type	IDU Inlet Temperature (°F)	Outdoor Air Temperature (°F)	18-kBtu/h IDU Fan Setting	9-kBtu/h IDU Fan Setting
Maximum Capacity	68	47	High	High
		17		
		5		
		-15		
		-20		
		-25		
Part-Load Capacity	68	47	High	Off
		17		
		-5		
		-15		
		-20		
		-25		
		47	Off	High
		17		
		5		
		-15		
		-20		
		-25		
		47	Low	Low
		17		
		5		
		-15		
		-20		
		-25		
Altitude Impact	68	47	High	High
		17		
		5		

4 Results and Discussion

4.1 Central Heat Pump

The results for the central heat pump system are presented and discussed in the following three subsections. We first discuss the IDU blower evaluation because the results from this set of experiments determined the airflow rates used for the maximum capacity tests in Section 4.1.2. Lastly, we estimate the impact of the laboratory's elevation on the heat pump's performance.

4.1.1 IDU Blower Evaluation

Prior to evaluating the heat pump performance, we characterized the IDU blower performance at all five speed taps by measuring the airflow rate at different ESP levels, which were imposed by the HVAC Laboratory fans. The manufacturer literature states the blower motor has five speed taps and is designed for two-stage operation. Motor speed tap 4 is the default for high-stage operation, and motor speed tap 2 is the default for low-stage operation.

The goal of characterizing the blower was to determine the IDU airflow rates and ESPs to use for the maximum capacity tests. Figure 8 compares the measured IDU volumetric airflow rates (solid lines) to the manufacturer-reported airflow rates (dashed lines) at different ESPs for motor taps 3–5. The measured ESP for each test was adjusted to a sea-level equivalent ESP by scaling the measured value by the ratio of sea-level barometric pressure to the laboratory's barometric pressure.

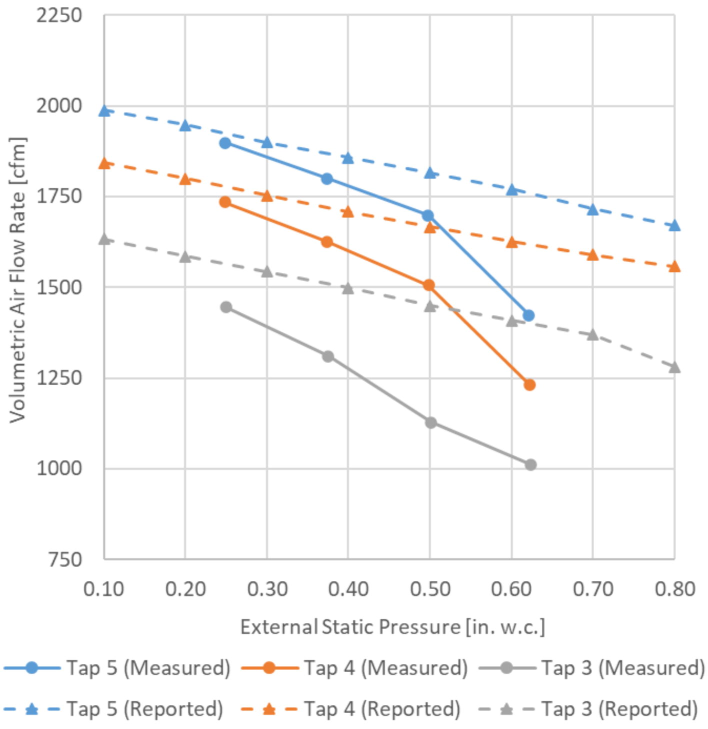


Figure 8. Central heat pump IDU measured airflow rates (solid lines) compared to manufacturer-reported airflow rates (dashed lines) at different fan taps

Because one goal of the project was to determine the impact of high duct ESP on system performance, the minimum ESP imposed on the system was 0.25 in. w.c. The measured volumetric airflow rate was close to the reported airflow rates at low ESPs. However, as the ESP increased, the measured airflow was significantly below the reported values. The constant torque motor reached the maximum programmed RPM at an ESP between 0.5 and 0.62 in. w.c. At ESPs greater than 0.62 in. w.c., the motor torque significantly decreased, resulting in low airflow and decreased power. This trend is noticeable in Figure 8 and Figure 9 by the slope change between 0.5 and 0.62 in w.c. Note that ESPs greater than 0.62 in. w.c. could not be reliably maintained to collect data and thus are not included in Figure 8. The maximum programmed RPM would need to be increased to achieve higher ESPs.

Figure 9 compares the measured IDU blower power to the reported values.

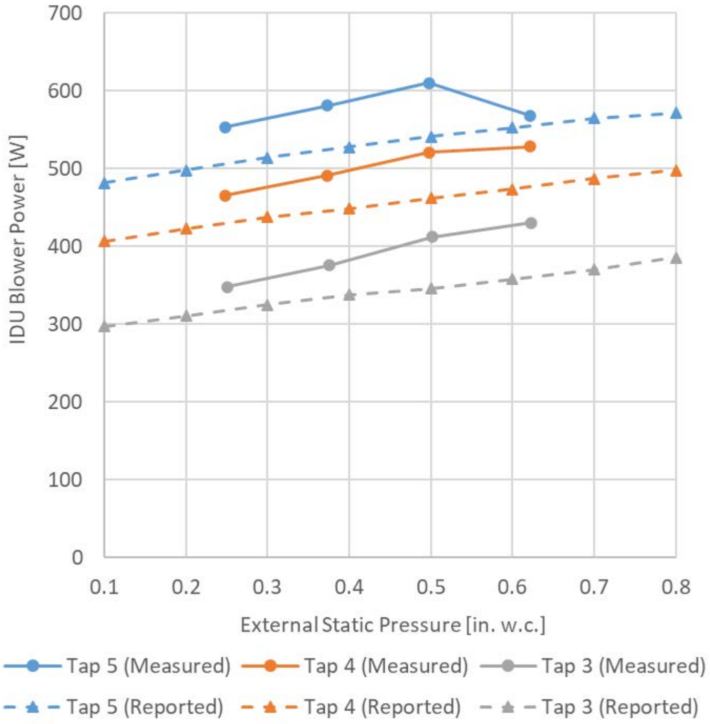


Figure 9. Central heat pump IDU measured power (solid lines) compared to manufacturer-reported airflow rates (dashed lines) at different fan taps

Since the maximum blower motor speed programmed in the motor limited the IDU airflow rate at high ESPs, we selected three IDU airflow rates to measure the sensitivity of IDU airflow rate on the heat pump's maximum capacity and COP. The selected airflow rates were then imposed on the IDU using the HVAC Laboratory fans for the maximum capacity tests.

