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Low-Load Efficient Heat Pump Investigation:

2023 – 2025 Summary Report

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Acronym List

Acronym	Meaning
AHRI	Air-Conditioning, Heating, and Refrigeration Institute
aMW	Average megawatt
BHEC	Bruce Harley Energy Consulting
BPA	Bonneville Power Administration
Btu	British Thermal Units
C_{low}	AHRI 210/240 cooling test data
COP	Coefficient of performance
COPMin47F	Coefficient of performance at minimum capacity at 47°F (same as MinCapCOP47)
CSA	CSA Group
CVP	Controls Verification Procedure
DOE	Department of Energy
EEV	Electronic expansion valve
$H1_{low}$	AHRI 210/240 heating test data for MinCapCOP47
HP	Heat pump
HSPF	Heating Seasonal Performance Factor
HSPF2	Heating Seasonal Performance Factor (new standard)
kW	kilowatt
kWh	Kilowatt hour
LCTool	Levelized Cost Tool
MinCapCOP47	Minimum capacity coefficient of performance at 47°F
MNCEE	Minnesota Center for Energy and Environment
MW	megawatt
NEEA	Northwest Energy Efficiency Alliance
NEEP	Northeast Energy Efficiency Partnerships
NW	Northwest
OEM	Original equipment manufacturer
ORNL	Oakridge National Laboratory
RAT	Room ambient temperature
sCOP	Seasonal coefficient of performance
SEER	Seasonal Energy Efficiency Ratio
SEER2	Seasonal Energy Efficiency Ratio (new standard)
TEE	Thermostat Environment Emulator
TMY3	Typical Meteorological Year, version 3
TXV	Thermostatic expansion valve
UNL	University of Nebraska at Lincoln
VCHP	Variable capacity heat pump
VSHP	Variable speed heat pump (NEEA used term that is interchangeable with VCHP)

Executive Summary

Northwest Energy Efficiency Alliance's (NEEA's) Advanced Heat Pumps program aims to transform the residential heat pump market through improved differentiation of heat pump systems that deliver more cost effective and reliable savings. One such differentiator is how well a variable speed heat pump operates under low load conditions when outdoor temperatures are relatively mild, and variable speed systems can generate increased performance. NEEA defined and identified heat pumps that demonstrate superior efficiency at moderate outdoor temperatures as low-load efficient (LLE). This report provides a summary of the investigations funded by NEEA to understand and verify low-load efficiency of variable speed heat pumps (VSHP).[1]

NEEA's current definition of a low-load efficient heat pump is a variable speed system that achieves a minimum coefficient of performance of at least 4.5 when the system is operating at its minimum capacity when the outdoor conditions are steady at 47°F. This value is referred to as the MinCapCOP47 within this report. This metric is intended to be the same as the AHRI 210/240[2]: Performance Rating of Unitary Air-Conditioning & Air-Source Heat Pump Equipment test procedure, test condition $H1_{Low}$ which is a static test of a heat pump's performance and is currently found in the Northeast Energy Efficiency Partnership (NEEP) Cold-Climate Air Source Heat Pump Specification and Product database.[3]

Between 2020 and 2025, NEEA funded research investigations to understand and verify low-load efficiency of VSHP. This report summarizes the investigations and provides evidence of the value and market potential for heat pumps that operate more efficiently under low-load conditions when outdoor temperatures are relatively mild, and variable speed systems can generate increased performance with little to no incremental cost.

Modeling Results

Modeling results using a tool developed jointly with NEEA and the Minnesota Center for Energy and Environment (MNCEE) in 2022 uncovered the LLE archetype. The modeling tool was updated and analyzed with focus on low-load efficiency using heat pump data observed in lab testing of well-performing systems. The revised modeling showed that an increase in low-load efficiency of 12.5% would generate 2%–7% reduction in annual energy consumption compared to an average non-LLE variable speed heat pump. The modeling revealed the importance of appropriately sizing a heat pump system and the reduced benefit of LLE in very hot or very cold climates. Under sizing a heat pump system limits the amount of time the heat pump system gains benefits from LLE, whereas oversizing may mean most of the LLE benefit occurs when outdoor temperatures are too cold to fully take advantage of LLE performance gains.

AHRI and NEEP Data Investigation

The ability to identify LLE heat pumps currently relies on the manufacturer's self-reported extended equipment performance data provided to NEEP and accessible through the NEEP database. Unfortunately, because the NEEP database contains voluntarily reported data without 3rd party

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[1] NEEA uses the term VSHP (variable speed heat pump) term interchangeably with VCHP (variable capacity heat pump). Variable speed is simply a more consumer-friendly term that NEEA chose to use for its program name.

[2] AHRI 210/240: Performance Rating of Unitary Air-Conditioning & Air-Source Heat Pump Equipment test procedure.   AHRI Standard 210/240-2024 (I-P)

[3] NEEP ccASHP Specification & Product List | Northeast Energy Efficiency Partnerships. NEEP does not define the low speed performance at 47°F in their specification as the $H1_{low}$ test result, and not all manufacturers report $H1_{low}$ to NEEP.

verification, and original equipment manufacturers (OEMs) are not required to publish the data used to calculate MinCapCOP47, published values have, in some cases, been found to lack accuracy or consistency. For example, it was observed that roughly 2% of the reported MinCapCOP47 in the data appear to be on the outer edge of what is thermodynamically possible, and roughly 3% of the data shows uncharacteristically low values.

Three challenges with the database have emerged: 1) NEEP reported values do not always match lab test data, 2) the data is poorly reported to NEEP (data entry errors), and 3) the capacity at which the minCapCOP47 is reported is inconsistent.

Virtual and Physical Teardowns

The investigation used both a comparison of product specifications as outlined in this report and a physical teardown workshop to explore what, if any, specific design feature is the source of low-load efficiency. Neither approach revealed a singular component or feature that has an outsized impact on low-load efficiency. Most efficiency gains are obtained through two different operating factors of a heat pump. The first is the reduced fan power when operating during mild outdoor temperatures. The second is when the heat pump operates at low compressor speeds, the heat exchangers are effectively oversized for the load, which can improve system efficiency. Discussions with OEMs underscored the interconnectedness of system design in enhancing low-load efficiency. Design considerations, such as compressor type and turndown, metering device type, heat exchanger geometry, and fan turndown, are interrelated. Control algorithms also appear to be ultimately responsible for maximizing how well a heat pump takes advantage of low-load efficiency gains.

Lab testing

Using load-based testing to generate performance mapping of heat pumps under their own control confirmed that low-load efficiency exists under normal operating conditions for some heat pumps. The testing also revealed that not all NEEP-listed data are accurate. Two of the six systems tested had significantly reduced low-load efficiency, and four of them had low-load modulating limits that varied by more than 40% from the capacities reported in the NEEP database. This suggests that the performance under static conditions of the AHRI 210/240 test condition needs to be augmented by a controls verification procedure (CVP) to verify that the variable speed heat pump does in fact operate as a variable speed heat pump under low load conditions.

Interestingly, one unit tested had exceptional full-load performance with only minor improvements under low load, where it demonstrated frequent cycling behavior. Speculatively, better modulation control of the compressor and fans could result in significant low-load performance gains of such a system. Lastly, testing revealed that two units that reported turn-down ratios that are much higher than the typical limits of around 4:1 to 5:1 were unrealistic and not supported by the equipment operating under its native controls. Reporting performance at much higher turndown ranges than the equipment operates at results in underreported low-load COP, as well as overstated turndown. This further supports the need for a CVP to validate the AHRI test condition at low speed.

Field testing

Data from field testing is naturally subject to significant variability and the conditions of low-load efficiency can be difficult to isolate. Six of the 18 systems from the Bonneville Power Administration (BPA) field test revealed low-load coefficients of performance (COPs) higher than reported, and four of the systems' low-load efficiency was roughly equal to what was reported. The remaining eight systems showed lower, and in a few cases, much lower low-load COP values than reported. The source of this variability could not be determined with certainty, though it appears to be related to the manufacturer. Some manufacturers have distinctly superior LLE performance compared to others. This correlation suggests that control algorithms (which are likely common for each manufacturer) may play a significant role in reaching LLE.

Call to Action

NEEA believes a 12.5% gain in market average MinCapCOP47 is possible. Such a gain would generate an additional 2%–7% energy savings of variable speed heat pumps, potentially without an increase in system cost. In the Northwest, with roughly 1 million electric heated and an additional 2.5 million potentially dual-fuel-heated residential buildings, such a change represents a technical potential energy savings of roughly 45 aMW.[4] The next steps to make this a reality include:

1. Secure improved heat pump performance data reporting to support utility forecasting and climate-appropriate equipment selection. Ideally, the NEEP database should be based on AHRI test results, not on ill-defined and independent reporting. If possible, reporting should include verification that the heat pump meets the controls verification procedure (CVP) defined in Appendix I of AHRI 210/240 test procedure.
2. Continue improving and validating modeled energy performance based on lab and field data.
3. Work with OEMs to ensure all VSHPs can achieve a MinCapCOP47 value greater than 4.5. NEEA and its partners should conduct new low-load load-based testing of systems in 2028, and recognize those manufacturers that exceed this target within their variable-speed product lines.

The independent reporting of heat pump performance data by manufacturers to NEEP has called into question some of the resulting data listed in the NEEP database, in particular the MinCapCOP47 value as it is currently reported. We are working with NEEP to update definitions to be consistent with AHRI testing, and to get all data in the NEEP database to be provided by manufacturers reporting directly to AHRI. Once we have completed these steps, and the new AHRI controls verification procedure has been fully incorporated into the AHRI rating process,[5] we will have greatly improved trust in MinCapCOP47 as reported by NEEP. This is expected to all be in place by early 2027..

1. Introduction

The Northwest Energy Efficiency Alliance (NEEA) has identified “low-load efficient” (LLE) heat pumps as a strong product differentiator capable of driving cost-effective savings. Put simply, a low-load efficient heat pump operates exceptionally efficiently under mild heating and cooling conditions. This is a unique capability of machines that can optimize efficiency as they modulate fan and compressor speeds to reduce power consumption when less than full-load conditions exist.

This work began in 2020 in collaboration with Minnesota’s Center for Energy and Environment (MNCEE) on a project that compared different archetypes of heat pumps that represent a range of capacity and coefficients of performance (COPs) compared to outdoor temperature. The study (Smith 2022) revealed that the lowest levelized cost of heating and cooling in most applications is achieved by low-cost variable speed heat pumps with excellent part-load efficiency. Subsequent modeling analysis revealed

[4] 1 million HP homes x 200kWh/yr + 2.5 million dual fuel homes x 100 kWh/yr = 4 million kWh = 45.7 aMW
[5] The CVP is in Appendix I of the AHRI 210/240 (2024) test procedure and is in the process of being implemented by AHRI.

that increasing the part-load efficiency of a heat pump by 25% reduced annual energy consumption by 6% in very cold climates and 17% in milder climates of the Pacific Northwest and California.

This analysis is supported by lab testing of heat pumps using load-based testing methods developed by Purdue University (Harley 2022). Lab testing using the CSA Group test procedure EXP07-19[6] revealed the significant impact on an annualized rating metric (SCOP) when the equipment was tested under its own native controls, under heating and cooling loads commensurate with outdoor test chamber conditions. Heat pumps with superior part-load efficiency were found to have controls that modulate the compressor and fans to reduce the output without dramatic cycling behaviors (Harley 2022).

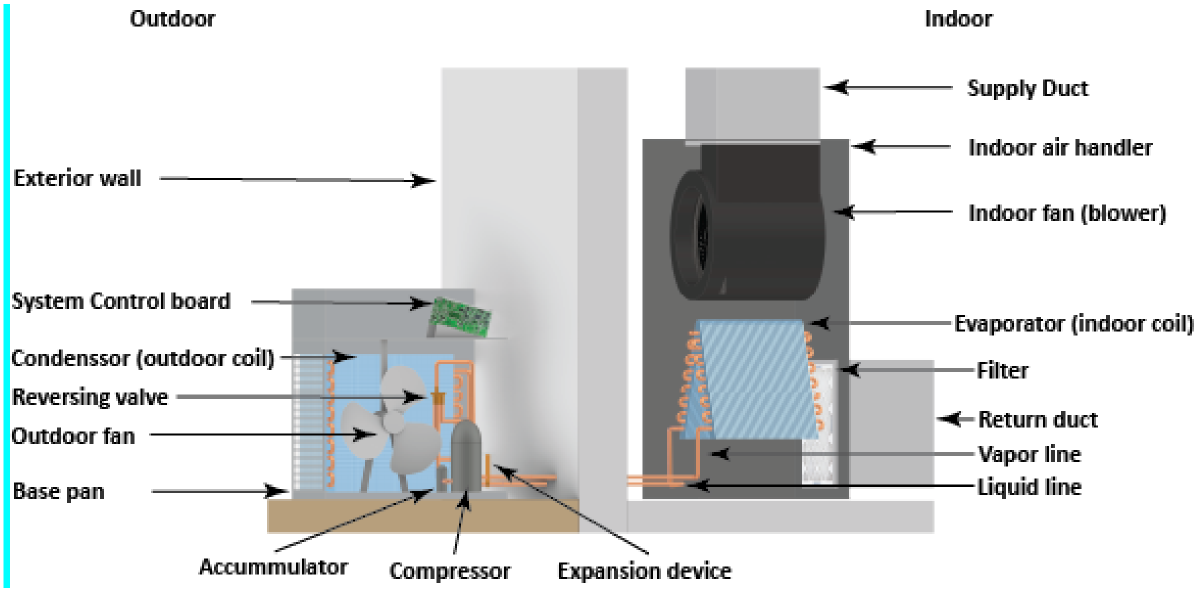

Figure 1: Primary components in a heat pump in heating season.

[6] CSA EXP-07 was superseded by CSA SPE-07:23, https://www.csagroup.org/store/product/CSA%20SPE-07%3A23/

Figure 2 illustrates the characteristic efficiency "bump" of a low-load efficient heat pump with COP values that increase as compressor and fan speeds are reduced. The graph shows both low- and full-speed COP values across heating and cooling ranges. This performance "bump" occurs in a temperature range in which a significant portion of the annual load finds the heat pump modulating at reduced fan and compressor speed. During hours when the house load is below the minimum operating capacity of the heat pump, it will need to cycle on and off, somewhat reducing efficiency at the lowest loads.

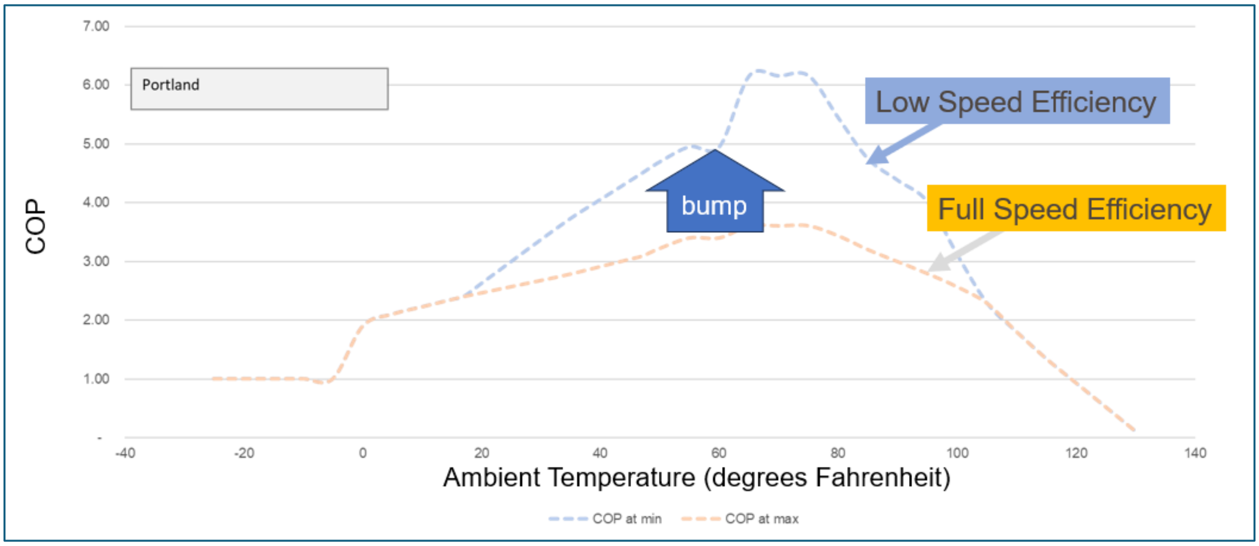

Figure 2: Heat pump efficiency at both low and full speed vs. ambient temperature

NEEA has defined LLE heat pumps as heat pumps with a COP greater than or equal to 4.5 at its minimum output capacity at 47°F. This COP data is readily available on the Northeast Energy Efficiency Partnerships (NEEP) cold climate air source heat pump product list as the COPMin47F value.[7] This value represents the COP of a heat pump at an outdoor air temperature of 47°F while the heat pump operates at its lowest compressor speed.

The COP at MinCapCOP47 is, in most cases, derived from AHRI 210/240, based on H1 test results. For a single-speed heat pump, this COP value is synonymous with maximum capacity. For a two-speed heat pump, the value is at the low-speed condition, which is well-defined. But for variable speed heat pumps, the minimum compressor speed is not universally defined. For AHRI reporting, heat pump manufacturers can choose the speed at which the unit operates for low-load test conditions. In addition, manufacturers can decide which resulting test values they report to NEEP, and not all use the AHRI test results.

Because of this manufacturer discretion, and the fact that AHRI does not publish $H1_{Low}$ data on the AHRI directory, there may be a difference between the MinCapCOP47 values found on the NEEP list and the corresponding values reported to AHRI for test condition $H1_{Low}$. Conversations with manufacturers

[7] The NEEP field is labeled "COP Min 47°F". This paper refers to this term as MinCapCOP47 to make it clear that this is the COP at the minimum capacity, and not the minimum COP, at 47°F.

suggest a preference that data for AHRI be reported to NEEP to reduce discrepancies and provide a level playing field.

While the NEEA selection of a "MinCapCOP47" value of 4.5 is not a perfect differentiator of low-load efficiency, it is roughly a 12.5% increase over the current market average of just under 4.0. About one-third of heat pumps listed in the NEEP database (as of 2023) reported a MinCapCOP47 of at least 4.5. This clearly indicates that the specification is achievable.

While the Heating Seasonal Performance Factor 2 (HSPF2) is a metric that reports an estimated heating efficiency of a heat pump over the entire heating season, the MinCapCOP47 is the COP at 47°F at the heat pump's minimum capacity. Figure 3 is a graph of HSPF2 vs. MinCapCOP47 values for all M1-rated[8] products on the NEEP database as of 2023. The graph shows that the MinCapCOP47 can vary significantly for a given HSPF2 value. Products with the same annual HSPF2 value can have a MinCapCOP47 value that ranges from 3.0 to 6.0. The poor correlation between MinCapCOP47 values and HSPF2 values suggests that manufacturers are not paying attention to performance at low-load conditions, despite operating at these conditions for a large amount of time in most climates.

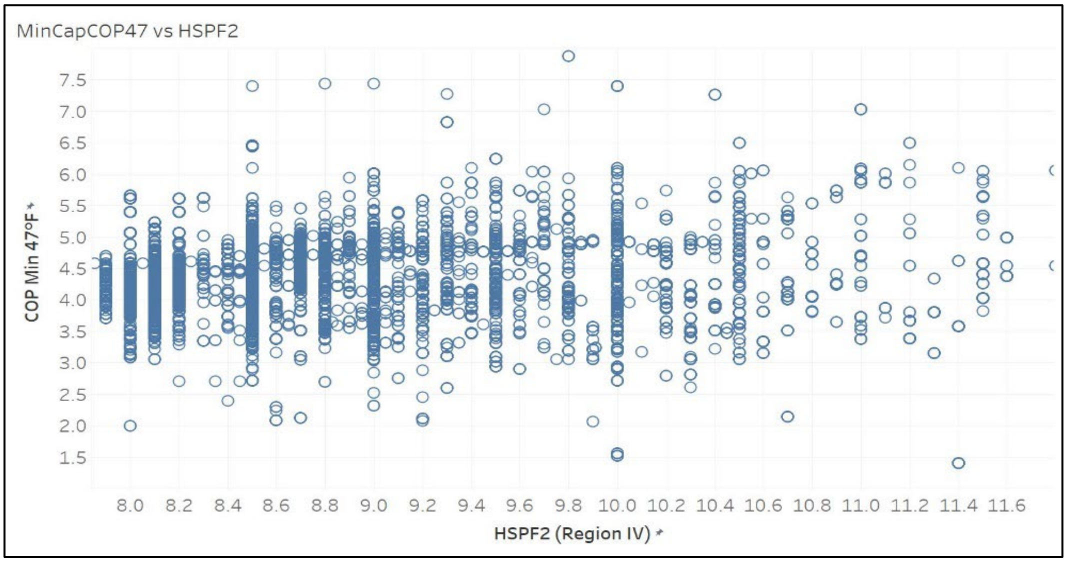

Figure 3: COPMin47°F vs. HSPF2 (source: NEEP ccASHP Database, 2023).

Figure 3 shows the market distribution of variable speed heat pumps sold in the Northwest during 2020 (source: NEEA sales data from NW distributors). Compared to Figure 2, which is looking at a distribution of an array of all listed products, the distribution of sales data is a better indication of how most installed systems are likely to be currently performing in the field ("market performance"). Sales data shows that roughly 1/3 of all systems at that time claimed to have a MinCapCOP47 of 4.5 or greater. Most of these LLE systems at the time were non-ducted systems.

[8] M1-rated is the DOE compliance test corresponding to the AHRI 210/240-2023(2020) updated testing and rating standard. It became effective on 1/1/2023, so in 2023 NEEP data included models that had not yet been rated using M1.

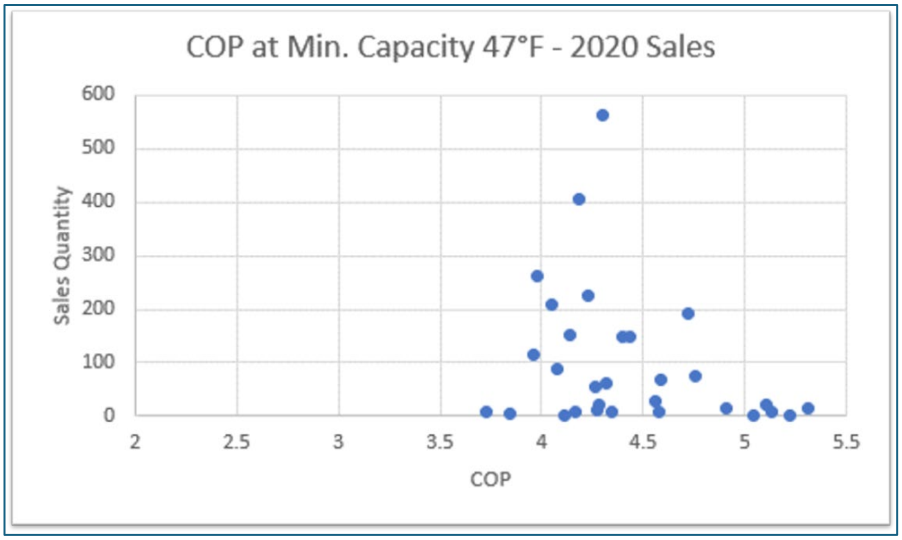

Figure 4: Northwest ducted heat pump sales data, 2020

The most important reason to pursue LLE in heat pumps is that the improved energy savings performance does not come at an increased cost. *[See Figure* 5

Comparing equipment costs of different machines with the same or similar HSPF2 values but different MinCapCOP47 values revealed no consistent cost difference between those variable speed machines with high MinCapCOP47 values and those with low values. Figure 5 shows 2021 wholesale price data for 11 ducted heat pumps of the same rated capacity (3 tons) and comparable HSPF values (10.2–10.5, which is about the same as an HSPF2 of 8.8). The lack of price sensitivity suggests that strong part-load efficiency is likely driven by non-hardware changes, such as control algorithms or design decisions driven by other manufacturer objectives, rather than efficiency.

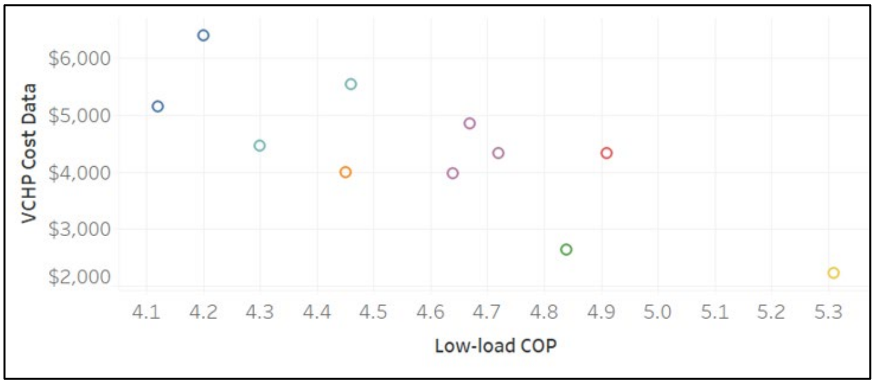

Figure 5: Wholesale equipment cost of similar ducted 3-ton heat pumps vs. MinCapCOP47.

Previous work (Smith 2022) found evidence that MinCapCOP47 based on AHRI 210/240 test condition $H1_{low}$ could be a strong performance indicator. To validate this, NEEA pursued the answers to several remaining questions (Table 1) to ensure the efficiency gains are real. The following sections of this report present those findings. While the focus of this investigation was on heating season performance, no substantial reason exists not to expect similar benefits in reporting low-load cooling performance using AHRI 201/240 test condition B_{Low} values. Those tests reflect part-load efficiency during low-cooling load hours, and will also be validated by the CVP using native controls.

Table 1: LLE research questions

1	Is $H1_{low}$ (i.e. MinCapCOP47) a good indication of part-load efficiency?
2	Is the impact of MinCapCOP47 already adequately captured by HSPF2?
3	What is the lab evidence of improved part-load efficiency?
4	What is the field evidence of improved part-load efficiency?
5	What is the likely source of improved part-load efficiency?

1.1. MinCapCOP47

This section provides key findings related to the effectiveness of MinCapCOP47 as a metric for gauging low-load efficiency and whether it is represented accurately in the NEEP database. This is followed by a brief assessment of the heat pump performance data in the NEEP database, highlighting correlations between MinCapCOP47 and key parameters such as HSPF2 ratings, rated cooling capacity, and turndown ratios.

1.1.1. What is MinCapCOP47?

MinCapCOP47 represents the coefficient of performance (COP) of a heat pump at an outdoor air temperature of 47°F while the compressor operates at low speed.[9] The metric signifies the heat pump's efficiency when it operates at reduced capacity, and at moderate outdoor air temperatures. The value reported in the NEEP database defines this value at the same temperature as the AHRI $H1_{low}$ condition, but the manufacturer is asked to report the performance of the heat pump as it would operate at the lowest speed the unit is capable of under its own controls (that likely corresponds to field conditions).

After discussing this subtle difference with manufacturers, the team concluded that the value reported for most units is almost certainly the performance of the $H1_{low}$ test condition, as defined in the AHRI 210/240: *Performance Rating of Unitary Air-Conditioning & Air-Source Heat Pump Equipment* test procedure (AHRI 2024). The $H1_{low}$ test condition measures the efficiency of a heat pump where the outdoor temperature is 47°F, the indoor chamber is held at 70°F, and the equipment operates at its low-speed heating output (as chosen by the manufacturer). This is one of over a dozen ***static test measurements*** defined in AHRI 210/240 for VSHPs, which corresponds to the U.S. Department of Energy's (U.S. DOE's) test procedures for consumer air conditioners and heat pumps[10].

The input power and capacity measurements at $H1_{low}$ test conditions are included in the calculation of the DOE's Heating Seasonal Performance Factor 2 (HSPF2) metric but manufacturers are not required to publish the $H1_{low}$ data itself. Additionally, the influence of the $H1_{low}$ condition on the HSPF2 value is relatively small because of the way the HSPF metric calculation is weighted at various outdoor temperatures.

1.1.2. Why is MinCapCOP47 a useful metric for low-load operating conditions?

As stated above, MinCapCOP47 is already measured by manufacturers in the required AHRI $H1_{low}$ test conditions. MinCapCOP47 serves as an accessible metric for gauging a heat pump's efficiency at the moderate outdoor air temperature of 47°F, making it the best proxy for quantifying the heat pump efficiency at low-load conditions. What is missing is the requirement that the choice of low speed used in the $H1_{low}$ test needs to be tied to what the equipment can actually achieve using its native controls, rather than chosen by the manufacturer in a special test mode. The CVP will help ensure this choice over time.

Using recent climate data (Typical Meteorological Year, version 3, or TMY3) shows that significant operating hours for heat pumps occur during low-load conditions (defined as ambient temperatures above 35°F and below 55°F). For example, in the mild climate of Portland, Oregon this represents 4,405 hours (75% of heating load hours) while even the cold climate of Bozeman, Montana, has 3,012 hours of

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[9] AHRI 210/240-2023 defines low compressor speed as "the speed as specified by the manufacturer at which the unit operates at low load test conditions." This vague definition allows manufacturers to test the system at any desired turndown ratio for the $H1_{low}$ test condition. Challenges related to this ambiguous definition are discussed later in this report.

[10] https://www.regulations.gov/document/EERE-2021-BT-TP-0030-0027

low-load conditions (47% of heating load hours). So performance at mild temperatures affects the operation for a large percentage of the heating season, especially in the Northwest.

1.1.3. How do $H1_{low}$ measurements affect HSPF2 values?

The team investigated the sensitivity of HSPF2 to changes in heat pump performance at the AHRI 210/240 $H1_{low}$ test condition. Baseline conditions were established (Test 3), the team held heat capacity at the $H1_{low}$ condition constant and adjusted the $H1_{low}$ power consumption to change MinCapCOP47 to reasonable values, based on available NEEP data. The sensitivity analysis suggests that $H1_{low}$ measurements have a limited impact on HSPF2. The result showed that reducing power consumption by 33% (Test 5) increased MinCapCOP47 by 50%, but only improved HSPF2 by 4%. Table 2 presents the sensitivity analysis of $H1_{low}$ measurements using the AHRI HSPF2 calculator.[11]

Table 2: $H1_{low}$ Measurements' Impact on HSPF2

	Heat Capacity @ 47°F min ($H1_{low}$) (Btu/hr)	Power Consumption @ 47°F min ($H1_{low}$) (Watts)	MinCapCOP47	% Difference MinCapCOP47 Relative to Baseline	HSPF2	% Difference HSFP2 Relative to Baseline
Test 1	7,740	800	2.84	-25%	7.76	-4%
Test 2	7,740	700	3.24	-14%	7.92	-2%
Test 3	7,740	600	3.78	Baseline	8.08	Baseline
Test 4	7,740	500	4.54	20%	8.23	+2%
Test 5	7,740	400	5.67	50%	8.38	+4%

The limited impact that $H1_{low}$ measurements have on HSPF2 means that manufacturers are not likely to pay much attention to this performance value, despite operating at these conditions for so much of the time.

1.1.4. What is the savings potential of optimal MinCapCOP47?

Modeling by the Center for Energy and Environment (MNCEE) have shown that heat pumps with higher MinCapCOP47 values can save significant amounts of energy. MNCEE's modeling showed that a 25% increase in MinCapCOP47 led to a 17% decrease in annual energy consumption in mild climates like Portland, Oregon and a 6% decrease in colder climates like Bozeman, Montana.[12] These savings estimates are relative to a similar variable speed heat pump with an "average" MinCapCOP47 rating. Recent, as-yet published work by Performance Systems Development (PSD) for New York State Energy Research and Development Authority (NYSERDA) has found similar outcomes using U.S. DOE Energy Plus modeling.[13]

1.1.5. Do manufacturers agree that MinCapCOP47 is a good metric for low-load efficiency?

The team interviewed six heat pump OEMs. All six manufacturers agreed that MinCapCOP47 is the best available metric for assessing low-load efficiency, and would be the most representative efficiency metric for operation at temperatures as low as 35°F. Two manufacturers suggested that the metric should be paired with a comparable turndown ratio, the minimum capacity at 47°F divided by the rated

[11] AHRI SEER2/HSPF2 Calculation App, https://seerhspf2.ahrianalytics.org/app/seer2hspf2app

[12] https://neea.org/product-council-documents/variable-speed-heat-pump-product-assessment

[13] ACEEE 2024 Hot Air Forum presentation, and NY TRM custom measure categories 5 and 6, are the only published information that uses PSD's sizing and selection tool, which relies on differentiation in part-load efficiency.

capacity. Because AHRI's "low speed" condition is not clearly defined, it leaves room for a manufacturer to test their system at any desired turndown ratio[14] for the $H1_{low}$ test condition. As a result, comparing MinCapCOP47 values across models does not account for differences in compressor turndown ratio. For example, a heat pump with a turndown ratio of 50% and a MinCapCOP47 value of 4.5 would not likely operate as efficiently as an otherwise identical heat pump that had a MinCapCOP47 of 4.5 at 25% of maximum output.

Once the low-speed condition in the AHRI test is confirmed as being at or near the actual low speed operating capacity using the system's native controls (and this information is made available, for example via the NEEP database), it will be much easier to account for realistic performance at varying loads, by interpolating between the actual maximum and minimum capacities (as confirmed by the CVP) for the modulating range, and applying cycling degradation models to loads that are below that modulating limit.

Manufacturers also warned that creating a specification associated with the MinCapCOP47 metric could lead manufactures to optimize their products for that test condition at the expense of other conditions. NEEA's intention is not to replace seasonal metrics (HSPF2, SEER2) but to supplement them with a metric like MinCapCOP47 that acknowledges heat pumps that exhibit better low-load efficiency, with otherwise comparable seasonal ratings.

1.1.6. How is MinCapCOP47 represented in the NEEP database?

The NEEP dataset includes MinCapCOP47 values. These are intended to be the same as the $H1_{low}$ measured test data but are not specifically required by NEEP to be the same. Through conversations with manufacturers, the team learned that some manufacturers claimed use of $H1_{low}$ measurements, while others claim to use artificially conservative values, and some acknowledged (at the time of the interview) that the values in the NEEP database may not reflect in-field performance.

Figure 6 shows a scatter plot of MinCapCOP47 values as a function of the heat pumps' maximum rated capacity at 95°F. The figure is separated into two graphs, one for single zone and centrally ducted units and another for single zone non-ducted units (i.e., ceiling, floor, and wall placement). Figure 6 shows that lower quartile values for both configurations are near 3.5 while the upper quartile values are around 4.7. This suggests a wide variation in MinCapCOP47 values observed in the market. Figure 6 also illustrates erroneous MinCapCOP47 values. The values greater than about 7 exceed the thermodynamic limits of current heat pump designs and in some cases even the Carnot efficiency limit. These erroneous values are specific to only a few brands and are likely reporting errors. Improving the accuracy of the NEEP database by requiring manufacturers to publish the $H1_{low}$ data used to calculate HSPF2 will improve the consistency of the MinCapCOP47 data significantly; the ongoing introduction of the CVP test during the AHRI rating process will provide much more confidence that the values used in the rating test are realistically achievable in the field.

[14] Turndown ratio = Min capacity at 47 divided by rated capacity.

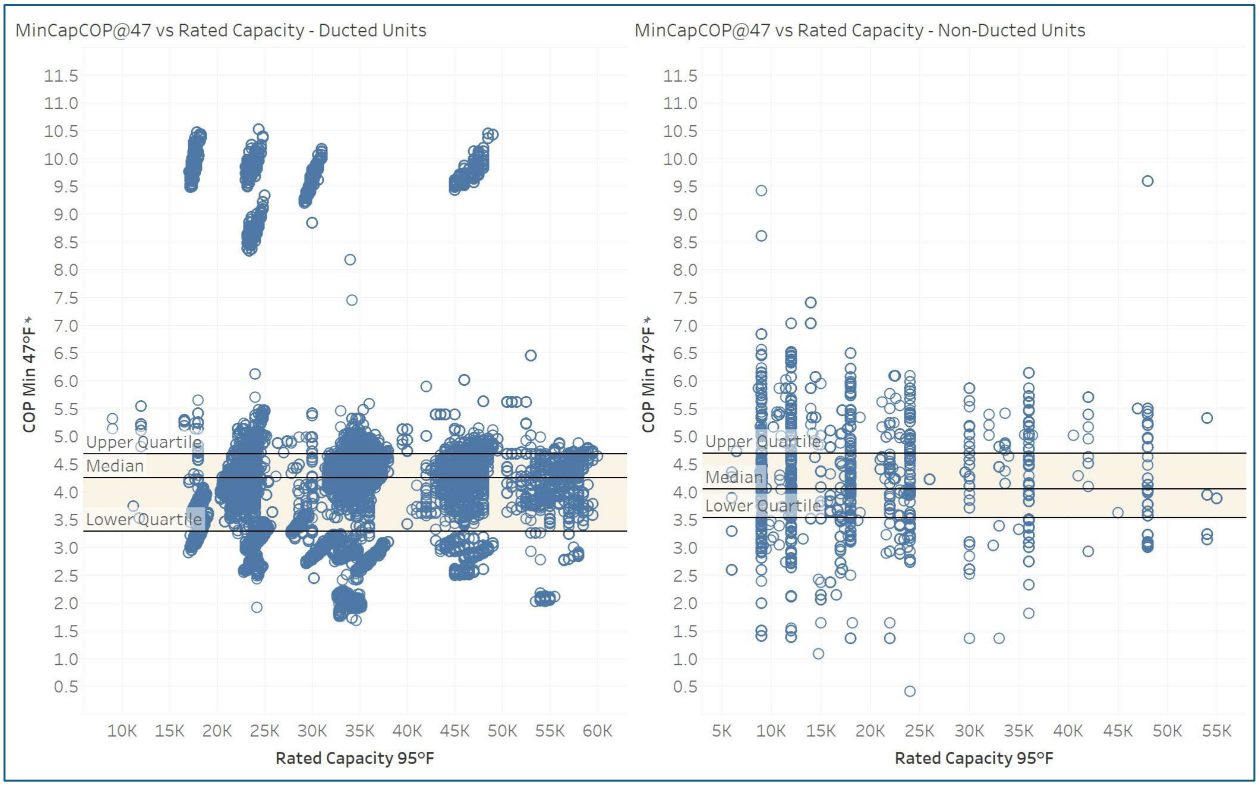

Figure 6: MinCapCOP47 vs. Rated Capacity @ 95°F for all Ducted and Non-Ducted NEEP Database Products.