The three selected volumetric airflow rates were 1,250 cfm, 1,600 cfm, and 1,950 cfm (Table 7). The highest tested airflow rate was based on a low ESP condition assuming the blower was set up to use motor tap 5 for high-stage operation. Though this configuration may not be commonly seen in the field since it would require the installer increase the fan speed for a home with a large duct system, this case served as an upper bound to determine performance sensitivity with respect to IDU airflow rate. The lowest tested airflow rate was based on a high ESP condition assuming the blower was set to use the motor tap 4 for high-stage operation, which is the default setting shipped from the factor. The medium tested airflow rate was simply the midpoint between the low and high airflow rates.

Table 7. Central Heat Pump Tested Airflow Rates

Airflow	IDU Airflow Rate (cfm)	Fan Tap Used for Test
High	1,950	Tap 5 (low ESP)
Medium	1,600	Tap 4 (mid ESP)
Low	1,250	Tap 4 (high ESP)

4.1.2 Maximum Capacity Tests at Different Airflow Rates

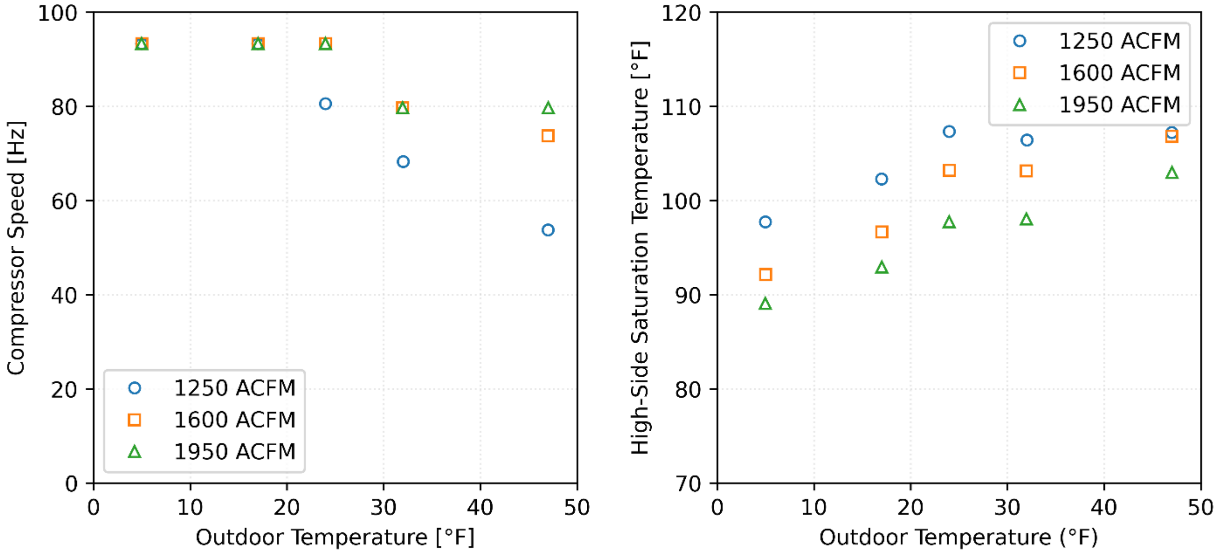
As noted in Section 1.4.1, the Bosch IDS 2.0 heat pump is a non-communicating system; this means it is similar to a traditional constant-speed system, in which the thermostat energizes a set of individual wires to control the heat pump. A communicating heat pump system relies on proprietary digital communication between the thermostat, IDU, and ODU, which allows the heat pump to adjust the compressor speed based on the measured indoor temperature reading and match the building load accordingly. Since the Bosch IDS 2.0 heat pump is a non-communicating heat pump, it uses onboard pressure sensors in the ODU to adjust the compressor speed.

Recall that the Bosch IDS 2.0 heat pump adjusts the compressor speed to maintain a constant high-side refrigerant pressure/saturation temperature. Presumably when the heat pump is installed in a home, as the return air temperature increases during a heating cycle, the compressor speed will decrease to maintain a constant high-side pressure.

Figure 10 plots the compressor speed (left) and high-side saturation temperatures (right) for the maximum capacity tests for the three tested airflow rates. The Bosch literature stated the maximum allowable compressor speed when the outdoor temperature is warmer than 28.4°F (-2.0°C) is 80 Hz. The ODU boosts the maximum compressor speed limit to 94 Hz when the outdoor temperature is colder than 28.4°F. This trend is clear in Figure 10a, in which we see the measured compressor speed was below the maximum allowed value when the IDU airflow rate was 1250 cfm and outdoor temperature was above 24°F due to the system achieving the target high-side saturation temperature of 108.5°F. At the other test points, the compressor ran at the maximum allowed compressor speed. From Figure 10b, we see that the programmed maximum compressor speed prevents the ODU from achieving the target high-side pressure at low IDU airflow rates and/or cold outdoor temperatures.

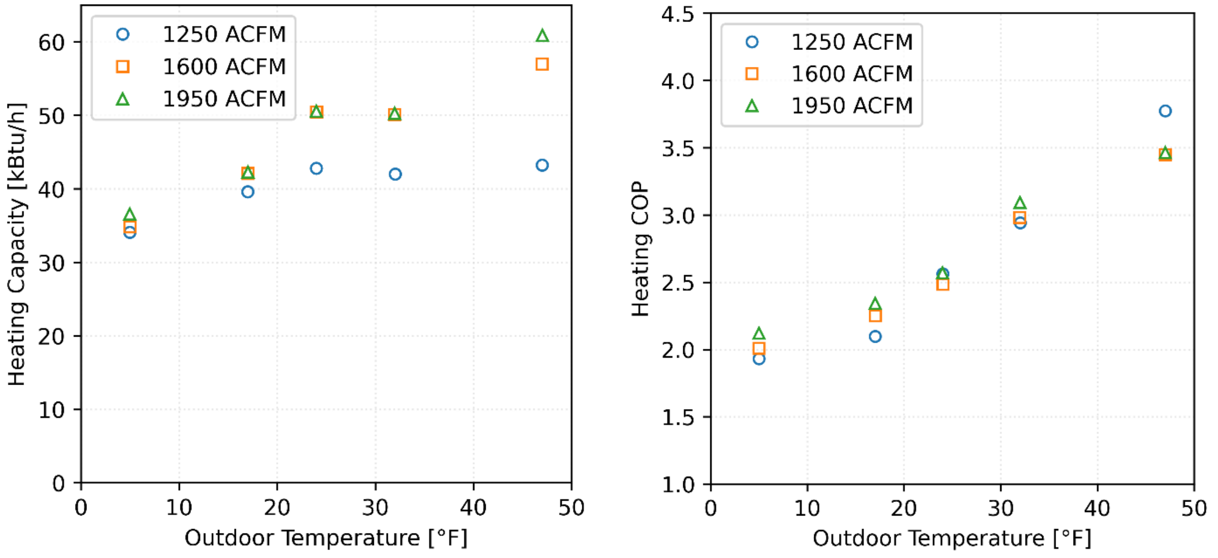
Figure 11 shows the measured heating capacity (left) and COP (right). In Figure 11a, we see the heating capacity was impacted by the low indoor airflow rate because the compressor speed was limited based on the high-side pressure control. However, the heating capacity was not significantly impacted by the indoor airflow rate for test points when the unit operated at the maximum compressor speed, which included the coldest temperature test conditions, i.e., when the outdoor temperature was less than 20°F. At cold outdoor air temperatures, the COP was higher at higher indoor airflow rates. At 5°F outdoor air temperature, the COP was ~11% higher at the highest tested IDU airflow rate. However, at a mild outdoor air temperature, the COP was highest when the IDU airflow rate and capacity were the lowest due to the lower power consumption at reduced compressor speeds.