1.1.7. What trends in MinCapCOP47 are observed in the NEEP database?

The team investigated high-level trends in MinCapCOP47 for 14 major brands of heat pumps. Figure 7 shows separate analysis for single zone and centrally ducted units and single zone non-ducted (i.e., ceiling, floor, and wall placement) for the following comparisons of MinCapCOP47 as a function of:

- HSPF2
- Rated capacity @ 95°F
- Low-load turndown (Max Capacity 47°F/Min Capacity 47°F)

As anticipated, Figure 7 reveals a modest correlation between MinCapCOP47 and HSPF2, and also reveals wide variation. Figure 8 and Figure 9 show no correlation to MinCapCOP47 by rated capacity @95°F and low-load turndown (Max capacity 47°F/Min capacity 47°F), respectively. The wide variation in MinCapCOP47 as a function of these key variables suggests significant potential for collaboration with manufacturers to enhance the part-load performance of their products.

Figure 7: MinCapCOP47 vs. HSPF2

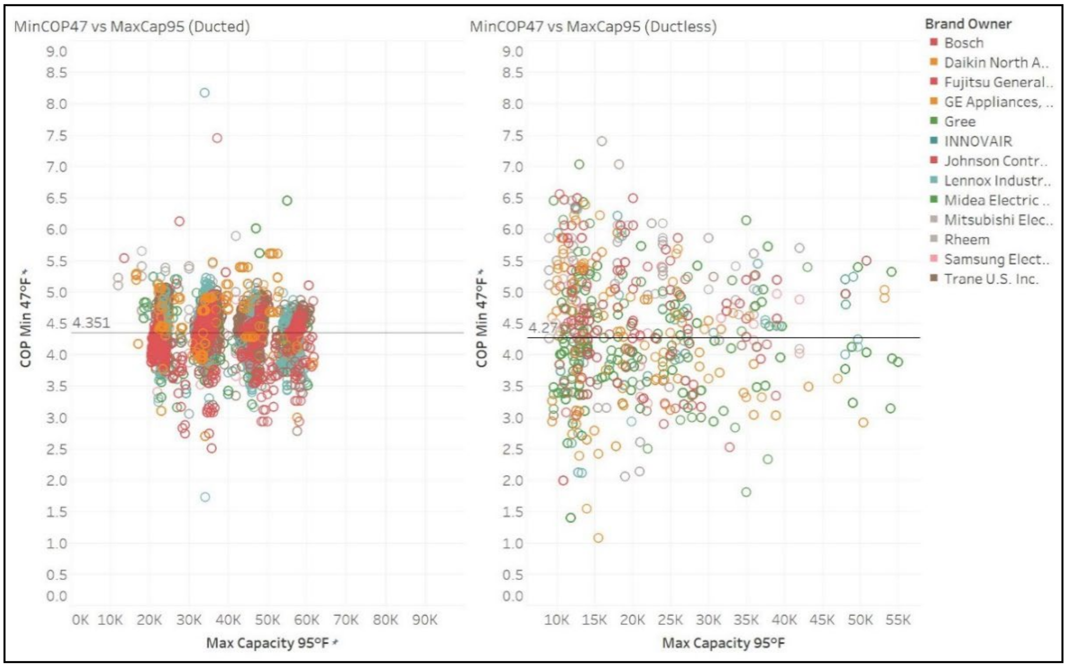

Figure 8: MinCapCOP47 vs. Rated Capacity

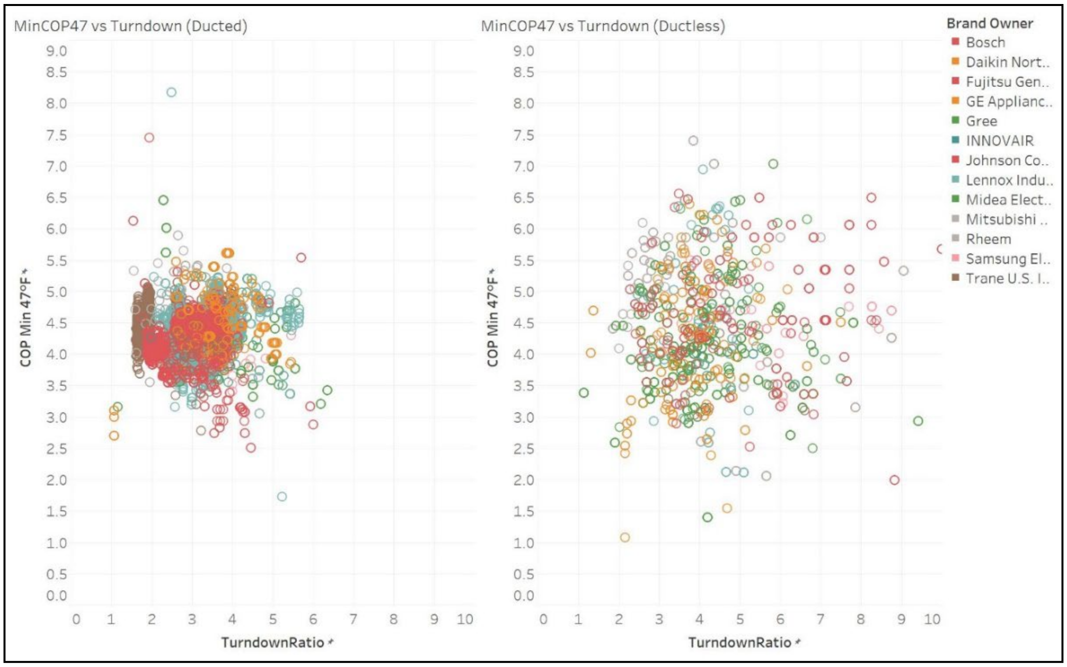

Figure 9: MinCapCOP47 vs. Low-Load Turndown (Max Capacity 47°F/Min Capacity 47°F)

1.2. Design choices that affect low load efficiencies

This section presents key findings related to an investigation into the technologies and design decisions that contribute to exceptional low-load efficiency. As part of this investigation, the team interviewed engineers at seven manufacturers. Six of the seven make heat pumps and three of the seven make compressors used in heat pumps. The team also interviewed a heat pump research engineer at the Oak Ridge National Laboratory (ORNL). Throughout these discussions, engineers shared their perspectives on design decisions that influence heat pump operation at low loads, and identified opportunities for enhancing efficiency under these conditions.

To substantiate findings from the interviews, the team conducted a *paper teardown* of 22 heat pumps across six manufacturers. This involved cataloging data from product specifications, service manuals, and performance data pulled from the NEEP database. By assessing trends in NEEP values for MinCapCOP47 associated with various technologies and design decisions, the team could test theories discussed with OEMs about features that lead to improved low-load efficiency.

The team chose to simplify the analysis by focusing on 36 kBtu (3-ton) inverter-driven heat pumps, the majority of which were single-zone ducted units. The team evaluated multiple product lines (e.g., “good,” “better,” “best”) for each OEM. Selection of indoor/outdoor pairings adhered strictly to OEM manuals, prioritizing recommended combinations. The deliberate limitation of the scope was designed to isolate variables that could potentially skew the analysis of features that affect low-load efficiency.

The findings from this investigation are separated into five sections highlighting primary components that impact overall system efficiency:

1. Compressor design
2. Metering device(s)
3. Heat exchanger design
4. Indoor and outdoor fans
5. Control algorithms

By examining these components individually, the team aims to provide a comprehensive understanding of the multifaceted factors influencing heat pump performance in low-load scenarios. Each section gives information captured from OEM interviews, followed by a section with results of the paper teardown.

1.2.1. Compressor Design Considerations

Compressors are at the heart of heat pump systems and account for the majority of their energy consumption. The efficiency of a compressor changes in relation to volumetric flow rate and the suction and discharge pressures (pressures at the evaporator outlet and condenser inlet, respectively). While compressors are fluid movers that should follow the affinity laws (a cubic relationship between power and flow rate), they also need to maintain delivered pressures of the refrigerant cycle. Consequently, the power drawn from a compressor decreases fairly linearly with a decrease in flow rate. Compressor efficiency gains can be achieved under low-load conditions if the controls are able to further reduce the pressure necessary to achieve desired subcool and superheat[15] conditions.

1.2.1.1. Manufacturer Insights into Compressor Design

Some OEMs explained that all compressors operate most efficiently within a specific range of pressures and flow rates; this range is typically optimized for operation at or near full-load conditions. They also shared that the fixed losses as a percentage of total power consumption increase as the compressor turns down. This means at very high turndown ratios the COP values will be reduced.

One OEM explained that the further one can turn down the compressor, the more efficient the system will be, due to reduced cycling. In addition, under variable speed operation when the heat pump is operating between minimum and maximum capacity (i.e., part-load, but not cycling conditions), the fixed heat exchangers are effectively oversized for the reduced refrigerant energy flow. This is equivalent to having a very large heat exchanger relative to the (reduced) compressor size. They emphasized that the primary driver of heat pump efficiency for a given compressor selection is the size or effectiveness of the condenser and evaporators. Thus, the refrigeration cycle will be more efficient under part-load conditions because the system is able to limit the amount of subcool and superheat as the flow rate decreases. The OEM was careful to note that discrepancies may exist between real-world compressor turn-down and the level listed in the published data.

These two findings suggest that while *compressor* efficiency tends to decrease as the compressor speed unloads during part-load conditions, higher compressor turndown improves *overall* efficiency of a heat pump system, and increases during low-load conditions. However, at very high turndown ratios (perhaps beginning at less than 20% of rated output), the fixed losses of the system become dominant, and the overall efficiency will begin to decrease again. Lab data seemed to suggest that turndown ratios greater than 5 are plagued by troubles with operational stability and proper oil return needs.

[15] Superheat in a heat pump is the temperature increase of the refrigerant beyond its boiling point.

Oak Ridge National Laboratory (ORNL) and some manufacturers suggested that rotary compressors maintain better efficiency at partial loads compared to scroll compressors. While the other OEMs suggested that the differences in partial load efficiency between compressor types were negligible, no manufacture outright disagreed with the statement that rotary compressors maintain higher efficiency at lower speeds. The explanation lies in the fact that scroll compressor pressure is more tightly connected to rotational speed, whereas rotary compressors are closer to a positive displacement compression cycle and less reliant on rotational speed.

One OEM also mentioned that compressor oil return is critical to equipment longevity. At lower speeds, OEMs are always concerned about ensuring adequate oil return. This may be implemented as a limit on the turndown ratios, or initiation of timed oil return cycles which run the compressor briefly at high speed to enhance oil return, in some combination. NEEA has observed oil return cycles in heat pumps under load-based testing where the unit is allowed to operate under its own native controls.

1.2.2. Metering Device Considerations

Modern heat pump metering devices are available in two main types: the thermostatic expansion valve (TXV) and the electronic expansion valve (EEV). These devices regulate the pressure and temperature of the refrigerant. They are located upstream of the evaporator coil and cause a large pressure drop that results in the phase change of the refrigerant. As refrigerant circulates, both the TXVs and EEVs adjust the size of the valve opening to control the amount of superheat across the evaporator coil and optimize heat absorption of the refrigerant. This careful control of superheat ensures enhanced efficiency and performance in the heat pump system.

1.2.2.1. Manufacturer Insights into Metering Devices

One OEM explained that when a TXV is appropriately sized and configured, its performance is comparable to that of an EEV. However, under low-load conditions where capacity is reduced, TXVs face challenges in effectively regulating flow. Excessive hunting (cyclical fluctuation in suction superheat levels) can result when a TXV operates outside of the range it is designed and configured for. The same OEM highlighted the advantages of EEVs, especially in scenarios involving equipment with a broad capacity range (large turndown). It should be noted that achieving higher low-load efficiencies may require a wider operational range, thus requiring the use of an EEV, and a heat pump may thus show better performance when paired with a larger outdoor condenser relative to lower compressor speeds.

1.2.3. Heat Exchanger Design Considerations

The indoor and outdoor heat exchangers do not consume power directly, but design choices related to their materials, surface area, and refrigerant path geometry play a critical role in a heat pump’s performance and overall efficiency.

1.2.3.1. Manufacturer Insights into Heat Exchangers

One OEM explained that the efficiency of a heat pump can be influenced by the ratio of indoor and outdoor coil sizes. This ratio has a direct impact on the charge balance during both heating and cooling operations. The OEM explained that heat exchanger design always requires a compromise due to the need for both heating and cooling operation. In effect, other design constraints may limit how much a manufacturer optimizes for efficiency at low loads.

Other OEMs explained and confirmed that larger outdoor heat exchanger size increases the opportunity to increase efficiency at low loads, but only if the system is designed to take advantage of the larger heat exchanger. The OEM suggested that doing so would require better refrigerant control through the use of an EEV.

Other OEMs explained that reducing discharge pressure of the compressor reduces the input power required by the compressor. However, the extent of this reduction is constrained by the design of the condenser heat exchanger. To maintain effective heat transfer and satisfactory supply temperatures, engineers need to keep the system's discharge pressure at a reasonable level, a parameter intricately linked to the design of the heat exchanger. For example, a condenser with one long refrigerant path will require higher discharge pressures and have more capacity, at the expense of operational efficiency. Alternatively, a condenser could have multiple shorter parallel paths reducing the discharge pressure. This design may lead to less capacity, but a more efficient system.

These findings point to the intricacy of heat pump design and demonstrate that system efficiency improvements cannot always be isolated to a specific component. Instead, achieving optimal performance from the heat pump requires coordinated optimization of the compressor and metering device in conjunction with heat exchanger design. Optimizing performance during part-load conditions likely also benefits from microprocessor control with adequate onboard sensors to inform the modulation of the EEV and compressor speed.

1.2.4. Refrigerant Control Considerations

Control algorithms are responsible for orchestrating the interaction among the various physical elements, dictating whether the system functions optimally or falls short in terms of efficiency. Specifically, controls determine the operation of all variable components, including variable speed compressors, indoor and outdoor fans, and EEVs.

1.2.4.1. Manufacturer Insights into Control Algorithms

OEMs agreed that control algorithms optimize heat pump performance, especially during part-load scenarios, by adjusting fan speeds and refrigerant flow. Effective control also minimizes cycling losses that occur when the compressor turns off and on, which loses energy in each cycle because of the need to regain pressure and heat exchanger temperatures.

OEMs also emphasized that controls can enhance or detract from a good design, but they can't overcome the physics of the system. Oversized heat exchangers relative to compressor capability can limit part-load operation by requiring sufficient flow rates for turbulent fluid flow and high heat exchanger effectiveness. One OEM engineer that was interviewed pointed out that a large heat exchanger may sound more efficient, but can become far less effective when refrigerant flow is reduced to a point where it becomes laminar, causing the heat exchanger effectiveness to plumet.

1.2.5. Indoor and Outdoor Fan Considerations

Fan energy plays an important role in total energy use, especially during part-load conditions. This is because increased air flow generally increases the heat transfer across a heat exchanger. At the same time, the power needed increases exponentially with increased airflow rate at a given pressure drop. Therefore, if a system appropriately modulates the fan speed, there can be significant reduction in fan power needs during part-load conditions.

OEMs acknowledge that for optimal efficiency, variable capacity heat pumps should vary indoor and outdoor airflows using variable speed fans. However, this approach isn't uniformly adopted across all models. Variations in fan motor turndown capability and discrepancies between lab testing and observed field operation suggest inconsistent implementation of fan controls among OEMs, limiting the exploitation of fan power unloading under part-load conditions.

As an illustration, in a standard 3-ton ducted system, the outdoor and indoor fans typically draw around 600 watts at full power. Using a well-controlled variable speed motor, these fans will draw less than 100 watts when operating at one-third of the flow rate, a savings of around 500 watts when compared to constant speed fan motors operating at part-load conditions.

1.2.6. Virtual Teardown

1.2.6.1. Compressor Design

The paper teardown allowed the team to assess compressor design based on compressor type, compressor control (all heat pumps assessed were inverter-controlled), and compressor turndown. The following hypothesis related to compressor impacts on low-load efficiency was assessed.

Hypothesis 1: Heat pumps with inverter-driven rotary compressors tend to have a better MinCapCOP47 than inverter-driven scroll compressors because scroll compressors do not turn down as efficiently.

Figure 10 presents a scatter plot that compares MinCapCOP47 values by compressor type (rotary or scroll) and turndown ratio for all ducted units assessed. The graph shows a wide range of MinCapCOP47 values for both rotary and scroll compressors, suggesting that compressor type is not a dominating factor in determining low-load efficiency. A focused examination of three ducted units by one manufacturer, including one with a rotary compressor and two with scroll compressors, effectively underscored this point. Despite similar rated capacities and turndown ratios among the three units, no discernible advantage exists in terms of MinCapCOP47 for rotary compressors. At the same time, the units equipped with a scroll compressor from another manufacturer achieve an impressive 4.1:1 turndown, challenging this hypothesis by achieving a MinCapCOP47 of 4.83. These findings suggest that scroll compressors are at least capable of high efficiency at low loads.

Hypothesis 2: Heat pumps with larger (but not excessive) compressor turndown are more efficient at low loads.

Figure 10 also shows no strong correlation between MinCapCOP47 and compressor turndown. While MinCapCOP47 does not account for cycling losses, the measured efficiency of systems with lower compressor turndown was not significantly different than those with high compressor turndown.

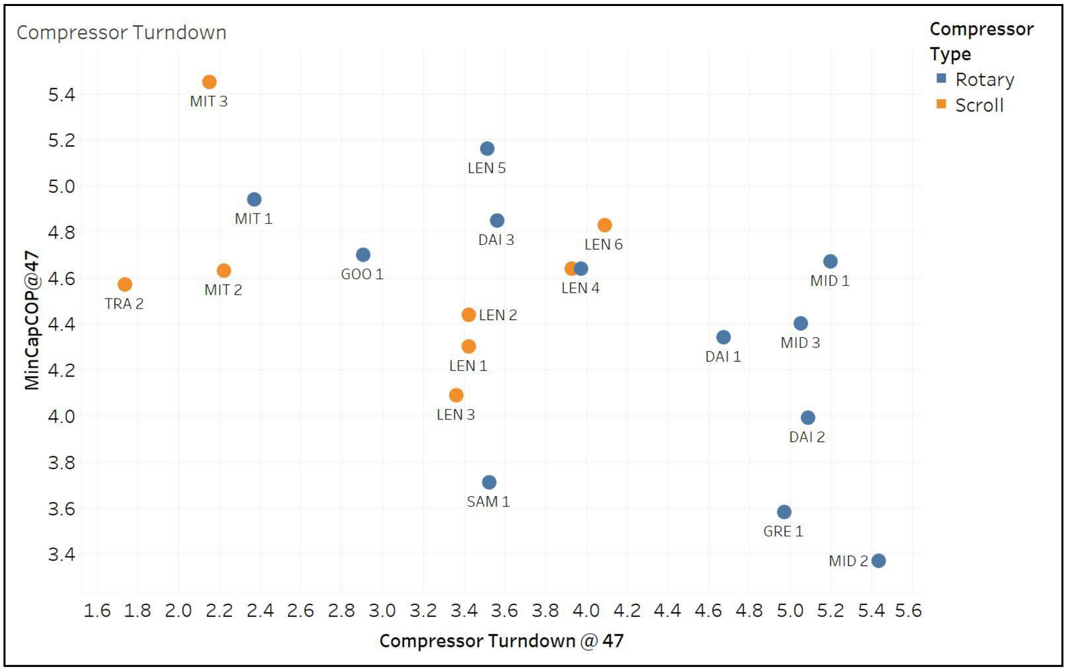

Figure 10: MinCapCOP47 as a Function of Compressor Type and Turndown (Ducted Units Only)

1.2.6.2. Metering Devices

The paper teardown allowed the team to assess whether different metering devices resulted in different MinCapCOP47 values. The following hypothesis related to metering device impacts on LLE was assessed.