Figure 12 shows the ODU power consumption for the maximum capacity tests. The power consumption is dependent on the compressor speed.



(a) **(b)**

Figure 10. Central heat pump (a) compressor speed (Hz) and (b) high-side saturation temperature (°F) for the maximum capacity tests



(a) **(b)**

Figure 11. Central heat pump (a) heating capacity (Btu/h) and (b) heating COP for the maximum capacity tests

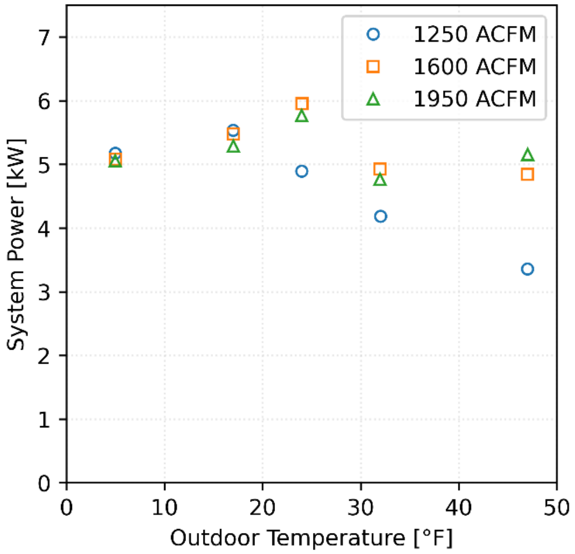


Figure 12. Central heat pump total system power for the maximum capacity tests

In general, the measured performance aligns with the manufacturer-reported data in Table 2 at outdoor temperatures of 47°F, 17°F, and 5°F. (While manufacturer-reported performance at -4°F is listed in Table 2, the performance was not measured at this temperature due to laboratory inabilities to reach this temperature at the time of testing.) Potential sources of discrepancy need to be considered when comparing the manufacturer-reported data listed in Table 2 to the data shown in Figure 11 and Figure 12. These include:

- Operating conditions: The heat pump was operated at a different indoor airflow rate and return air temperature than the manufacturer-reported data.
- Control: The heat pump was operated using onboard controls during these experiments and thus compressor and fan speeds may have been different than the manufacturer-reported data.
- Method of test: Though accurate instrumentation and approaches were implemented for this study, there are differences between the approach we implemented and standard test procedures (10 CFR Part 430 2022).

In Table 2, the capacity, COP, and power are quite different between rated and maximum speeds at 47°F. Since compressor speed and airflow rate are not published for these points, it’s unclear which point should be used for comparison. However, the measured capacity and COP at 47°F span the rated and maximum capacity values listed in Table 2.

Specific metrics of interest are the maximum capacity COP at 5°F and the percent of maintained heating capacity at 5°F compared to 47°F. The manufacturer-reported maximum capacity COP at 5°F was 2.02 and the laboratory-measured COP ranged from 1.93 at the lowest IDU airflow rate to 2.06 at the highest IDU airflow rate. The manufacturer-reported percent of maintained heating capacity (calculated from Table 2) using maximum capacity at 47°F was 64%. Capacity maintenance calculated using the rated capacity at 47°F was 65%. We measured a capacity maintenance percentage ranging from 60% at the high airflow rate to 79% at the low airflow rate. The low airflow rate tests had a higher capacity maintenance percentage because the compressor speed was controlled below the maximum allowable value due to the target high-side pressure being achieved.

Figure 13 plots the measured supply air temperatures for the maximum capacity tests. As expected, the supply air temperature is generally higher at lower IDU airflow rates. The exception is at 47°F when the ODU controls reduced the compressor speed based on the high-side pressure control. Based on the airflow impact on COP (Figure 11b), house heating load requirements, and occupant thermal comfort preferences, lower airflow rates may be desirable to achieve higher supply air temperatures.

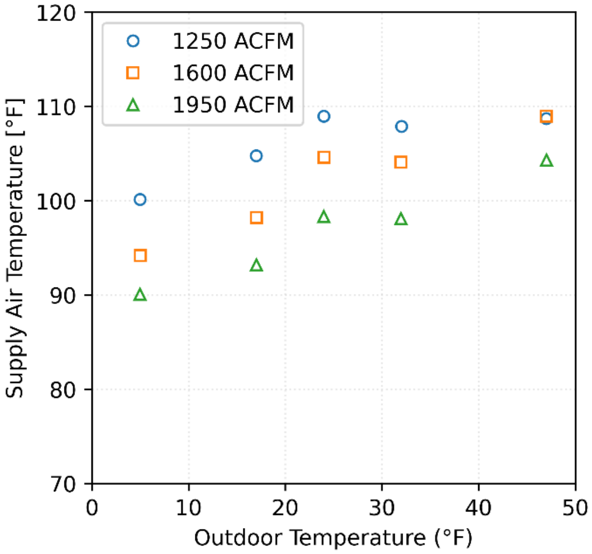


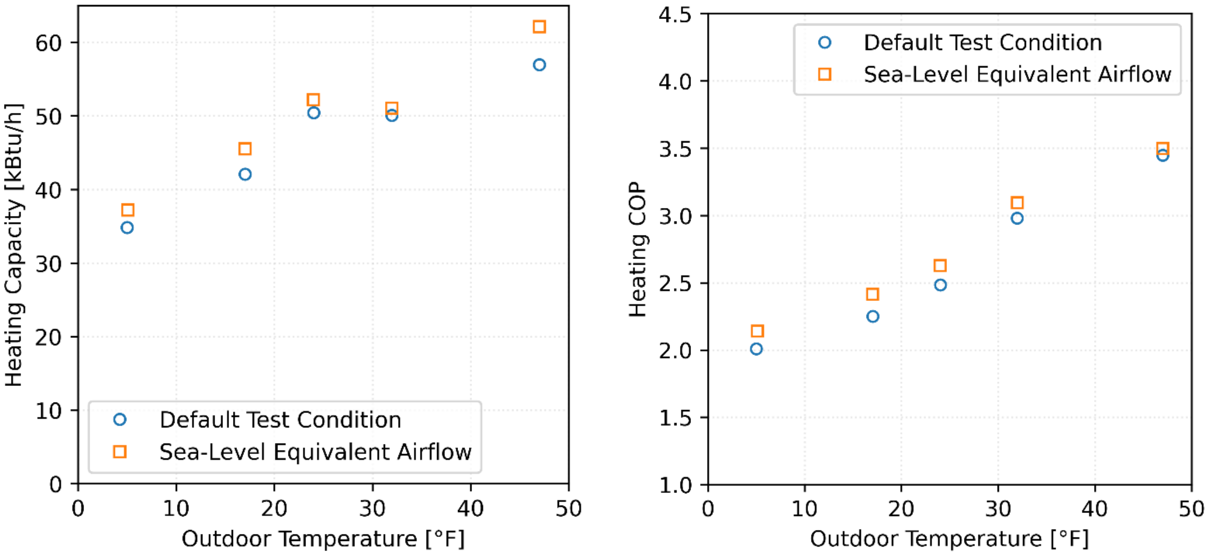
Figure 13. Central heat pump IDU supply air temperatures for the maximum capacity tests

4.1.3 Estimated Elevation Impact

Figure 14 compares the heat pump's performance when forcing a sea-level equivalent mass airflow rate though the IDU and ODU to the series of tests with an indoor airflow rate of 1600 cfm (labeled "Default Test Condition"). As expected, the heating capacity and COP increase when IDU and ODU airflow rates are increased to sea-level equivalent values.

The largest increase in capacity occurred at the 47°F test condition. Recall from Figure 10 that the compressor did not operate at maximum speed when the outdoor air temperature was 47°F and the IDU airflow rate was 1600 cfm due to the system's high-side pressure control, which satisfied the desired indoor coil saturation temperature. When the IDU and ODU airflow rate was increased to a sea-level equivalent value, the system increased the compressor speed at 47°F to the maximum allowed value.

On average, the capacity increased by 5.5% and the COP increased by approximately 4.7% when forcing a sea-level equivalent air mass flow rate through the system. The measured impact on capacity was less than the adjustment recommended by ACCA Manual S, which was approximately 9.7% when linearly interpolating the Manual S table (ACCA 2023). The ACCA Manual S recommended value relies on data from older, less efficient equipment. Modern, high-efficiency, central heat pumps are designed with significantly more heat exchanger surface area, which could mitigate the impacts of reduced air mass flow rates at higher elevations.



(a) **(b)**

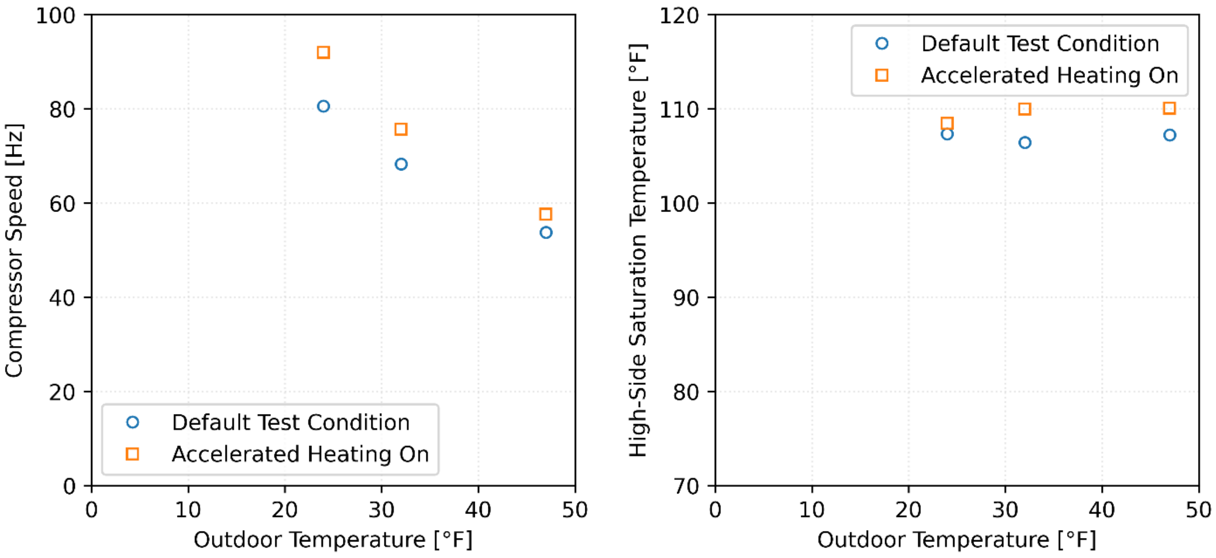
Figure 14. Central heat pump (a) heating capacity (Btu/h) and (b) heating COP for tests with a sea-level equivalent airflow rate

4.1.4 Accelerated Heating Mode (SW4-4 Enabled)

The Bosch IDS 2.0 ODU contains a dip switch (SW4-4) that enables an “Accelerated Heating” mode to boost the capacity. The default position of SW4-4 disables the accelerated heating mode. However, a limited number of tests were conducted with the SW4-4 dip switch enabled to investigate the impact on performance.

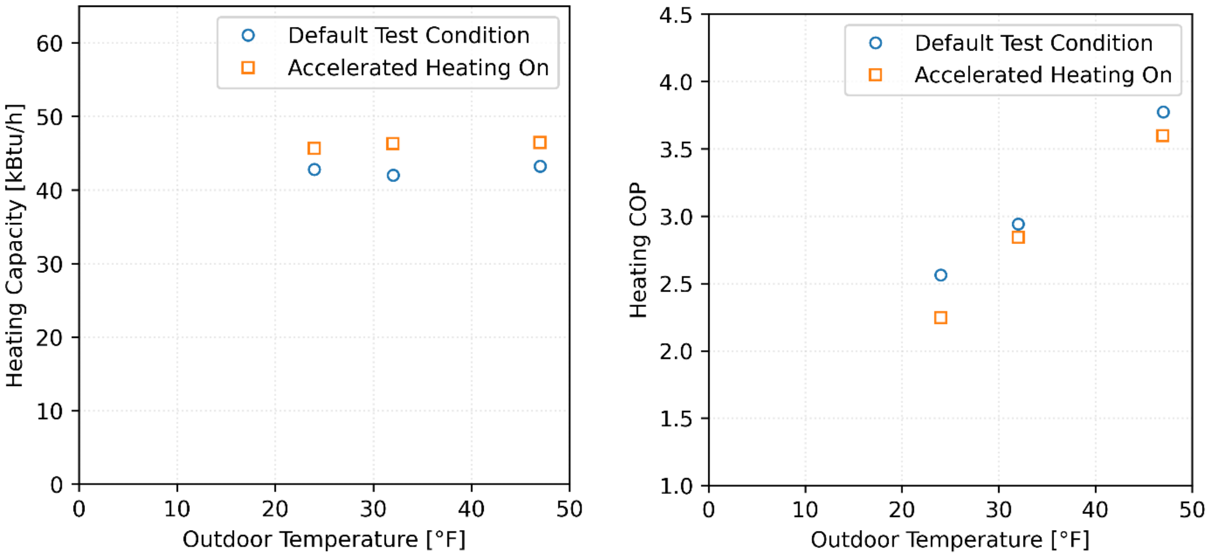
From Figure 10a, we saw the compressor speed was only below the maximum allowed value when the IDU airflow rate was 1250 cfm and outdoor temperature was above 24°F. This was due to the system achieving the target high-side saturation temperature of 108.5°F. Enabling the SW4-4 dip switch did not increase the maximum allowed compressor speed but rather increased the target high-side saturation temperature. Similar to the previous tests, the ODU boosts the maximum compressor speed limit from 80 Hz to 94 Hz when the outdoor temperature is colder than 28.4°F. Thus, enabling the SW4-4 dip switch did not affect the system operation at conditions when the maximum compressor speed was previously achieved. For this reason, results presented in this section only show points when the compressor speed was impacted by the SW4-4 dip switch.