Hypothesis 3: Heat pumps with EEVs have generally higher MinCapCOP47 than heat pumps with TXVs, because EEVs enable better control of superheat during low-load conditions.

Figure 11 is a scatter plot of MinCapCOP47 values for all analyzed ducted systems, correlating them with metering device type and turndown ratio. Heat pumps with EEVs are shown on the left and those with TXVs are shown on the right. Similar to the analysis of compressor types, the graph shows a wide range on MinCapCOP47 values for both metering device types. While most units evaluated had EEVs, the team looked at three units with TXVs. Notably, LEN 5 has a TXV, but maintains a very high MinCapCOP47of 5.16 with decent compressor turndown of 3.5:1. This suggests that it may be possible to maintain good low-load efficiency at a reasonable turndown ratio with a TXV.

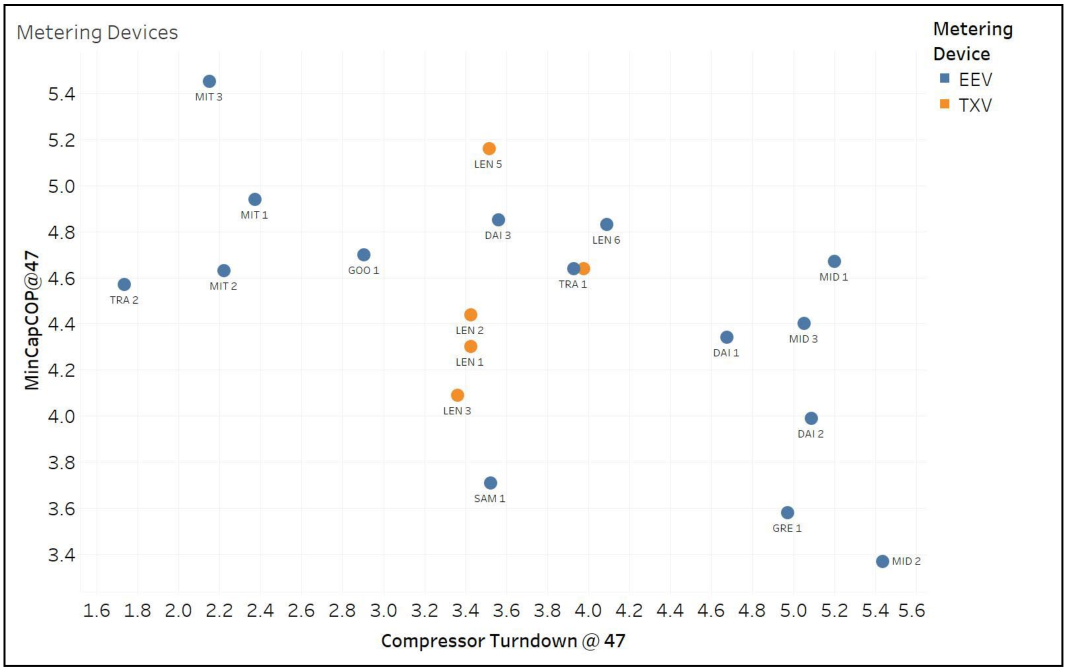

Figure 11: MinCapCOP47 as a Function of Metering Device Type and Turndown (Ducted Units Only)

1.2.6.3. Heat Exchangers

The paper teardown allowed the team to assess heat exchanger design based on indoor and outdoor heat exchanger size and circuit geometry, and materials. The following hypothesis related to heat exchanger impacts on LLE was assessed.

Hypothesis 4: Heat pumps with large heat exchangers generally have higher MinCapCOP47 than heat pumps with small heat exchangers.

Figure 12 shows MinCapCOP47 values as a function of outdoor and indoor heat exchanger size. Despite all units being 3-ton, Figure 12 shows a wide range of both indoor and outdoor heat exchanger sizes across all the units. The units with the smallest indoor and outdoor heat exchangers do have lower than average MinCapCOP47 values. This suggests that heat exchange size may be a limiting factor in determining low-load efficiency. However, the three units with the lowest MinCapCOP47 values have nearly average heat exchanger areas. The paper teardown results do not provide a conclusive correlation. One manufacturer's units stand out for having the largest outdoor heat exchanger sizes, yet their MinCapCOP47 values vary significantly among the units.

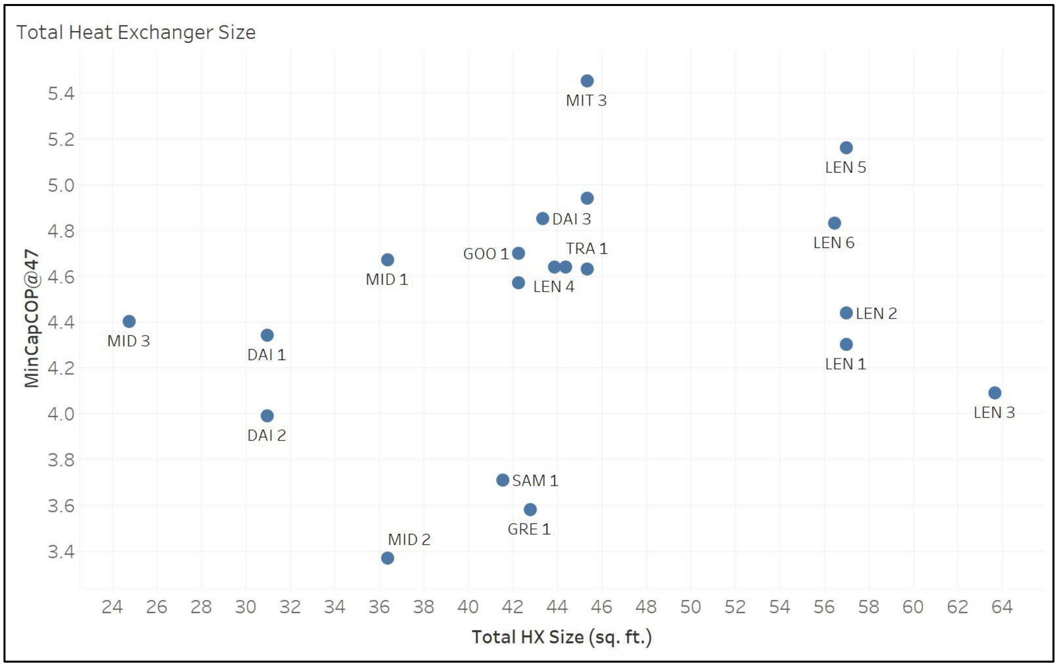

Figure 12: MinCapCOP47 as a Function Heat Exchanger Size (Ducted Units Only)

1.2.6.4. Control Algorithms

The team was not able to investigate heat pump control algorithms through the paper teardown directly but, as a proxy, the team did quantify the number of control devices in each heat pump. The team tested the following hypothesis.

Hypothesis 5: Heat pumps with more sensors have higher MinCapCOP47 than heat pumps with fewer sensors.

Figure 13 shows that higher MinCapCOP47 values do tend to be associated with heat pumps with a higher number of control sensors. This correlation suggests that a certain threshold of sensing capability is necessary to achieve high part-load efficiencies. While this observation doesn't provide a complete understanding on control algorithms, it does substantiate the notion that effective control is important for achieving high part-load efficiency.

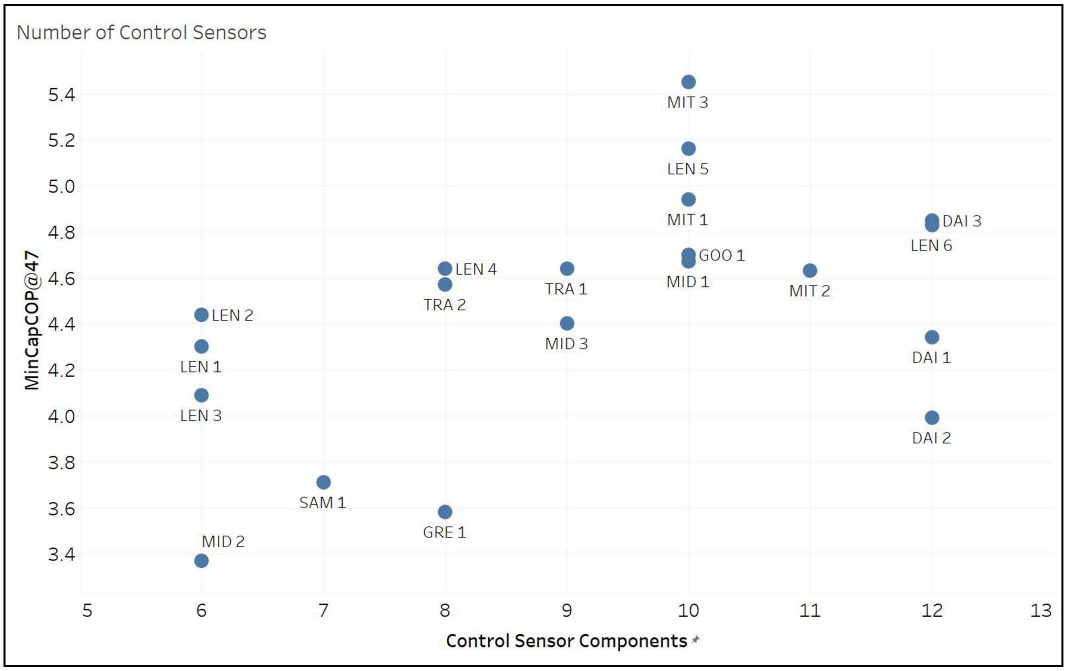

Figure 13: MinCapCOP47 vs. Number of Control Sensor Components

1.2.7. Physical teardown:

This section presents findings from a physical teardown of two different 2-ton ducted heat pump units. The physical teardown was performed by consultants that specialized in teardowns. The physical teardown was attended by fourteen heat pump experts, including two manufacturers' heat pump design engineers. Prior to any investigation into components or design of the heat pumps, the attendees established the following guidelines and possible outcomes:

1. Identify refrigerant flow paths and impacts on efficiency
2. Identify electrical component design and impacts on efficiency
3. Each manufacturer would be on hand to answer questions about their heat pump that would not reveal propriety information
4. Identify differences between manufactured heat pumps that could cause noticeable differences in testing
5. Discuss what additional data needs to be reviewed or researched

The attendees broke into three smaller groups to determine how the heat pumps were designed and built. The three groups were divided into the following:

1. In-depth analysis of manufacturer A heat pump hardware
2. In-depth analysis of manufacturer B heat pump hardware
3. In-depth analysis of manufacturer A and B heat pump electronics

After groups performed an in-depth review of the heat pumps, they reconvened to discuss findings and differences with the manufacturers' engineers. The attendees also participated in a question-and-answer session and shared key takeaways.

Analysis of both heat pumps showed little mechanical and electronic differences between the heat pumps. Electronically, both heat pumps were almost identical. Both heat pumps used some of the same manufactured circuit components and similar manufacturing techniques. The major difference between the two heat pumps electronically was the number of 24V power supply transformers. One manufacturer had two 24V power supply transformers; this was due to the manufacturer converting their ductless air source heat pump outdoor unit for use as a ducted heat pump, which only required one 24V power supply transformer but still contained the extra transformer needed in the ductless configuration.

Mechanically, both heat pumps were designed similarly. Differences between heat pumps were minor and would not be expected to contribute major impacts or differences between the heat pumps' efficiencies. Some of the differences noted were:

1. Different coatings on the outdoor units' heat exchanger fins
2. Type and location of regulating valve
3. Type and location of monitoring sensors
4. Number of installed accumulators
5. Outdoor fan pitch and design shape

Key takeaways learned from the physical teardown were that program control algorithm and proper sizing and designing of a heat pump system were responsible for good coefficient of performance (COP). Additionally, manufacturers may already be testing for, and are expected to have to report on, control verification data per the new AHRI 210/240 testing procedure starting in 2026. The newly tested CVP results are not expected to be made public, but may provide more information and feedback to manufacturers. More importantly, the CVP will help validate the choices of speed for the low speed tests and the resulting performance, providing more confidence in the reported NEEP data over time, and thus improved selection criteria for low-load efficient (LLE) heat pumps.

Additionally, the following questions were identified by the attendees as needing additional information and research:

1. Is it possible to determine maximum COP at any given outdoor temperature?
2. Will AHRI 210/240 Control Verification Procedure testing provide additional data that could be used to determine LLE-capable heat pumps?
3. At what turndown ratio should LLE be based on?
4. Would having a larger accumulator improve LLE capabilities?
5. How do systems using hot gas bypass on startup of the heat pump impact short-cycling and efficiencies?
6. Would using two temperature sensors and one pressure sensor, vs. using just two temperature sensors, improve compressor discharge pressure control?

Finally, the manufacturers provided an additional insight that could allow for heat pump system selection to be easier for contractors. Manufacturers do not spend any effort determining if certain heat pumps would be better suited for specific climates across the United States. If manufacturers did limit systems that were capable in specific climates, then installers would not select equipment that did not meet that region's needs for heating.

1.3. Lab Testing (UL & BHEC):

To obtain a better understanding of the accuracy of the MinCapCOP47 metric and how best to model heat pump performance, load-based testing of multiple heat pumps was conducted under low-load conditions. Six variable speed heat pumps were tested at the UL laboratory in Plano TX, which has extensive experience running load-based tests. Technical guidance was provided by Bruce Harley Energy Consulting, and the testing was conducted during the summer of 2024. The research questions below comprised the basis for the lab testing which was developed based on the SPE-07 test procedures, modified to focus on answering these questions. **Error! Reference source not found.** provides information about the tested heat pumps, which were chosen to provide a diverse range of reported low-load efficiency values and equipment types.

Low-load efficiency lab testing research questions:

1. Can MinCapCOP47 rating be used as a reasonable indicator for part-load efficiency?
2. How should we model part-load performance?
3. Should we evaluate this LLE at a standard turndown?
4. Are the performance values consistent with reported data in NEEP database?

Table 3: UL Plano lab tested equipment information

Unit	Test Dates (2024)	Type	Nominal Capacity (Btuh)	HSPF2	MinCap COP47	Minimum Cap 47°F
LLE 1	Jun 19 – Jun 26	Ductless	12,000	11.7	4.5	3,100
LLE 2	Jun 27 – Jul 15	Ductless	18,000	10.2	1.4	3,070
LLE 3	Jul 16 – Jul 24	Ductless	14,000	11.0	7.0	4,800
LLE 4	Jul 25 – Aug 1	Ducted	23,200	8.5	5.1	6,300
LLE 5	Aug 2 – Aug 12	Ducted	22,200	9.2	4.2	5,500
LLE 6	Aug 13 – Aug 20	Ducted	23,000	10.0	4.7	7,100

1.3.1. Test Method

The load-based test procedure imposes a target building load on the indoor chamber by the reconditioning equipment. As the machine heats and cools the space, the imposed load varies based on a calculation of a virtual building load minus the heat delivered by the unit under test. The reconditioning equipment changes the indoor chamber temperature to maintain the room ambient temperature (RAT) over time. The RAT is recreated in the Thermostat Environment Emulator (TEE), which ensures the heat pump thermostat is exposed to the correct indoor temperature and does not experience extended time delays or air flow differences that occur when the thermostat is located in the indoor test chamber.

The unit under test senses the RAT using its own native thermostat. Experiments have shown that the temperature seen by the thermostat is affected by location in the psychrometric chamber, which has lots of air movement and non-uniform temperatures. The thermostat is located inside a TEE that delivers a constant, low air velocity across the thermostat at the correct RAT, so that the unit under test can respond appropriately. This improves repeatability and reduces the impact of test chamber design on the test results.

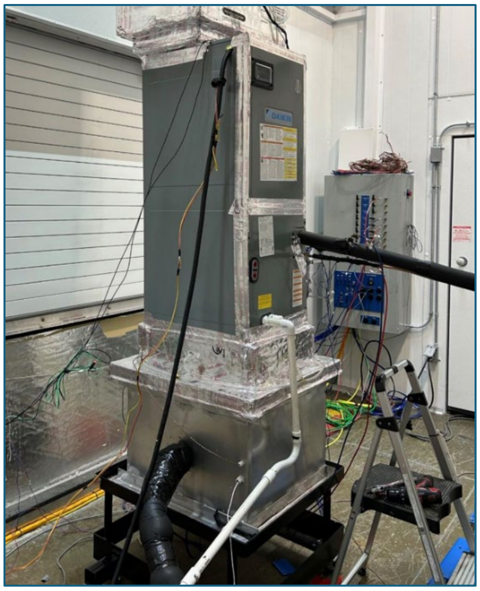

Figure 14: UL Plano testing lab indoor test chamber

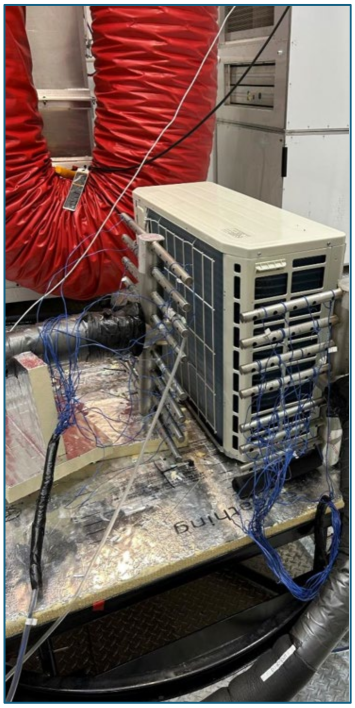

Figure 15: UL Plano testing lab outdoor test chamber

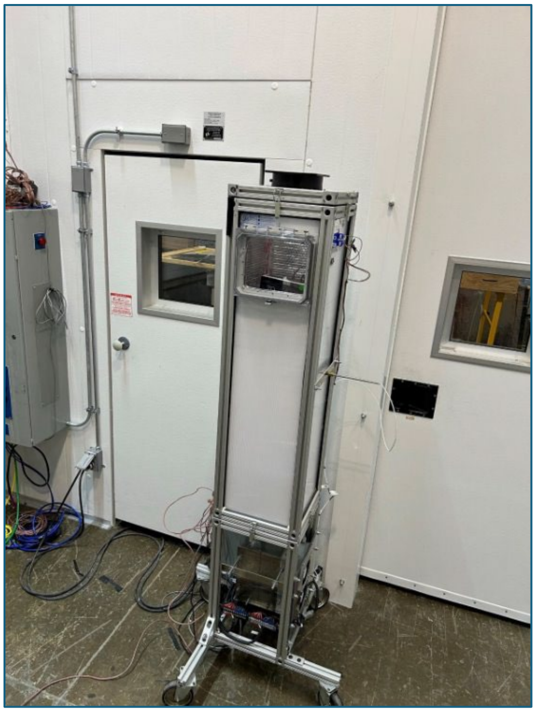

Figure 16: UL Plano testing lab Thermostat Environment Emulator (TEE)

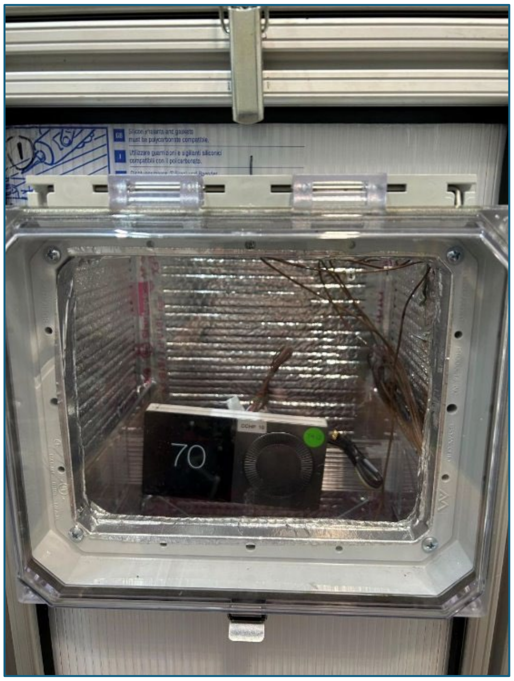

Figure 17: UL Plano testing lab thermostat measuring the RAT in the Thermostat Environment Emulator (TEE)

Testing sequence:

1. Unit starts at load (QB1) 3% above the NEEP-listed low capacity. Test continues until COP converges after 2–4 hrs. If cycling behavior occurs at QB1, increase load by ~20% at a time until stability occurs, and a converged COP can be determined (QBn).
2. Load is increased to the unit's rated capacity (QR); COP tested to convergence.
3. Load is ramped down to a load roughly halfway between the condition established in step 1 and the unit's rated capacity; COP is tested as QA.
4. Load is ramped down to the stability conditioned in step 1 (QBn).
5. Load ramps down to a point below Bn; COP at cycling is tested (QC).
6. Finally, the load is reduced even more to obtain a second COP result with cycling (QD).