Figure 15 plots the compressor speed and the high-side saturation temperature for the tree tests when the compressor speed was impacted by the dip switch, which only occurred at the lowest IDU airflow (1250 cfm). The points labeled “Default Test Condition” correspond to the points previously plotted in Figure 10 when the SW4-4 dip switch was disabled. The target saturation temperature appears to increase from 108.5°F with the SW4-4 dip switch disabled to 110°F with the switch enabled. This slightly increases the heating capacity (Figure 16a) but lowers the heating COP (Figure 16a) since the compressor is operating at higher speed.



(a) **(b)**

Figure 15. Central heat pump (a) compressor speed and (b) high-side saturation temperature for tests with the accelerated heating mode enabled



(a) **(b)**

Figure 16. Central heat pump (a) heating capacity (Btu/h) and (b) heating COP for tests with the accelerated heating mode enabled

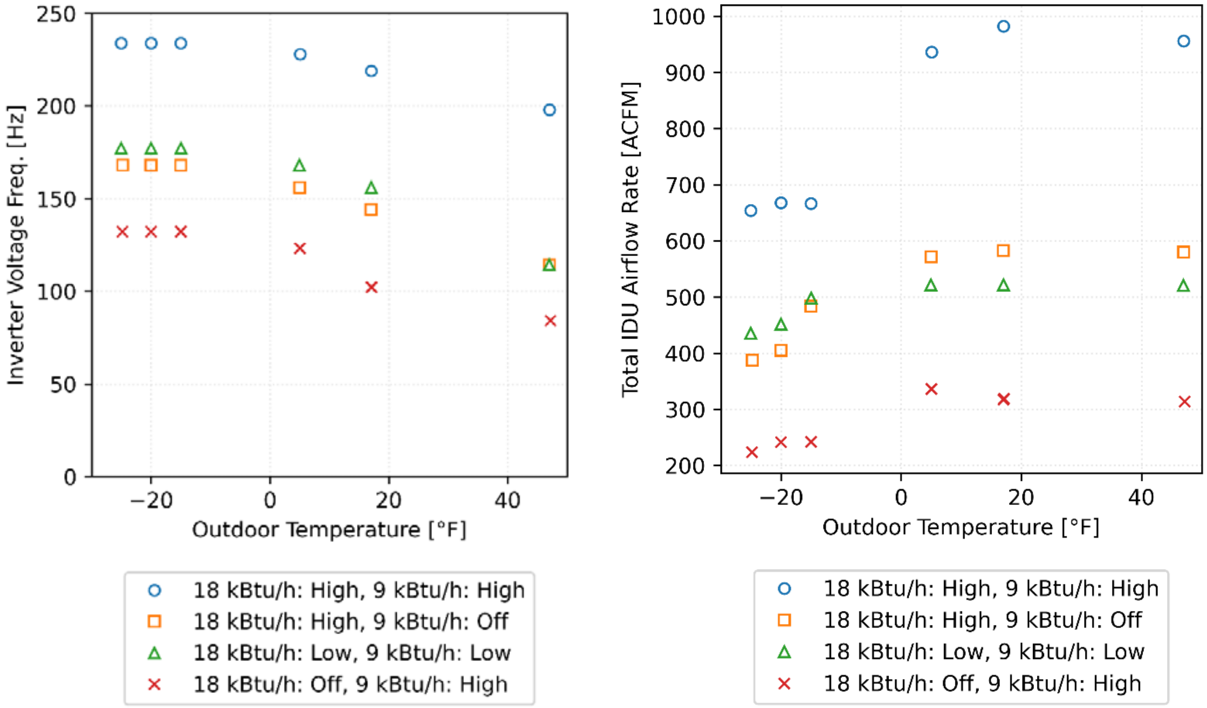
4.2 Multi-Zone MSHP

The results for the MSHP system are presented and discussed in the following two sections. We first discuss the maximum capacity and part-load capacity tests. We then estimate the impact of the laboratory's elevation on the heat pump's performance in Section 4.2.2.

4.2.1 Maximum Capacity and Part-Load Capacity Tests

Experimental data for the “Maximum Capacity” and “Part-Load Capacity” tests previously listed in Table 6 are typically plotted together in this section to show the impact of IDU operation on heat pump performance.

Figure 17 shows the ODU inverter voltage frequency (left), which is proportional to the compressor speed, and the corresponding total IDU airflow rate (right) for the maximum and part-load capacity tests. Each series in the plot represents a different IDU fan configuration. For example, the blue circles correspond to tests when both IDUs operated in the high fan setting, whereas the red x’s correspond to tests when the 18-kBtu/h IDU was turned off and the 9-kBtu/h IDU operated in the low fan setting.



(a) **(b)**

Figure 17. MSHP (a) inverter voltage frequency (Hz) and (b) indoor airflow rate (cfm) for the maximum and part-load capacity tests

We noticed that the heat pump generally increases the compressor speed at colder outdoor air temperatures until reaching a maximum compressor speed at temperatures below 5°F. This control feature is unique to variable-speed heat pumps and helps the heat pump maintain heating capacity at cold outdoor temperatures. We also noticed that the maximum allowable compressor speed is dependent on the IDU fan setting. This means the maximum compressor speed with both IDUs set to high was faster than the maximum compressor when both units were set to low.

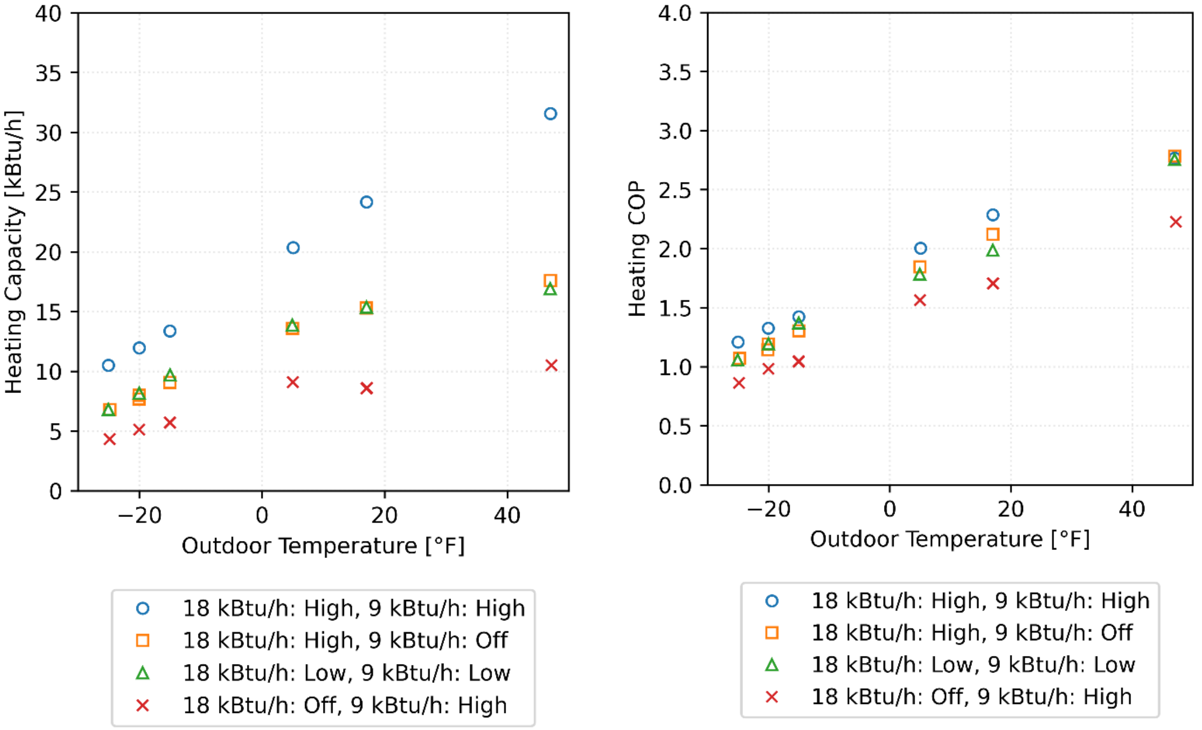
In Figure 17b, we see that total airflow rate decreased as the outdoor temperature decreased even though indoor unit fan settings were held constant for the given configuration. The decrease in the IDU airflow rate was caused by the controls slowing the IDU fan RPM at colder temperatures. This is a control strategy to help maintain warm supply air temperatures.

Table 8 shows the manufacturer-reported airflow rates for the 18-kBtu/h and 9-kBtu/h IDUs, respectively. From Figure 17a, we see the high-speed airflow rate for the 18-kBtu/h unit averaged 578 cfm, which was only 3.5% lower than the manufacturer-reported values. However, the high-speed airflow rate for the 9-kBtu/h unit was 324 cfm, which was ~23% lower than expected. It's important to note these airflow rate values are actual volumetric airflow rates (ACFM). Though the MSHP IDUs include variable-speed fans, the fan speed (RPM) will be constant at a given fan setting for a given outdoor air temperature. Since a fan is a constant volume flow device, the volumetric airflow rate will be independent of barometric pressure. However, the air mass flow rate will be lower at the laboratory's elevation compared to measured values at sea level.

Table 8. Manufacturer Listed IDU Airflow Rates (cfm)

IDU Model Number	Rated Cooling Capacity (Btu/h)	Low	Medium	High
BMS500-AAU018-1AHWXB	18,000	353	411	599
BMS500-AAU009-1AHWXB	9,000	247	324	418

Figure 18 shows the total heating capacity (left) and heating COP (right), and Figure 19 shows the total power consumption for the maximum capacity and part-load capacity tests. For these tests, the laboratory fans were controlled to maintain zero ESP across the IDUs, meaning the airflow though the unit during these tests would equal the airflow rate though the unit if it were installed in a home at the same elevation as the laboratory. We noticed the configuration with the 18-kBtu/h IDU set at high with the 9-kBtu/h off had similar performance to the configuration with both IDUs operating at low fan speed. From Figure 17b, these two configurations had a similar total IDU airflow rate.



(a) **(b)**

Figure 18. MSHP (a) heating capacity and (b) COP for the maximum and part-load capacity tests

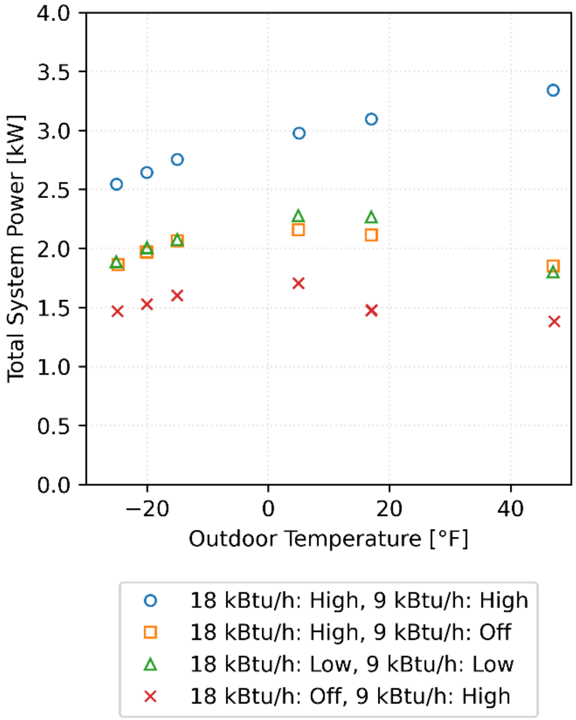


Figure 19. MSHP total system power for the maximum and part-load capacity tests

When comparing the heating capacity, COP, and total system power in Figure 18 and Figure 19 to the manufacturer-reported performance in Table 4, it's important to consider the following differences:

1. The manufacturer-reported performance was for a system configuration with three 9-kBtu/h IDUs.
2. The manufacturer-reported performance assumed sea-level air density and air mass flow rate.
3. Experiments conducted for this study used a 68°F return dry-bulb temperature; whereas manufacturer data was reported for a 70°F return dry-bulb temperature.