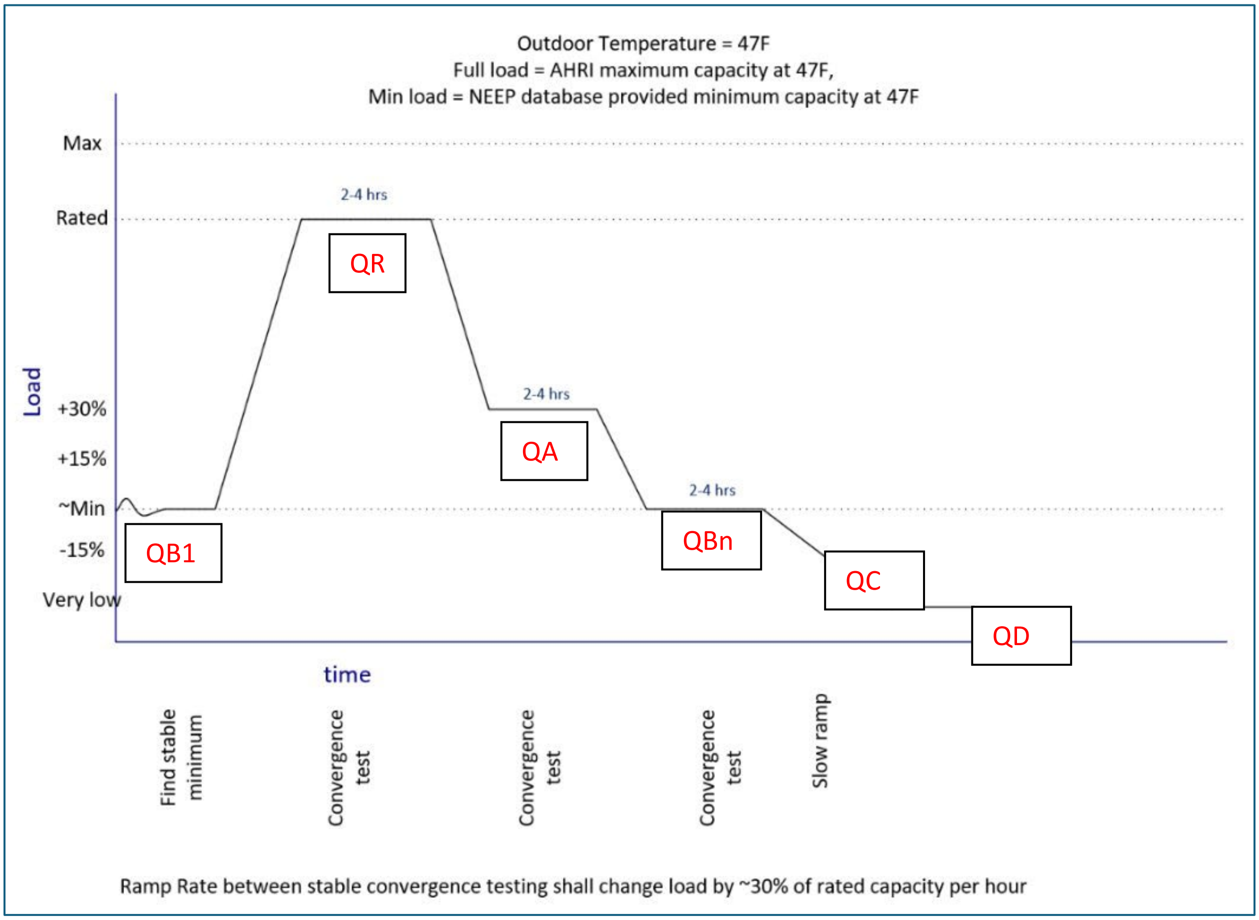

Figure 18: UL Plano testing lab testing sequence

1.3.2. Test Results

Figure 19 through Figure 30 show lab testing results for the tested heat pumps. The "building load" (BL) line varies considerably at times. The reason is that the "target" BL is constant, but the short-term "virtual" BL value used in the virtual model varies. As the room ambient temperature (RAT) varies, and the tested system manages the indoor conditions, the model adjusts accordingly. This deviation from the "target" BL is largest when the unit shuts off, because the room temperature changes the quickest when the heat pump capacity is 0 and then adjusts at full speed for the first few minutes when the unit starts running again.

All units exhibited cycling behaviors during the lowest-load portions of testing, except for NEEA LLE 5, which showed cycling behavior through most of the testing procedure. When the lab testing data was compared to the reported Northeast Energy Efficiency Partnership (NEEP) data, NEEA LLE units # 1, 4, and 5 aligned closely with NEEP reported MinCapCOP47 values (within 10%). Unit #6 was slightly lower (85% of NEEP reported COP). The lab-measured COP of unit #2 was almost triple the reported value from NEEP (which at 1.4 was exceedingly low); while the measured COP of unit #3 was only 57% of the reported value (which at 7.0, was exceedingly high). Although the range of reported COPs was between 1.4 and 7, the tested COP values were all between 3.8 and 5 at the lowest modulating capacity.

The NEEA LLE 6 heat pump unit uses R-32 refrigerant, which is different from the other five units. Additionally, this unit had not yet been commercially released, and the control algorithms were still being adjusted to improve performance.

The six NEEA LLE units exhibited a range of behavior, as shown in Figures 18-29.

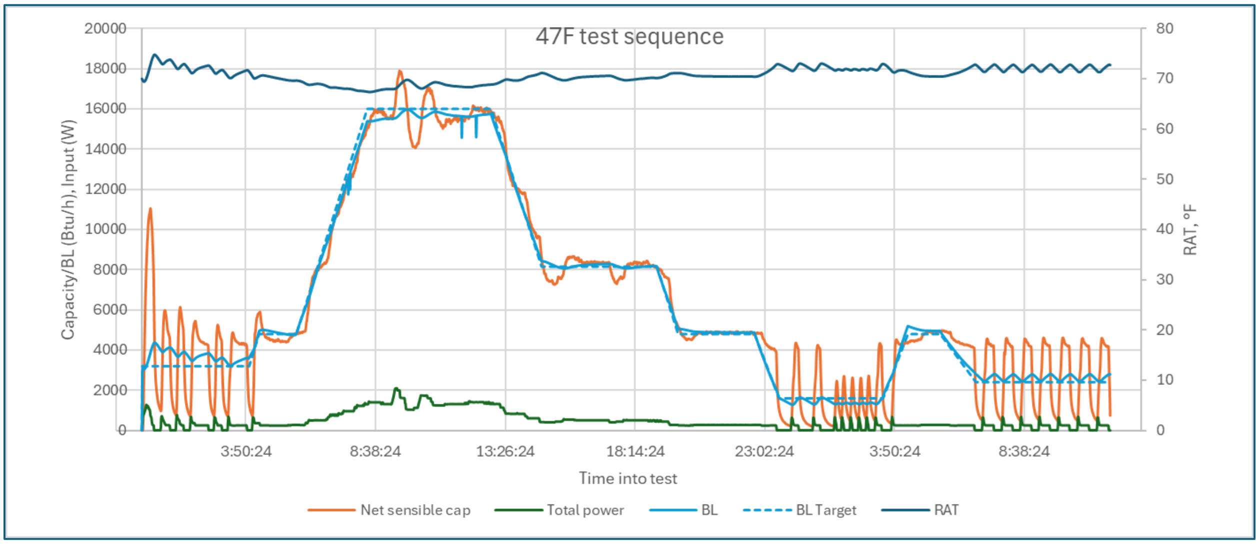

Figure 19: NEEA LLE 1 heat pump lab testing results for full testing procedure

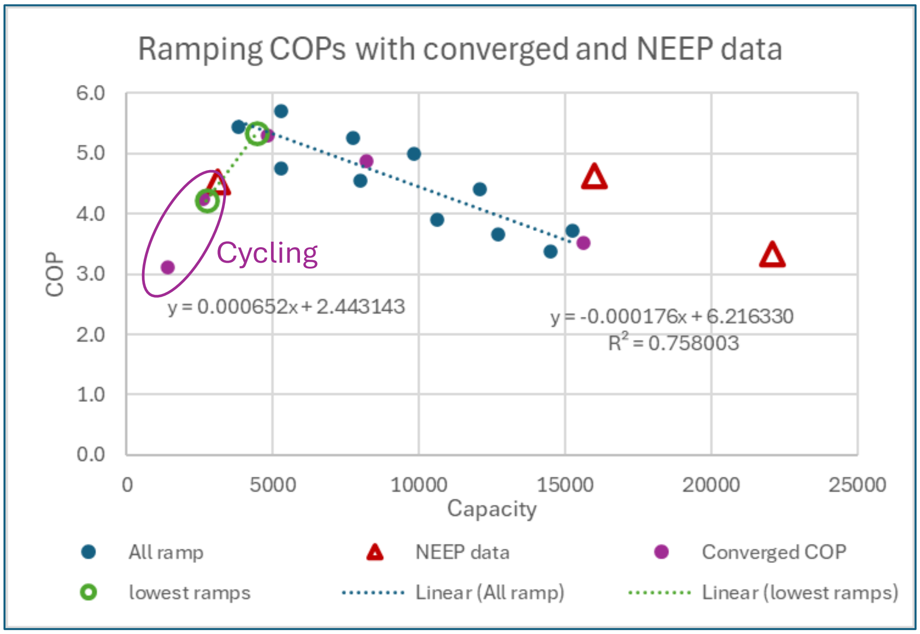

Figure 20: NEEA LLE 1 heat pump lab testing results compared to Northeast Energy Efficiency Partnership (NEEP) reported data

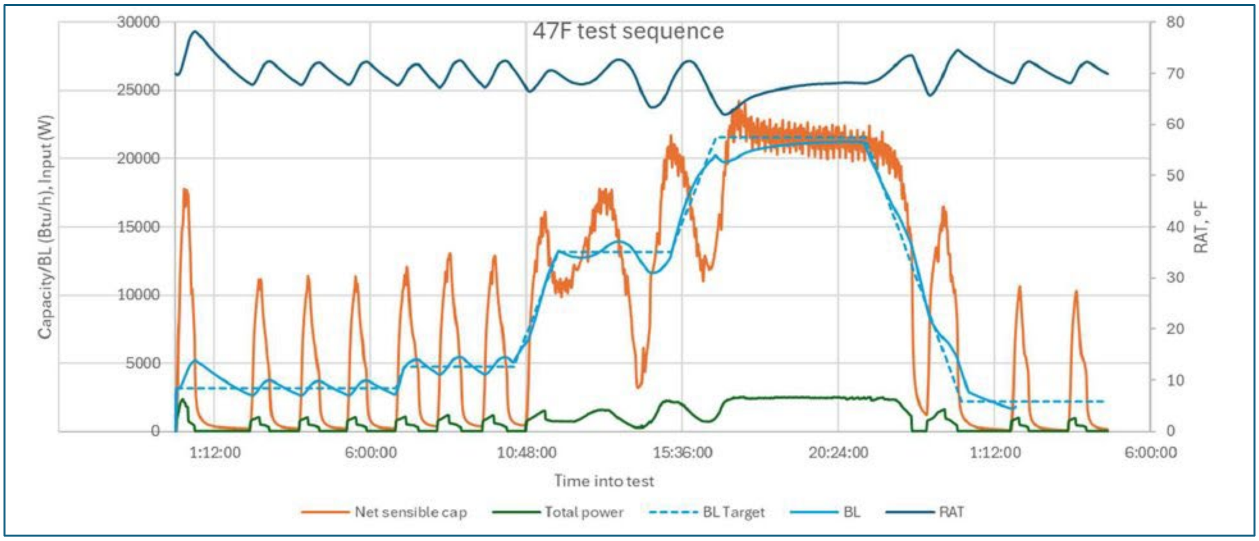

Figure 21: NEEA LLE 2 heat pump lab testing results for full testing procedure

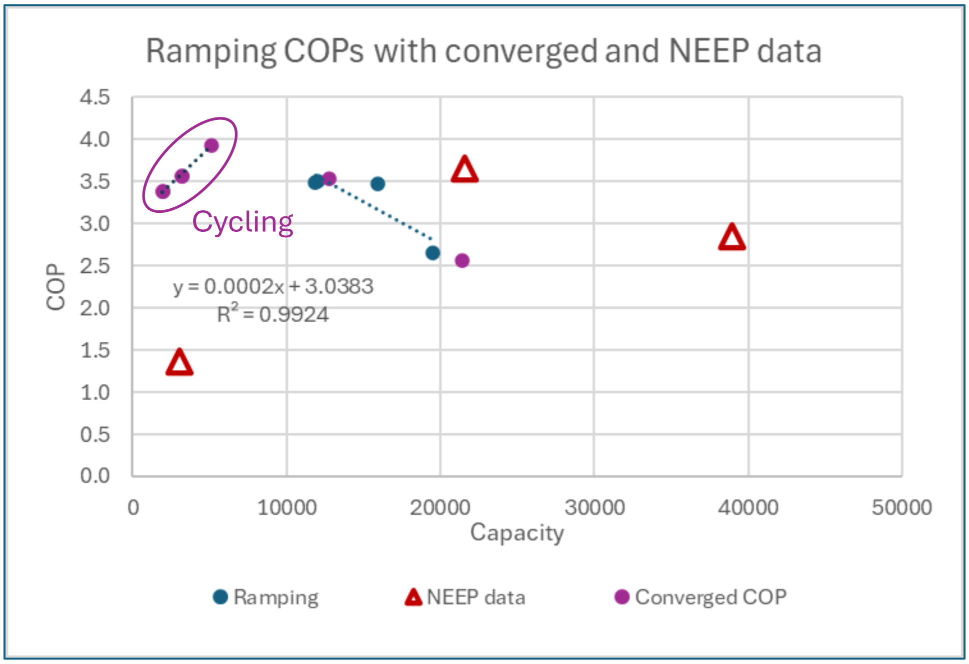

Figure 22: NEEA LLE 2 heat pump lab testing results compared to Northeast Energy Efficiency Partnership (NEEP) reported data

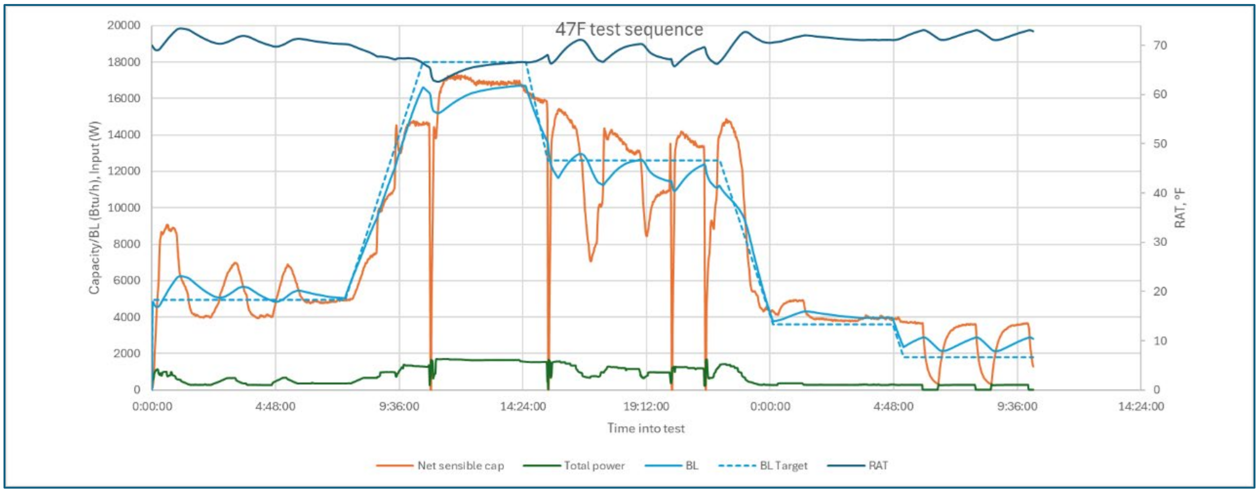

Figure 23: NEEA LLE 3 heat pump lab testing results for full testing procedure

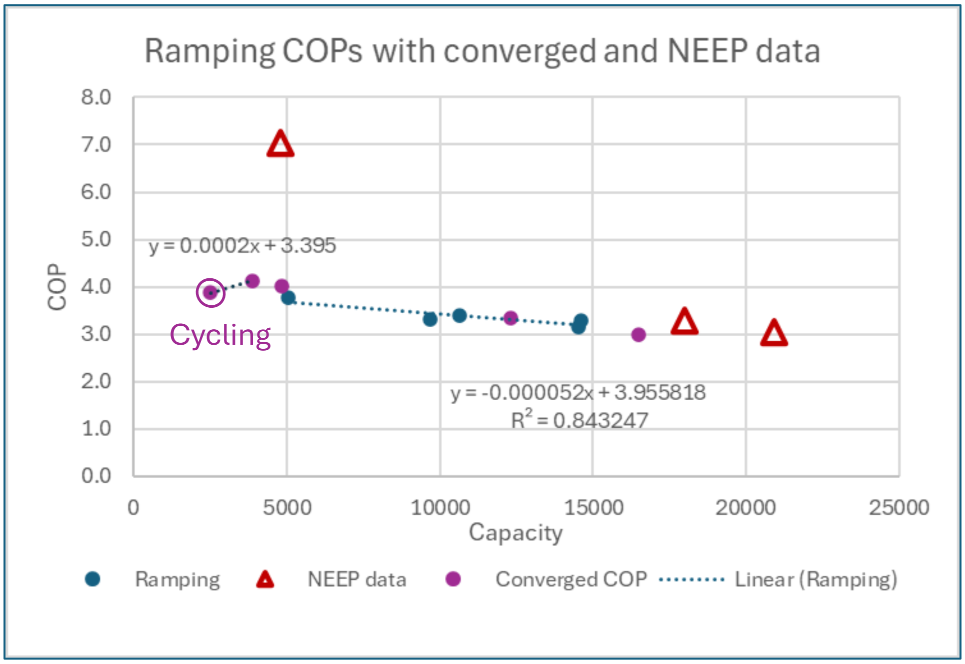

Figure 24: NEEA LLE 3 heat pump lab testing results compared to Northeast Energy Efficiency Partnership (NEEP) reported data

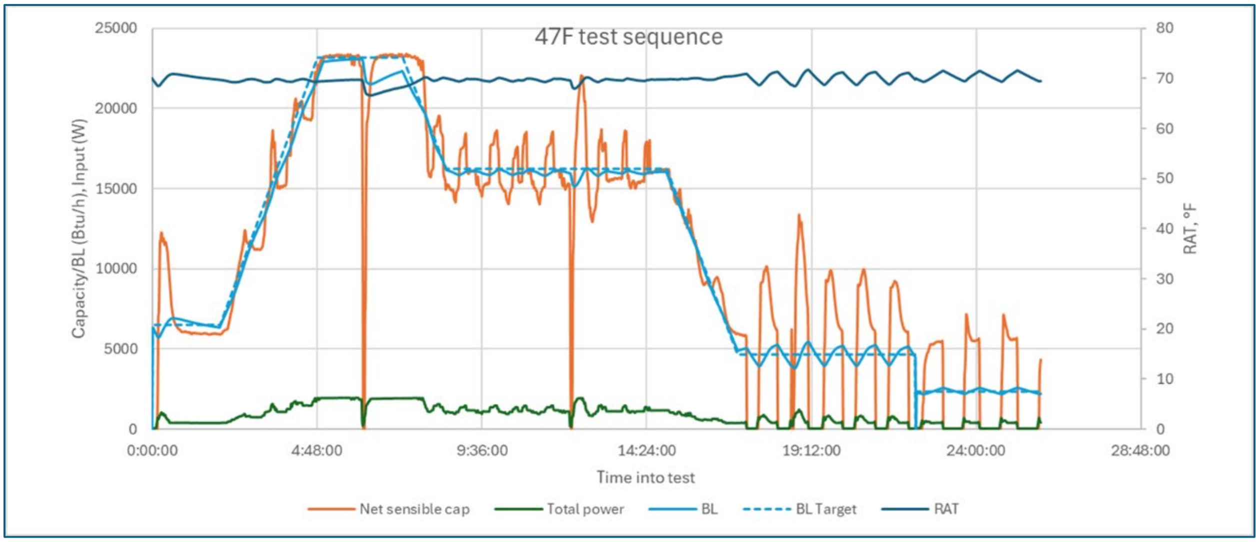

Figure 25: NEEA LLE 4 heat pump lab testing results for full testing procedure

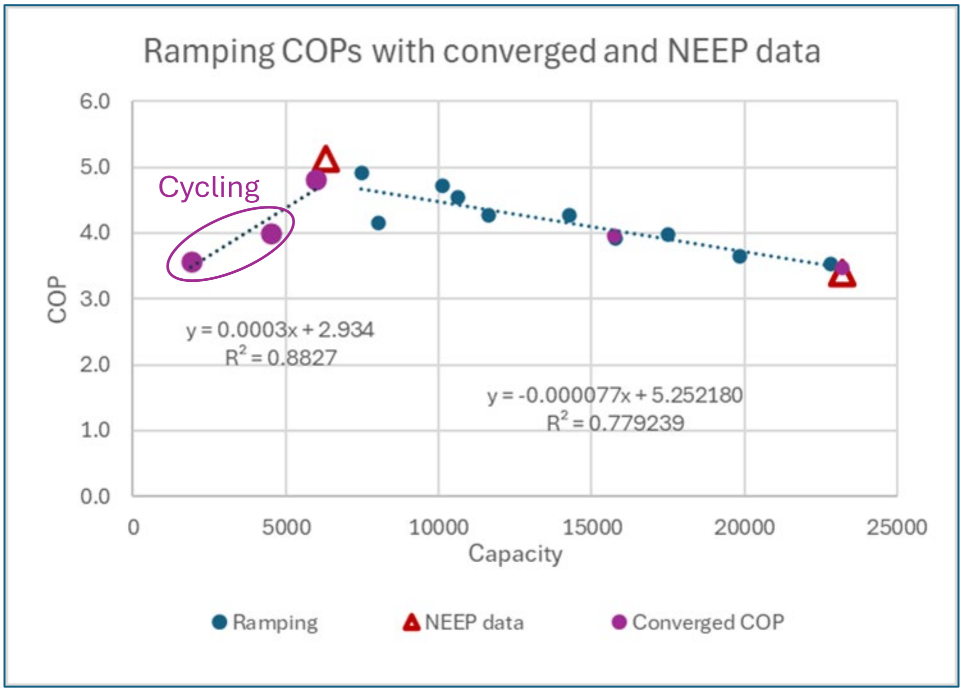

Figure 26: NEEA LLE 4 heat pump lab testing results compared to Northeast Energy Efficiency Partnership (NEEP) reported data

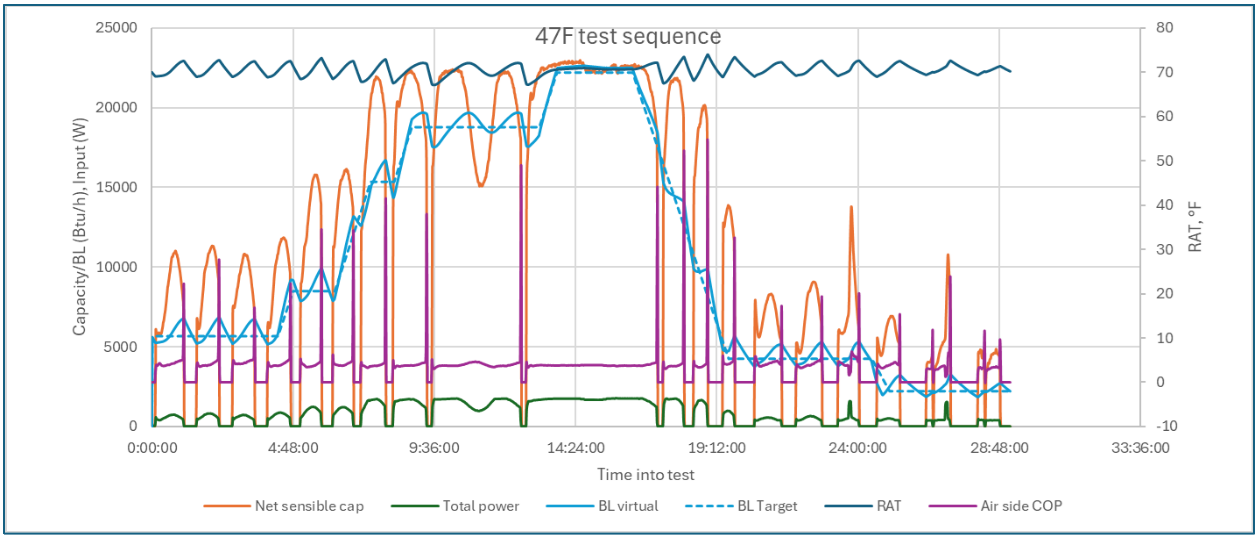

Figure 27: NEEA LLE 5 heat pump lab testing results for full testing procedure

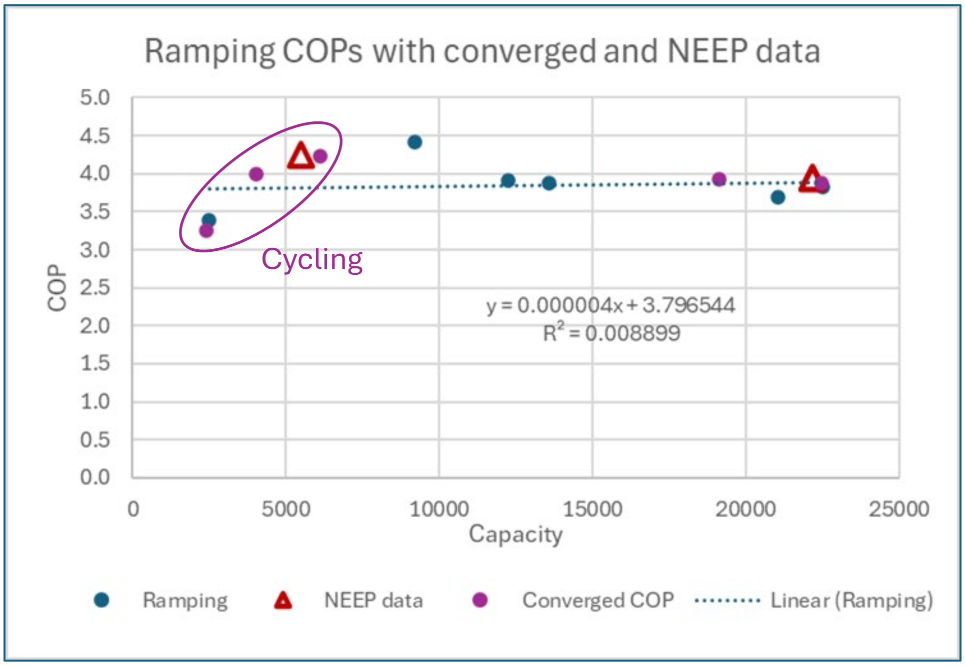

Figure 28: NEEA LLE 5 heat pump lab testing results compared to Northeast Energy Efficiency Partnership (NEEP) reported data

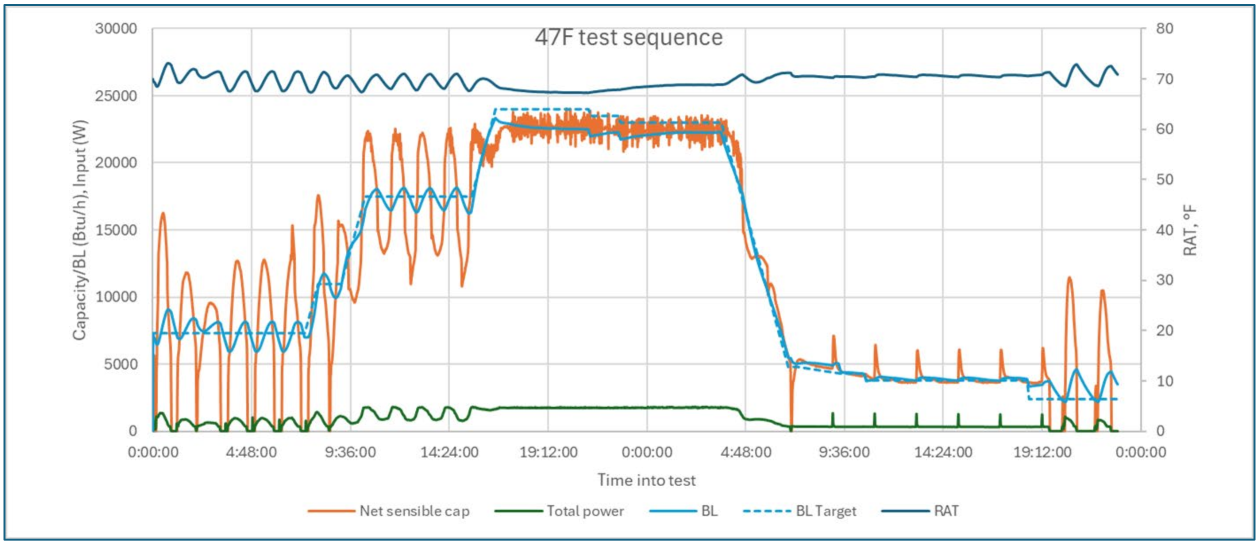

Figure 29: NEEA LLE 6 heat pump lab testing results for full testing procedure

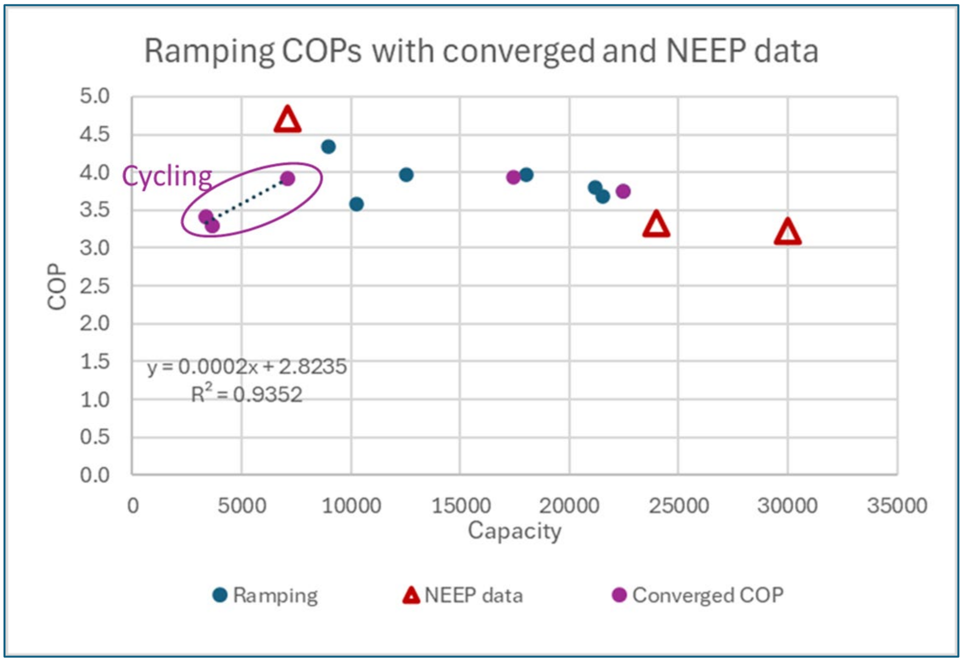

Figure 30: NEEA LLE 6 heat pump lab testing results

1.3.3. Lab Testing Observations

This section describes a range of observations overall and for each unit tested. Some observations are speculative about what the lab testing revealed.

1. Impact of cyclical behavior on COP: Heat pump cycling at low loads can potentially lead to lower efficiency gains at ideal LLE outdoor temperature bands.
2. LLE NEEA 1 unit: This is an older unit which was tested previously, and was chosen to assist with establishing the method of testing. It has exemplary LLE performance that matches well with the

NEEP low-speed capacity and corresponding COP at 47 °F, even though the COPs are a bit lower than NEEP -reported data at higher capacities.

3. LLE NEEA 2 unit: This unit demonstrated clear variable speed operation, but with considerable instability and cycling behavior. The reported NEEP data for MinCapCOP47 has a very high turndown ratio (approximately 7:1) and low COP that underreports the potential of this system. At more intermediate turndown ratios the unit performed reasonably well, but the unstable behavior could likely be addressed with an improved control algorithm and result in improved heat pump performance. A CVP test on this product would have revealed that the operating point used in the H1Low test (if that is indeed what was reported to NEEP) is not achievable by the unit using its native controls.
4. LLE NEEA 3 unit: This unit was chosen because it had a NEEP value of MinCapCOP47 well above all others, and that the manufacturer claimed was accurate. During testing it did not achieve the reported high COP. The lowest modulating capacity was close to that stated in the NEEP data. There is no clear reason why the COP was stated to be so high; it may be an administrative error. The lab-measured COP of 5 is still higher than, but much closer to the range of, the measured COPs for the other 5 tested units.
5. LLE NEEA 4 unit: This unit has exemplary LLE performance, and its NEEP reported data appears fairly accurate. The unit modulates well across the entire operating range. Although it did enter into defrost mode during the test, the defrost period was excluded from the COP calculation of the lab data because defrost impacts are not expected to be included in AHRI or NEEP-reported data.
6. LLE NEEA 5 unit: This unit has very high reported COPs at both full-load and low-load conditions. The unit has a larger heat exchanger size relative to other units tested. It demonstrated cycling behavior across a wide range of load conditions and the turndown in the lab was only 1.2:1, even though the NEEP data claimed 5:1. But despite the lack of turn-down, the COP was still quite high across the range of operation. The team speculates that additional improvements in performance may be possible with better modulation control under low load conditions. A CVP test on this unit would have revealed the cycling behavior at much higher loads with the unit using its native controls.
7. LLE NEEA 6 unit: This was the only A2L unit tested. It was a pre-production unit which was still undergoing final controls updates. Interestingly, the unit demonstrated cycling during the initial 8 hours of testing during the loading portion of the testing (while ramping up), but extraordinary modulation control during the last 8 hours of testing during unloading (ramping down). The manufacturer has used this data to inform and refine its control algorithm. The estimated COP from lab results is only slightly lower than NEEP reported MinCapCOP47, and the turn-down "average" of loading and unloading behavior was close to the NEEP data.

1.4. Field Data (BPA & NEEP/DNV)

1.4.1. Bonneville Power Administration (BPA) Field Study

The Bonneville Power Administration's (BPA's) "High Performance, High-Capacity Heat Pump" field study began in 2022 with the intent to understand how well the best heat pumps performed in the field, compared to their certified ratings (HSPF and SEER). The project installed and instrumented fifty-two heat pumps, from seven different manufacturers, throughout the Northwest region. The heat pumps selected were chosen to represent "high performance, high capacity" systems available at the time. Installation of heat pumps started in the summer of 2022. Performance data collection continued through the winter of 2025 and is expected to be halted before the end of 2025.

Heat pumps were installed in several different home archetypes, located in the Northwest's three different climates zones.[16] The mixture of systems consists of twenty-five centrally ducted systems and twenty-seven multi-head ductless systems. All systems were installed as whole home systems intended to provide 100% of the design heating load of the home. This included a mixture of multi-head and single head ductless systems and centrally ducted whole home systems. Manual J and blower door testing was used to determine the load on most (but not all) systems.

Heat pumps were installed and set up per the manufacturers' installation procedures. All but one heat pump used the corresponding manufacturers' thermostat control systems. Installing contractors did not manipulate manufacturer preset default settings. However, the homeowners did have the ability to change the thermostat control systems' default settings if they were inclined to. Two homeowners inadvertently adjusted presets without knowing. In both cases, default settings were restored, and data during those time periods were ignored.

Of the fifty-two installed heat pump systems, seventeen centrally ducted heat pump systems' data were evaluated to understand how they performed under low-load conditions. Low-load conditions were defined as an outdoor air temperature of 42°F to 52°F, as determined by the nearest local weather station to the site being analyzed.

Data collection was achieved by installing testing and monitoring equipment shown in Table 4: Field testing installed monitoring equipment (Table 4) .A one-time air flow test was performed on the centrally ducted systems to correlate the air flow rates to the air handling unit power, so that delivered capacity could be calculated from the measured temperature rise across the air handlers. All data was collected at one-minute intervals.

Table 4: Field testing installed monitoring equipment

Location	Number of sensors	Parameter monitored
Blower	1	Amperage
Return header	1	Temperature
Supply header	3	Temperature
Outdoor unit	1	Power
Air handler	1	Power
Ductless indoor unit	1 (per unit)	Power
Electric resistance heat	1	Power
Whole-home meter	1	Power

Figure 31 provides data available from the manufacturer and values found in the NEEP cold climate heat pump database. Of the 17 systems analyzed to date, 14 of the 17 (82%) systems met the LLE criteria. This is a much higher fraction than the average in the NEEP database (or in NEEA territory generally) because the BPA study intentionally selected systems with higher MinCapCOP47 values.