Item #1 above warrants additional explanation. From Figure 17, we saw the maximum compressor speed was dependent on the IDU settings. Since the manufacturer-reported data is based on a configuration with three 9-kBtu/h IDUs, it's possible the maximum compressor speed would be higher with three 9-kBtu/h IDUs rather than the tested configuration, which would have resulted in higher heating capacity. Additionally, we see the total IDU airflow rate would have been higher with three 9-kBtu/h IDUs compared to a configuration with one 18-kBtu/h IDU and one 9-kBtu/h IDU, which would have resulted in higher heating capacity and COP.

Despite these considerations, comparing the measured performance to the manufacturer-reported performance is still useful for context. Table 9 compares the manufacturer-reported performance previously listed in Table 4 to the measured performance for tests with both IDU fans operating in high speed. Due to the caveats with this comparison mentioned above, Table 9 lists both the rated and maximum capacity values from Table 4.

As expected, the measured heating capacity was below the manufacturer-reported capacity due to the tested IDU configuration differing from the manufacturer-reported configuration and the impacts of lower density air at the laboratory's elevation, which is further discussed in Section 4.2.2. The measured capacity maintenance, defined here as the ratio of maximum heating capacity at 5°F to maximum capacity at 47°F, was very close to the reported capacity maintenance. Laboratory results showed a capacity maintenance of 64.6% compared to a reported value of 65.8%.

Similar to heating capacity, the total power consumption of the heat pump was also lower than the manufacturer-reported values. The COP was within the expected range at the outdoor temperatures of 47°F and 17°F and slightly exceeded the manufacturer-reported COP at 5°F and -22°F.

Table 9. Comparison of Measured and Manufacturer-Reported Performance for the MSHP

		Outdoor Air Temperature			
		47°F	**17°F**	**5°F**	**-22°F**[1]
Capacity [kBtu/h]	Measured	31.6	24.2	20.4	11.4
	Manufacturer-Reported	28 – 38	26.0 – 26.6	24 – 25	13.55
Total Power [kW]	Measured	3.4	3.2	3.0	2.6
	Manufacturer-Reported	2.24 – 4.07	2.89 – 3.67	4.02 – 4.07	3.13
COP	Measured	2.77	2.29	2.0	1.3
	Manufacturer-Reported	2.74 – 3.66	2.08 – 2.7	1.75 – 1.8	1.27

[1] Values determined by interpolating -20°F and -25°F test points.

Figure 20 plots the measured supply air temperature during the maximum and part-load capacity tests. As expected, the supply air temperature decreased at colder outdoor temperatures, which is consistent with the decreasing heat pump capacity shown in Figure 18a.

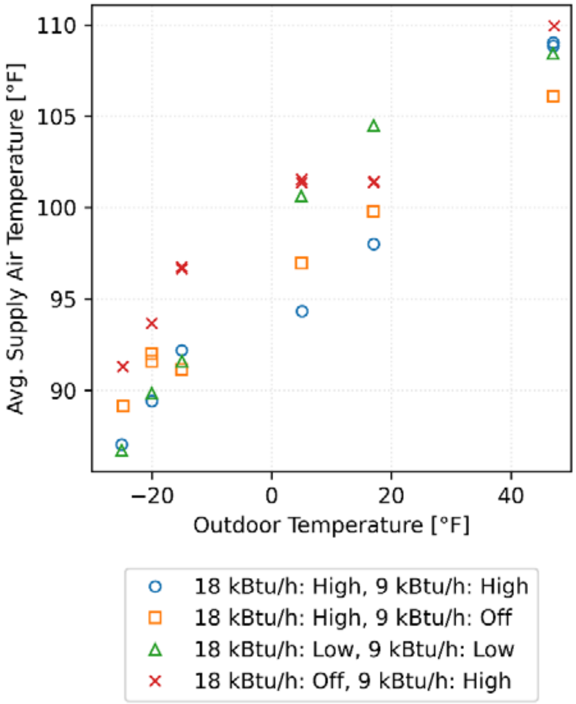


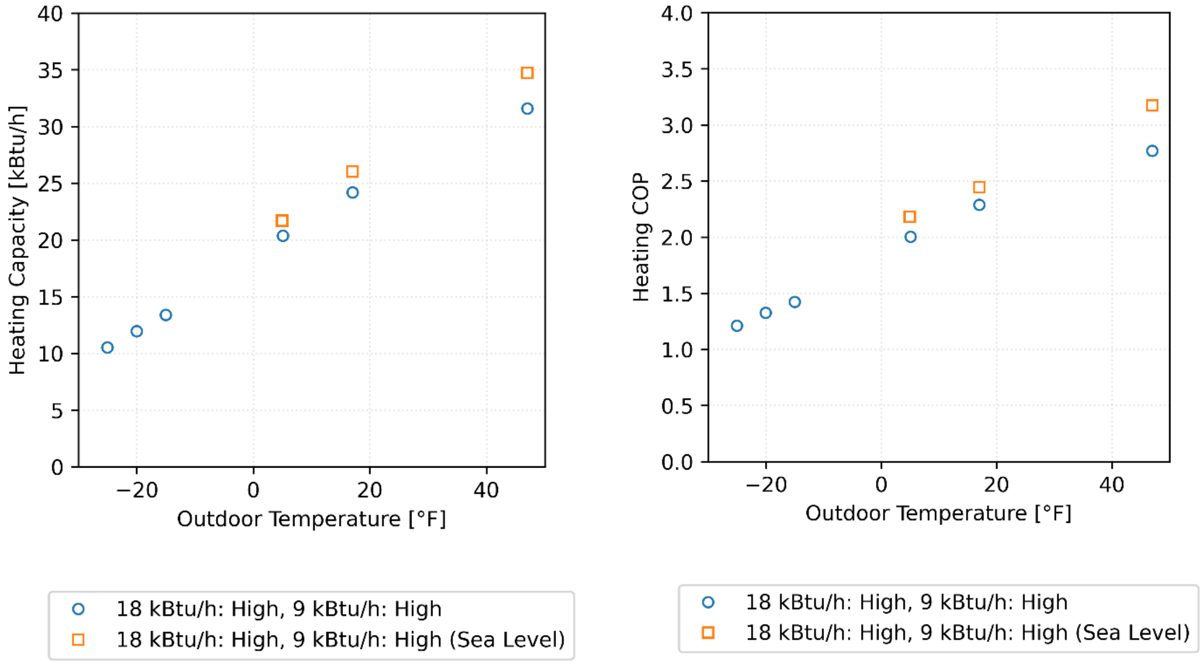
Figure 20. MSHP supply air temperature for the maximum and part-load capacity tests

4.2.2 Estimated Elevation Impact

The impact of the elevation was estimated by running both IDUs in the high fan setting and using the laboratory's blowers to force more air through the IDUs to match the manufacturer-reported standard volumetric flow rates (SCFM). These tests were conducted at outdoor air temperatures of 5°F, 17°F, and 47°F. The IDU fan power measurement had to be calculated using data from the previous tests since the fan power could not be measured directly when forcing more air through the IDUs using the laboratory's blowers. The IDU fan power measurements from the previous set of tests were scaled by the density ratio per fan affinity laws.

Due to laboratory constraints, sea-level airflow adjustments were not made to the ODU airflow rate. As a result of this limitation, the altitude impact for the MSHP may be slightly underpredicted. However, since the heat pump performance is more dependent on the high-side airflow rate (i.e., IDU airflow rate), most of the impact was captured in the data (Sezen 2023). Tests were conducted to ensure the compressor speeds matched the previously reported maximum capacity test at the given outdoor air temperature.

Figure 21 compares the MSHP's performance when forcing a sea-level equivalent airflow rate though the IDUs to the series of tests reported in Section 4.2.1 with both IDUs operating in high fan speed. As expected, the heating capacity and COP increase when the IDU airflow rates are increased to sea-level equivalent values. On average, the capacity increased by 7.4%, ranging from 9% at 47°F to 6.2% at 5°F. COP increased by 9.1% when forcing a sea-level equivalent air mass flow rate through the IDUs. The COP increase ranged from 6.5% to 12.8% across the temperature range. Similar to the central heat pump, the impact on capacity was less than the value recommended by ACCA Manual S, which was approximately 9.7% (ACCA 2023).



(a) (b)

Figure 21. MSHP (a) heating capacity (Btu/h) and (b) heating COP for tests with a sea-level equivalent IDU airflow rate

5 Conclusions

Under Technical Service Agreement TSA-21-17917 with Xcel Energy, NREL conducted laboratory and field research activities to evaluate the performance of current residential ASHP technologies in support of Xcel Energy's carbon-free electricity goals. Results from this research will be used by Xcel Energy to play a role in understanding the impacts that equipment, environment, and installation choices have on field operation and performance of residential ASHPs. This report focuses on the laboratory experiments.

The overall goal of the laboratory evaluation was to measure heat pump performance under a range of real-world heating mode operating conditions. Laboratory characterization was completed on one centrally ducted heat pump and one multi-zone MSHP (i.e., a multi-split heat pump). Xcel Energy selected and provided the heat pumps for this study. The selected central heat pump system was the Bosch Inverter Ducted Split (IDS) 2.0 5-ton ODU heat pump (BOVA-60HDN1-M20G) with the corresponding 5-ton indoor air handler unit (BVA-60WN1-M20), which is a non-communicating system with a constant torque, multi-speed ECM blower designed for two-stage operation. The selected MSHP system was the Bosch Climate 5500 Series 27-kBtu/h ODU heat pump (BMS500-AAM027-1CSXHC). Though the ODU supports up to three connected IDUs, the system was characterized with two different capacity wall-mounted, ductless IDUs with a total rated capacity of 27 kBtu/h (BMS500-AAS018-1CSXHB and BMS500-AAS009-1CSXHB). Additional details and specifications on the heat pump systems can be found in Section 1.4.

Specifically, the laboratory study measured:

- Heat pump capacity and COP at cold outdoor temperatures.
- The effect of different duct ESP on the centrally ducted heat pump.
- The impact of Golden, Colorado's elevation above sea level.

All experiments for this project were conducted at NREL's Thermal Test Facility in the HVAC Laboratory, which is an air psychrometric laboratory that delivers conditioned air to the heat pump using a custom, computer-based measurement and data acquisition system to control and maintain precise air temperature, humidity, pressure, and flow rates. Accurate, real-time measurements were recorded to determine the heat transfer performance and efficiency of both heat pump systems.

The centrally ducted heat pump was evaluated prior to the U.S. Department of Energy funding an upgrade to the laboratory capabilities. Prior to the upgrade, the laboratory could evaluate heat pumps at temperatures 5°F and above. However, after the facility upgrade which occurred during this project, the split system test stand evaluated the MSHP at an outdoor air temperature of -25°F.

In general, the measured performance of both heat pump systems aligned with manufacturer-reported metrics that are typically used to qualify heat pumps for program rebates. Though heat pump performance, system design, and control approaches can vary significantly across the product landscape, the experimental study resulted in the following conclusions:

- The impact of the laboratory's elevation resulted in an average decreased heating capacity of 5.5% for the central heat pump system and 7.4% for the MSHP. The measured impact on capacity for both heat pump systems was lower than industry standard suggested values. However, additional investigation is required for a complete general understanding of elevation impacts on heat pump performance.
- When installing constant-torque ECM blowers at high elevations, it's important for the installer to measure the duct system ESP, take steps to minimize excess ESP that could result in low IDU air flow rates, and measure the indoor airflow rate during heat pump commissioning. For the unit tested, low IDU airflow rates can significantly decrease heating capacity at mild outdoor air temperatures and the COP at cold temperatures.
- When installing MSHP systems, installers should understand how the selected IDU configuration will affect the heat pump's performance. For the multi-split system in this study, using three 9-kBtu/h IDUs would likely have resulted in higher heating capacity compared to the chosen configuration with one 18-kBtu/h IDU and one 9-kBtu/h IDU.

Future work will analyze the data collected on heat pump installed in the field, and where appropriate, make comparisons between the field and laboratory data sets.

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Appendix A. Laboratory Sensors

Table A-1 lists the sensors that will be used for the key measurements.

Table A-1. Summary of Key Measurement Sensors

Measurement Description	Sensor Type	Distributor	Model Number	Accuracy
Air-side differential pressure	Differential pressure transducer	Setra Systems, Inc.	239	±0.14% FS
Air mass flow rate	Thermal Test Facility laboratory nozzles	Custom fabricated	N/A	~ ±2%
Air dry-bulb temperature	Type-T thermocouple	Omega Engineering, Inc.	TT-T-24S-TWSH-SLE	±0.5°C
Air dew point temperature	Chilled mirror hygrometer	General Eastern	SIM-12H	±0.25°C
Air flow (velocity) measurement station	Pitot tube array	Dwyer Instruments	FLST-R-18x20	N/A
Blower and fan speed	Optical tachometer	Monarch Instrument	ACT-3X/ROLS-W	N/A
Electrical power	Revenue grade power meter	Accuenergy, Inc.	Acuvim II-D	±0.2%
Inverter voltage frequency	Current transducer	Continental Controls	Accu-CT	N/A
Inverter voltage frequency counter	Frequency counter	Red lion	IMFA0035	N/A
Refrigerant line surface temperature	Type-T, adhesive pad thermocouple	Omega Engineering, Inc.	N/A	N/A
Refrigerant pressure	Pressure transducer	Omega Engineering, Inc.	PX309-1KG5V	±0.25%
Refrigerant mass flow rate	Coriolis mass flow meter	Micro Motion	Elite Series CMF025	N/A
Defrost on/off detection	Current transducer	Aim Dynamics	DCT-0010-005	N/A
Barometric pressure	Pressure transducer	MKS Instruments	Baratron 220D	±0.15%