[16] U.S. DOE International Energy Conservation Code (IECC) climate zone map 2012. IECC climate zone map | Building America Solution Center

Site ID	Square Footage	Heating Load	95F Rated Cap	17F Rated Cap	47F Min Cap	COP,MIN 47	Ducted/Ductless	HSPF2	max backup	5/47 Cap Ratio	5/95 Cap Ratio
CEC 41	1,890	36,200	39,500	25,600	9,500	4.72	Ducted	8.1	30	70%	70%
INL 02	2,688	27,700	27,800	18,000	6,200	4.33	Ducted	8.2	15	59%	61%
INL 41	1,584	38,000	37,600	22,400	20,400	4.71	Ducted	8.7	25	52%	47%
INL 42	2,700	30,900	47,000	32,200	17,000	5.14	Ducted	9.0	50	59%	56%
INL 44	3,300	66,700	57,500	35,600	21,200	4.23	Ducted	-	2	53%	49%
SNO 41	1,082	10,500	34,600	28,000	12,000	3.86	Ducted	9.5	8	82%	66%
SNO 43	1,132	10,800	24,000	16,900	7,900	4.37	Ducted	-	5	61%	53%
SNO 44	5,631	75,500	60,000	38,500	16,000	4.64	Ducted	-	5	58%	53%
TAC 01	1,784	35,800	35,800	24,000	20,700	4.53	Ducted	9.0	10	53%	52%
TAC 02	1,396	57,699	35,800	24,000	20,700	4.53	Ducted	9.0	5	53%	52%
TAC 03	2,450	37,200	35,200	24,200	21,000	4.56	Ducted	9.0	10	52%	53%
TAC 04	1,740	26,500	35,800	24,000	20,700	4.53	Ducted	9.0	10	53%	52%
TAC 05	1,936	39,900	35,800	24,000	20,700	4.53	Ducted	9.0	10	53%	52%
TAC 06	1,716	38,500	47,500	30,800	17,300	4.92	Ducted	8.7	5	56%	53%
TAC 08	2,063	35,200	27,000	21,400	13,000	4.70	Ducted	8.5	-	100%	119%
TAC 09	1,034	19,000	35,200	24,200	21,000	4.56	Ducted	9.0	-	52%	53%
TAC 10	1,426	25,300	33,400	30,200	14,273	3.87	Ducted	-	5	71%	76%

Figure 31: Bonneville Power Administration (BPA) field-tested ducted heat pump system data

1.4.1.1. Examples of LLE performance differences

Figure 32 through Figure 36 show examples of four field-tested ducted heat pumps. The figures below show four scenarios characteristic of most of the heat pumps' performance. The scenarios were determined to be:

1. Good LLE performance (Figure 32)

Possible oversizing or instrument error (

2. Figure 33 and Figure 34)
3. Possible under sizing or instrument error (Figure 35)
4. Possible incorrect data input (Figure 36)

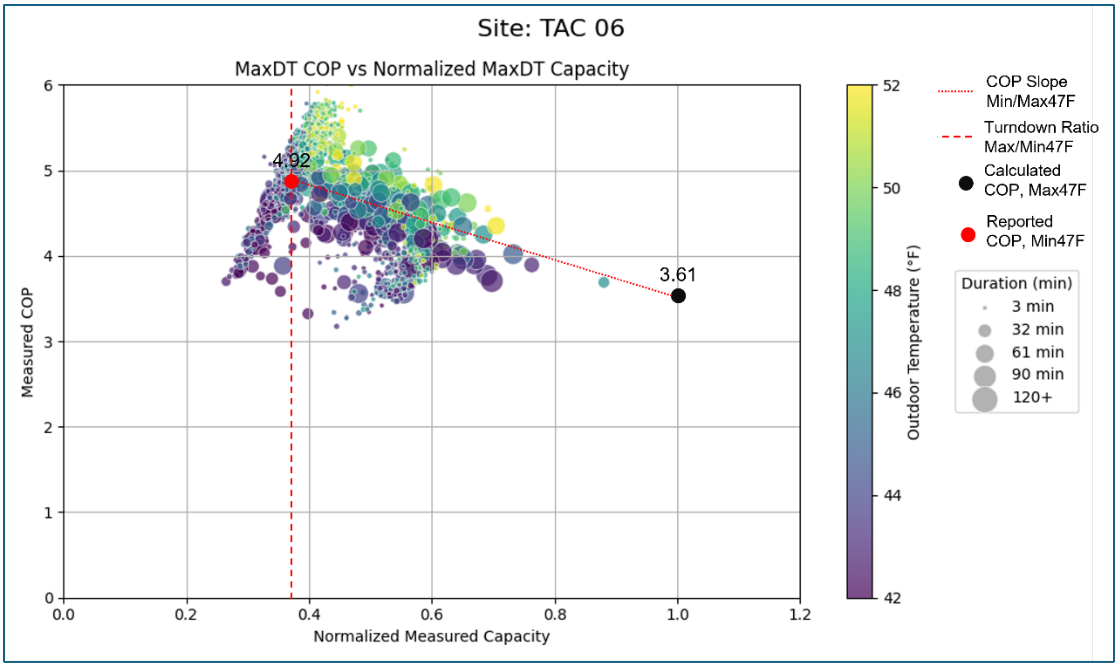

Figure 32: Field-tested heat pump TAC 06 measured COP vs. normalized measured capacity for outdoor air temperature 42°F – 52°F.

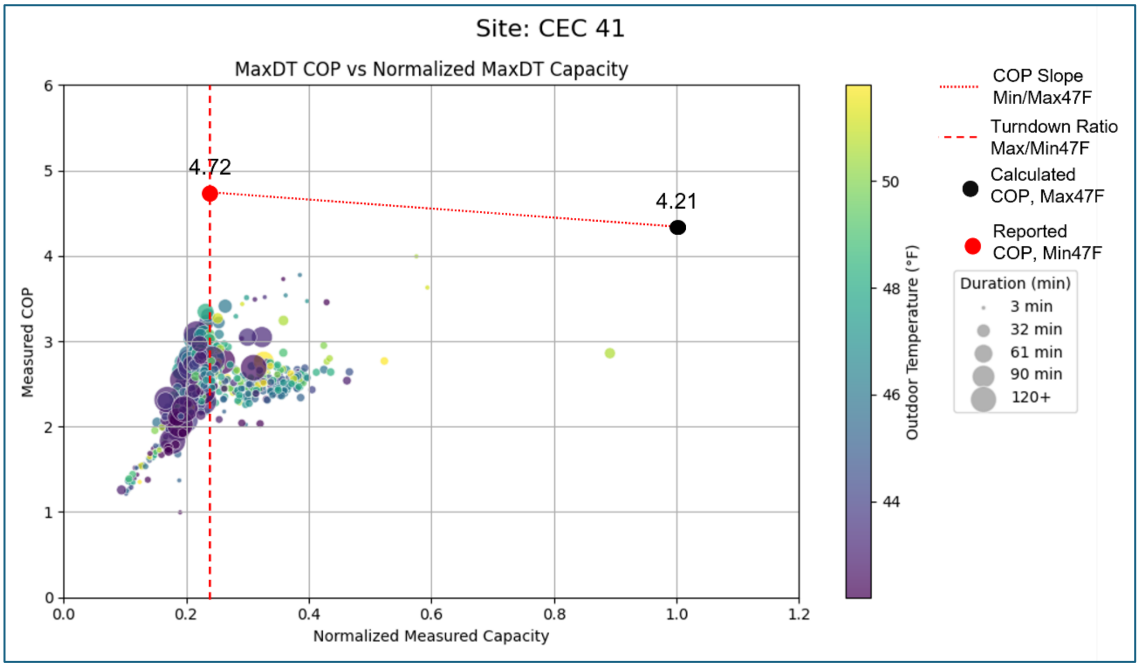

Figure 33: Field-tested heat pump CEC 41 measured COP vs. normalized measured capacity for outdoor air temperature 42°F – 52°F.

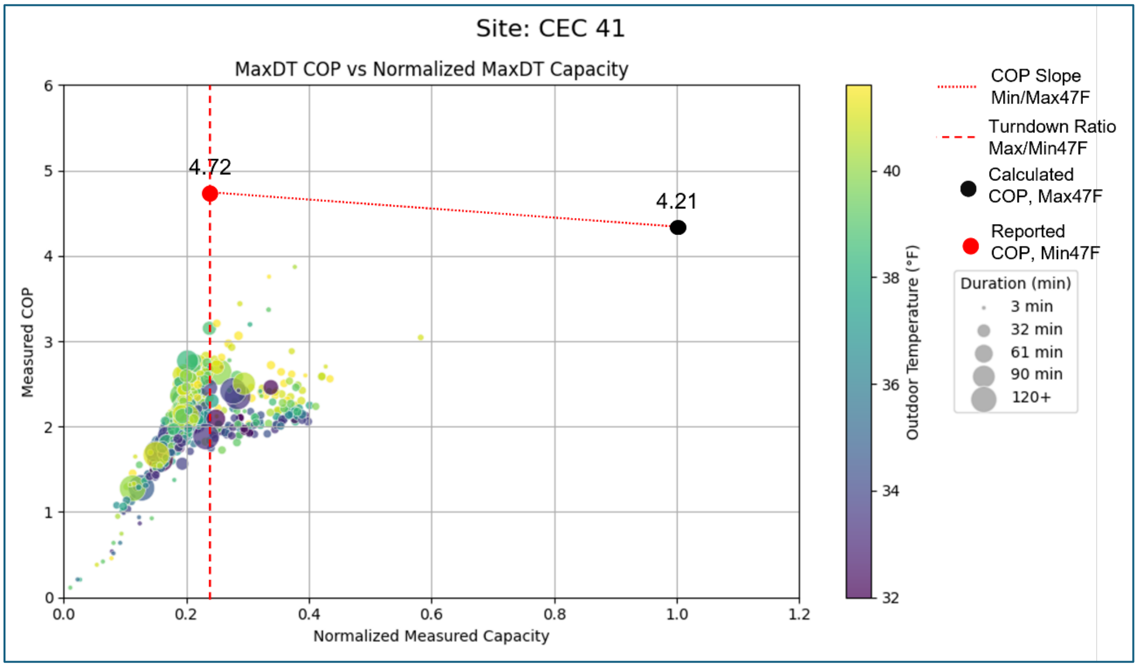

Figure 34: Field-tested heat pump CEC 41 measured COP vs. normalized measured capacity for outdoor air temperature 32°F – 42°F.

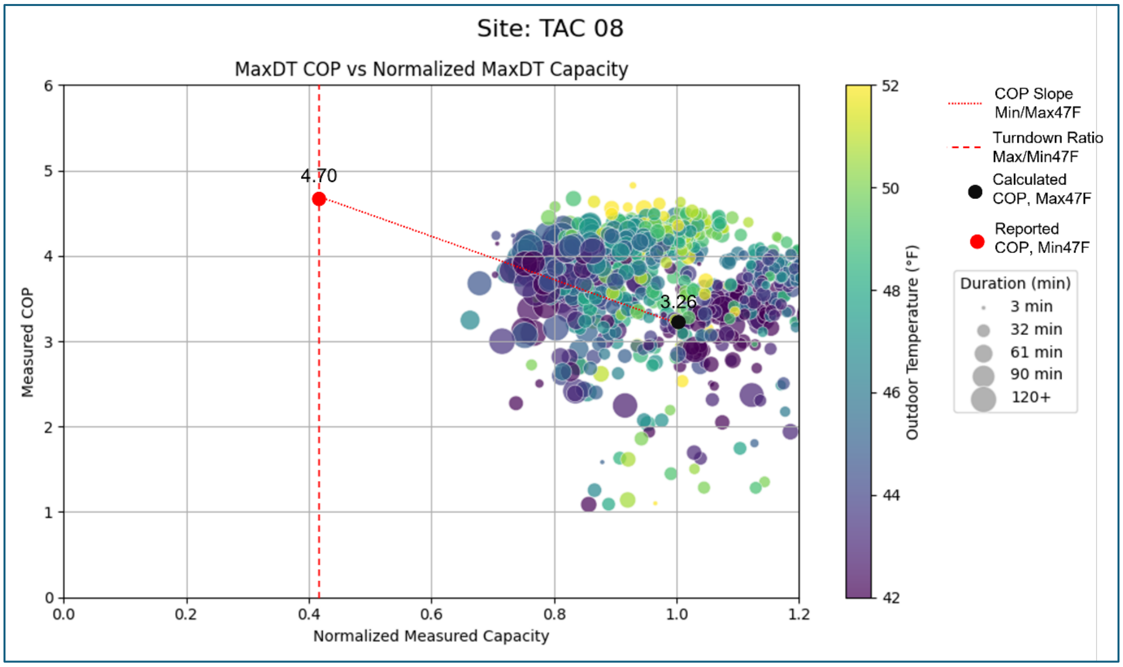

Figure 35: Field-tested heat pump TAC 08 measured COP vs. normalized measured capacity for outdoor air temperature 42°F – 52°F.

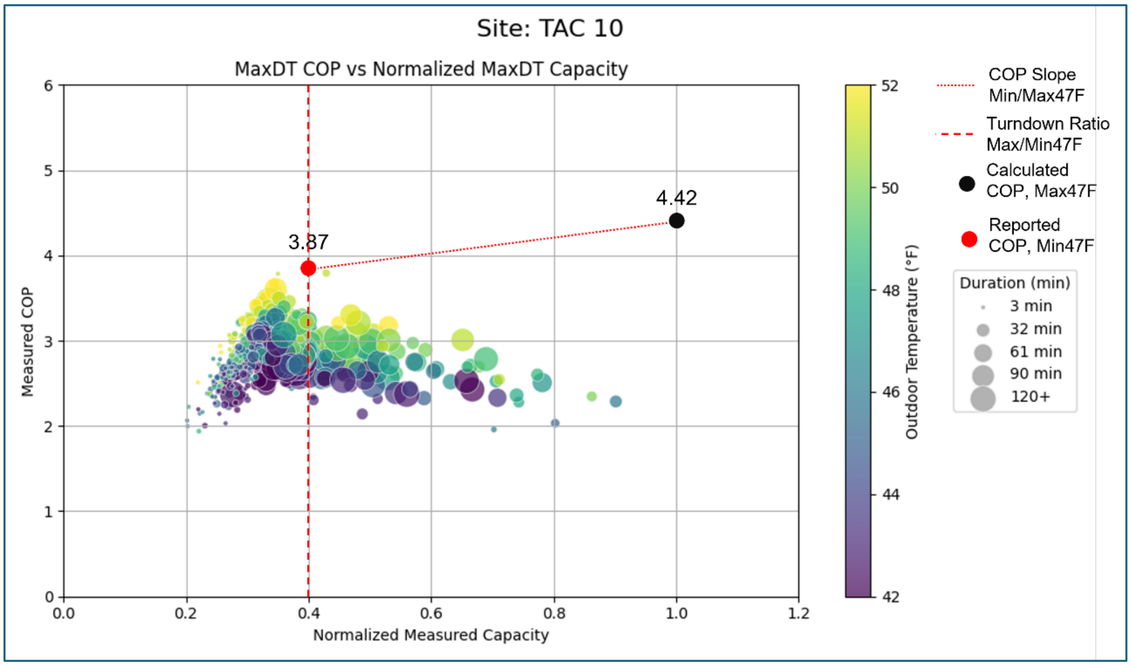

Figure 36: Field-tested heat pump TAC 10 measured COP vs. normalized measured capacity for outdoor air temperature 42°F – 52°F.

1.4.1.2. General Findings

Figure 36 shows the results of 17 BPA field-tested ducted heat pumps. The field data showed that among those 17, five (approximately 30%) of the ducted heat pumps exceeded the target low-load efficiency of 4.5 COP, despite a total of 12 having NEEP-reported COPs of at least 4.5. The field testing, which should be reasonably comparable to the NEEP-reported values, also showed that approximately 1/3 of installed ducted heat pumps performed poorly at low-load conditions, with a COP lower than 4; a few even had COPs lower than 3, including one with a NEEP listed value above 4.5.

The vertical red dotted line in Figure 36 represents NEEA's LLE COP, a MinCapCOP47 of 4.5, and the red dots are the NEEP database reported MinCapCOP47. The bell curves are the calculated COP performance for each ducted heat pump.

Field test data showed that Heating Seasonal Performance Factor (HSPF/HSPF2) was not a good indicator for a heat pump's low-load efficiency. Some heat pumps with a higher HSPF/HSPF2 did perform well; others with higher HSPF/HSPF2 performed poorly at low-load conditions.

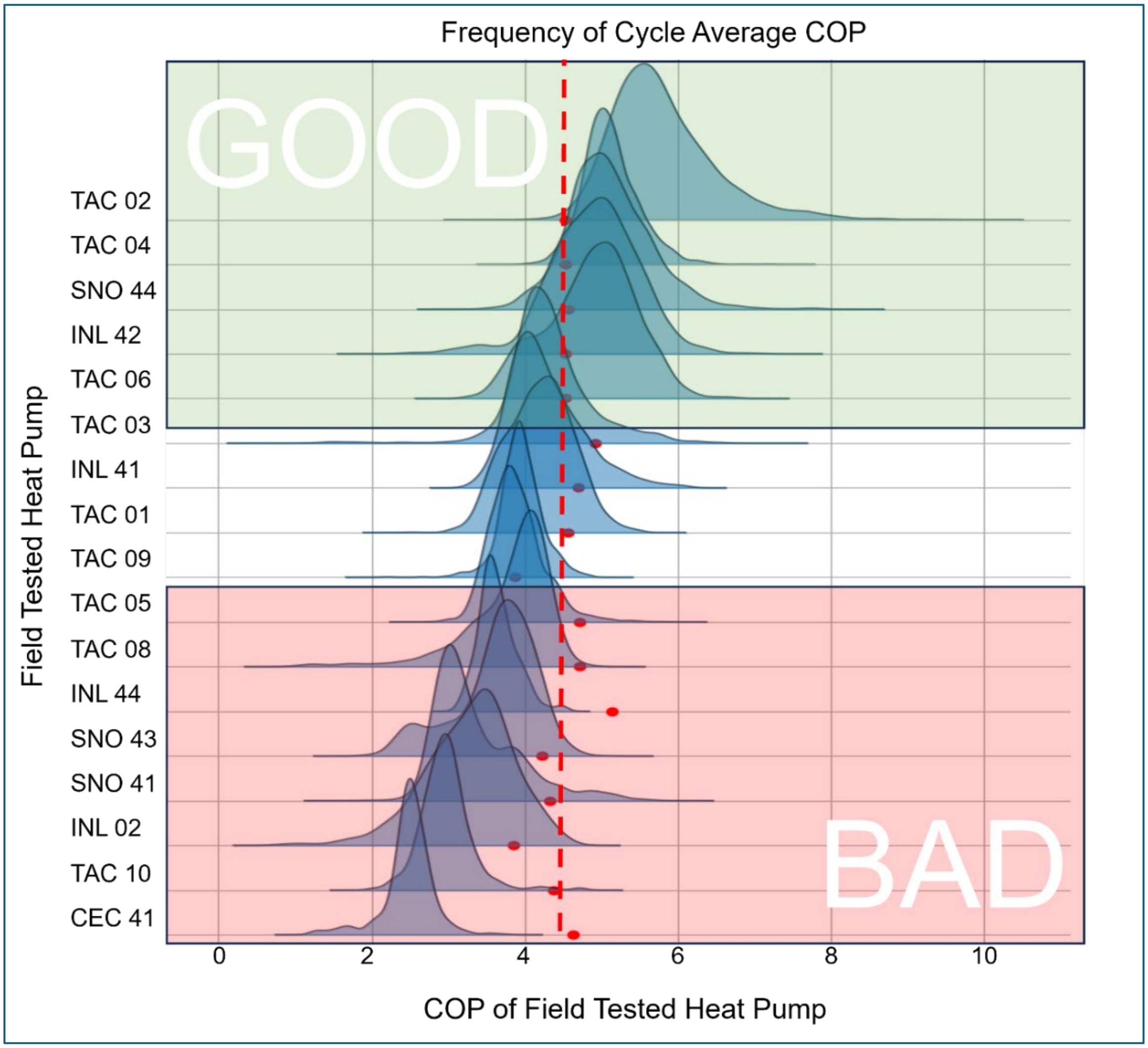

Figure 37: Field-tested ducted heat pump typical operating and average coefficient of performance (COP) compared to a COP of 4.5

Figure 38 is the average COP of each field-tested ducted heat pump (vertical axis) as it corresponds to the reported MinCapCOP47 on the NEEP database (horizontal axis). The field measurements are clearly below the NEEP-reported data for most units.

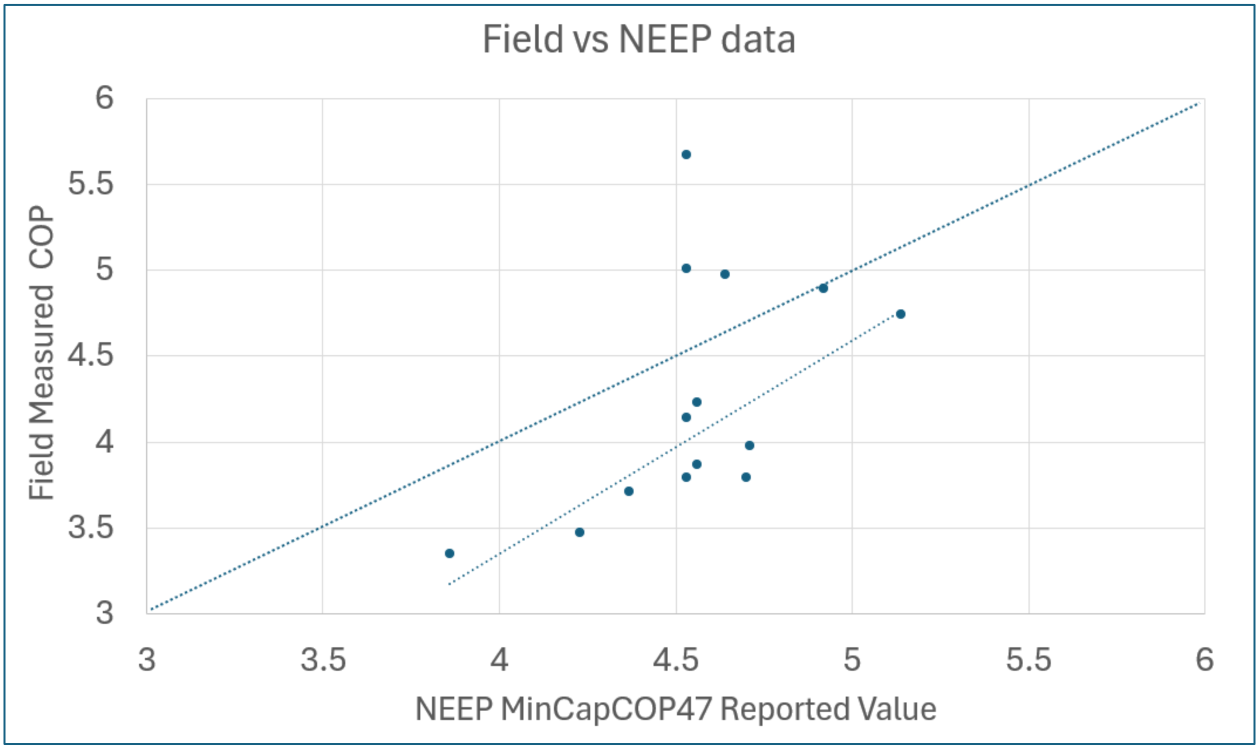

Figure 38: Field-measured COP vs. NEEP reported data

1.4.2. NEEP Rating Representativeness Project

The Rating Representativeness Project[17][18] was a collaboration of many parties, administered by NEEP, to determine representativeness of lab test procedure CSA Group SPE07:23[19] results, compared with field operation of 6 actual heat pumps. The project objective was to evaluate the test methods, rather than testing equipment performance. The project did, however, gather lab-quality field measurement data on three ducted and two ductless heat pump systems from June 2022 through April 2023.

Field testing was performed in three manufactured homes built in the same month from the same factory and placed in the same housing development in Lincoln, Nebraska. Each home had a ducted and a ductless heat pump installed. The two heat pump systems in each home were operated alternately for three to four days at a time. Homes were adjusted to be as close to the CSA SPE07:23 testing conditions as possible. Additionally, all three homes' testing sensors were set up the same, with over 100 sensors

[17] NEEP Residential Heat Pump Efficiency Rating Representativeness Project Phase 1 neep_heatpump_rating_representativeness_study_phase1_final_small.pdf
[18] NEEP Residential Heat Pump Efficiency Rating Representativeness Project Phase 2 neep_heatpump_rating_representativeness_study-phase2_final.pdf
[19] CSA SPE-07:23 CSA SPE-07:23 | Product | CSA Group

installed in each house to monitor the heat pumps' operation and home and outdoor conditions in detail.

After completing field testing, all units were shipped to a laboratory in May of 2023 for testing and rating in accordance with the CSA SPE07:23 and the AHRI 210/240-2023 (2020) test procedures. The results of this study revealed that the load-based testing per CSA SPE07:23 was more representative of field performance than the static condition testing of AHRI 210/240 under low-load conditions.. In 2023, the AHRI unitary small equipment standards technical committee (USE STC) members, with input from DOE and other stakeholders, decided to add the CVP to the AHRI 210/240 test to properly capture whether a heat pump is truly operating as a variable speed system under moderate-load conditions, or if it is performing as a single- or two-stage heat pump (as some units tested using SPE07 were behaving). The CVP also validates the low-speed operation claimed in the $H1_{Low}$ and B_{Low} tests for capacity and COP using the system's native controls. Once fully implemented by AHRI, this load-based CVP should improve the accuracy and representativeness of the low load metric that is used in part to calculate HSPF2. It should also improve the accuracy of reported values of H1low (MinCapCOP47) used in the NEEP database.

1.4.2.1. Additional NEEP Field Data Analysis

The NEEA team contracted University of Nebraska at Lincoln (UNL) to generate additional graphs of the rating representativeness results. Field testing showed that all five units that were successfully tested had higher heating capacity, and five of six units had a higher COP than was reported to AHRI and NEEP database. Testing also showed that one unit, a variable speed heat pump shown in Figure 39, operated at fairly fixed speeds, with results that were similar to the two-speed heat pump shown in Figure 39.

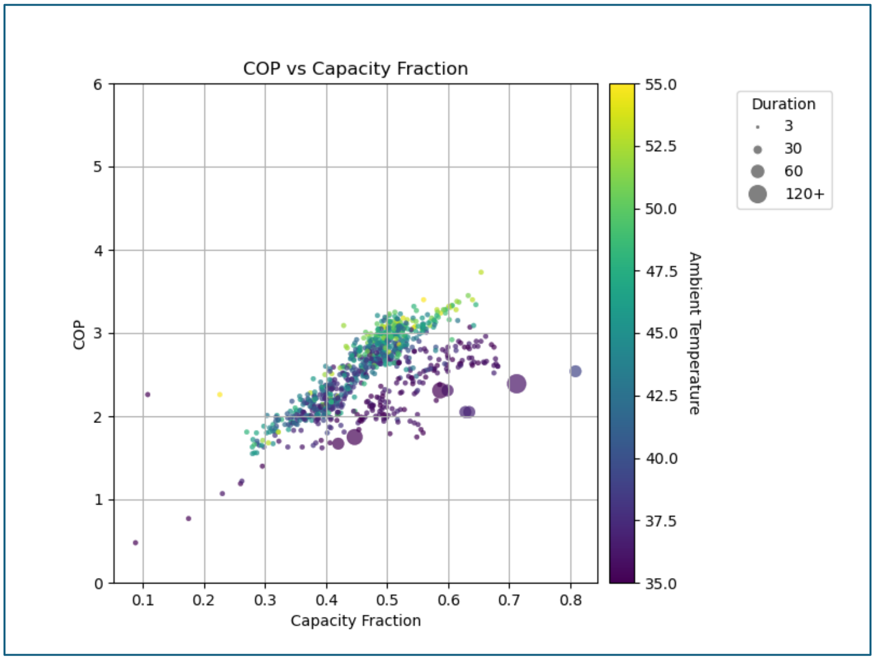

Figure 39: Field-tested Unit B two-speed system for partial load efficiency during heating with OAT 35°F - 55°F

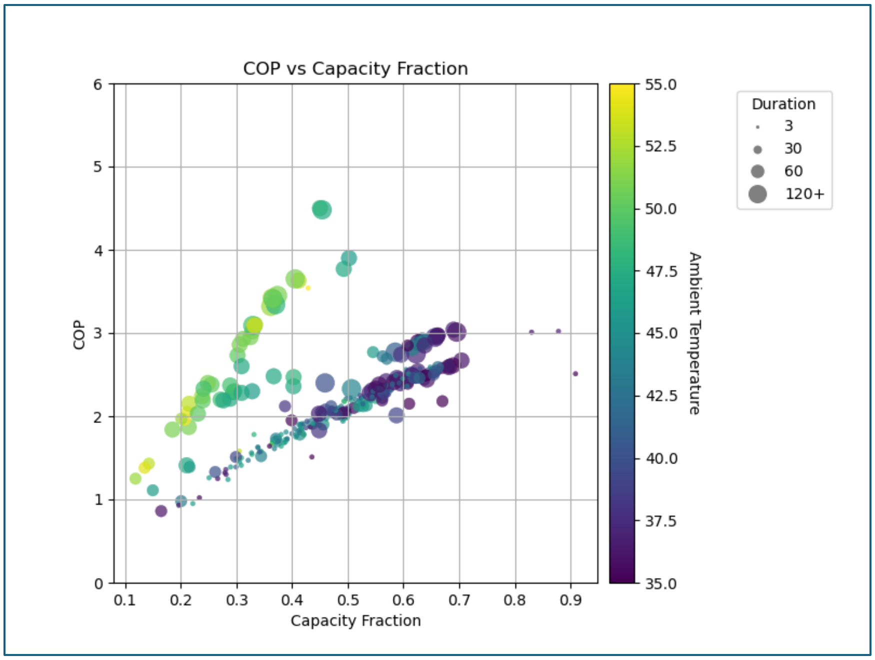

Figure 40: Field-tested Unit C variable speed system for partial load efficiency during heating with OAT 35°F - 55°F

2. Energy Modeling and Savings

"Essentially, all models are wrong, but some are useful." – George Box (paraphrase)

This section presents past and updated modeling of different heat pump archetypes. The purpose of modeling archetypes is to understand the relative importance of different factors by isolating them. In the field, these subtle changes in equipment performance cannot be isolated due to many compounding factors such as differing schedules, weather, occupancy, thermostat settings, refrigerant charge and changing air flow due to filter loading.

2.1. MNCEE Initial Modeling and Savings (2022 results)

This project assessed available data from centrally ducted VSHPs[20] with the objective of better understanding currently available products, pricing, performance specifications, and equipment features. The research team developed heat pump (HP) archetypes to explore the range of VSHPs on the market today, and key performance impacts of short cycling, coefficient of degradation, controls accuracy, sizing, defrost, and duct sealing on annual energy consumption and peak power use. The team also developed an 8,760-hour energy balance model that calculates the levelized lifecycle cost of heating and cooling.

The tool uses a building heat loss model with detailed COP and capacity mapping of heat pump performance. NEEA refers to this model as the VCHP Levelized Cost Tool (VCHP LCTool). The tool enables users to explore the relative performance differences of heat pump archetypes while holding other key inputs static (e.g., setpoint, duct losses, defrost control).

Figure 41 and Figure 42 show the results of the 2022 study for several different archetypes' performance as energy comparison graphs for Portland, OR (Figure 41) and Bozeman, MT (Figure 42). The graph shows the annual energy consumption of several different variable speed archetypes. The "Average VSHP" archetype was a system based on the average data collected from manufacturers and AHRI directory. The "Mild Master" archetype was a system defined as having a 25% higher minimum capacity COP relative to the "Average VSHP", presumably most important in milder heating climates. The "Capacity Champ" archetype was defined as a system with superior capacity, but no better efficiency. The "COP King" archetype is defined as a system with superior COP, but no better capacity. The 2022 study revealed just how important low-load efficiency was to annual energy consumption. By increasing the minimum capacity COP by 25%, the annual energy consumption dropped 8%–16% (depending on climate).

The "Mild Master" archetype produced nearly the same gains in performance as the "COP King" but without any increase in observable equipment cost, nor an increase in the HSPF values of the equipment. One of the most important outcomes of the study is its revelation of the potential hidden performance gain opportunity of heat pumps through improved low-load efficiency.

[20] NEEA uses the term VSHP (variable speed heat pump) term interchangeably with VCHP (variable capacity heat pump). Variable speed is simply a more consumer-friendly term that NEEA chose to use for its program name.

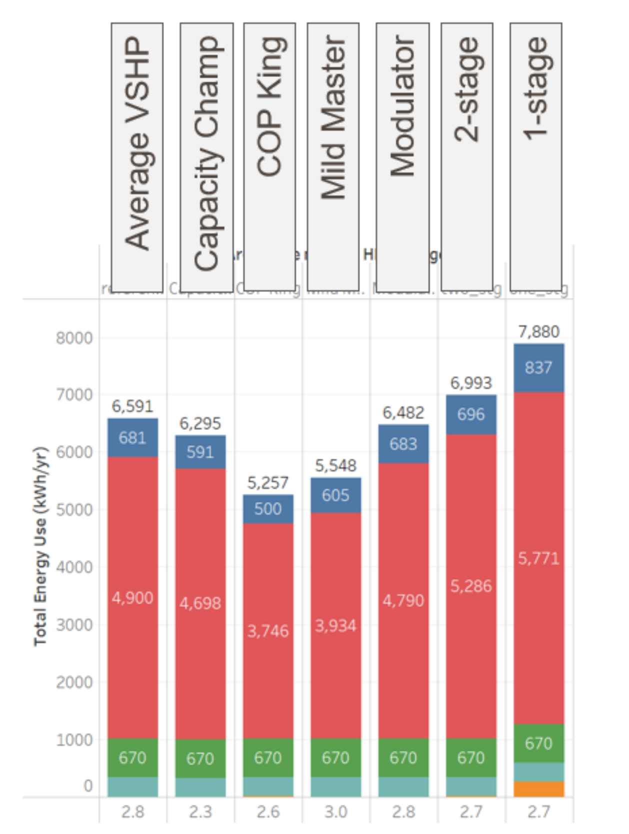

Figure 41: Variable capacity heat pump archetype energy comparison for Portland, OR

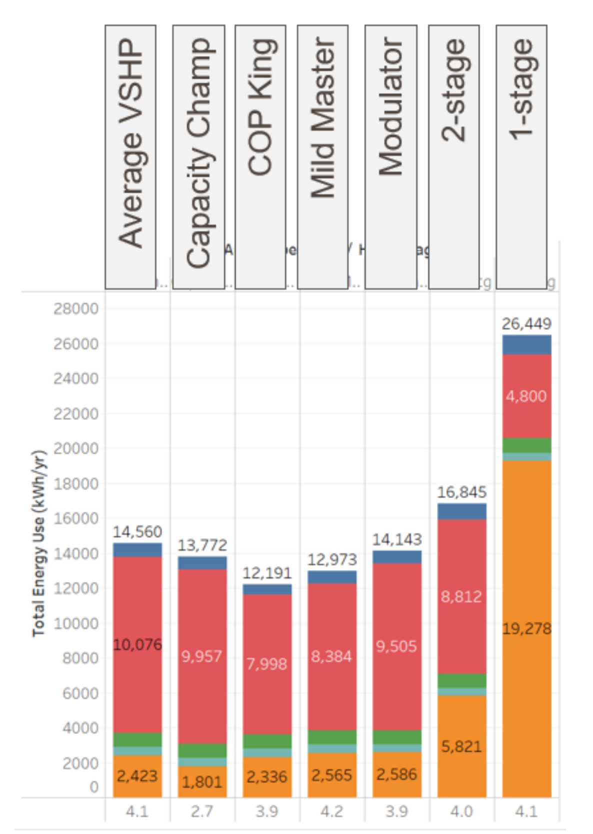

Figure 42: Variable capacity heat pump archetype energy comparison for Bozeman, MT

2.2. Updated Modeling and Savings (2025 results)

The initial MNCEE study was updated in 2025 to incorporate the improved and newly defined archetypes based on field and lab testing data gathered since 2022. The four heat pump archetypes modeled for comparison in Figure **43** through Figure 50 are listed below.

Heat Pumps Modeled

- Approximate Federal Minimum (Approx Fed Min)
- DOE Cold-climate Technical Challenge (DOE Tech)
- LLE VSHP 2025 (LLE 2025)
- VSHP Baseline

Each figure shows a comparison of energy used by four newly defined archetypes. In all cases the LLE 2025 archetype shows improved performance relative to the VSHP baseline. In temperate climates, such as Portland, OR and New York City, a 1% gain in LLE generates a 0.3% – 0.5% reduction in annual energy use, significantly better than is reflected by their rated HSPF/HSPF2. In colder climates, such as Denver and Minneapolis, where temperatures are colder than the LLE ideal operating temperature band, the benefits of LLE are smaller but still significant.

The Approximate Federal Minimum (Approx Fed Min) heat pump is based on a specific variable speed heat pump that has the same HSPF2 and SEER2 values required to meet the federal minimum standard.

It is considered “approximate” because the federal minimum standard does not specifically define all the intermediate values of capacity and COP.

The Baseline VSHP is a specific variable speed heat pump that closely resembles the average performance of a cold climate variable speed heat pump, based on 70% heating capacity and COP of 2.1, at 5°F.

The DOE Technical Challenge (DOE Tech) heat pump is an approximation of the specification developed by the U.S. DOE’s cold climate technical challenge 2021.[21] The heat pump must meet 100% capacity at 5°F, in addition to achieving the low-load efficiency of the LLE 2025 model, and finally, achieving full-load efficiency values well above that of the VSHP baseline.

The LLE 2025 heat pump model is identical to the VSHP baseline with one exception – the minimum capacity COP values at 34°F, 47°F, 55°F, 77°F and 82°F are all increased by 12.5%. Unlike the previous study by MNCEE which assumed the performance bump was across all temperatures, the LLE 2025 archetype only includes performance enhancement consistent with what was measured in the UL load-based testing. The 12.5% increase is equivalent to going from a COP of 4.0 to 4.5 which is consistent with performance observed in field, lab and product data provided in the NEEP cold climate heat pump database.

In the figures below, the graph’s x-axis is energy consumption, the y-axis is the heat pump archetype that was modeled, and the percentage in each bar is the percent change in energy consumption when compared to the VSHP Baseline. The same house and operating conditions are used in each different graph. The percentages displayed are the relative annual energy consumption compared to the VSHP baseline archetype.

Figure 43 through Figure 46 compare four heat pump sizes for an average home in Seattle, WA. The heat pump sizes that were compared were 2-ton, 3-ton, 4-ton, and 5-ton. The 2-ton heat pump is undersized for the average home, as noted by the need for a backup heating source, which is represented by the red portion of the bar graphs. The 3- and 4-ton heat pumps are closer to being correctly sized. Findings show that even though the heat pumps are larger, they consume the same amount of energy overall as the 2-ton but will have less of a need of backup heating sources, reducing total energy consumption. The 5-ton heat pump system indicates that it is oversized for the average home, will consume more energy than the smaller tonnage heat pump systems, but will require little to no backup heating.

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[21] U.S. DOE Residential Cold Climate Heat Pump Challenge. [Residential Cold Climate Heat Pump Challenge | Department of Energy]

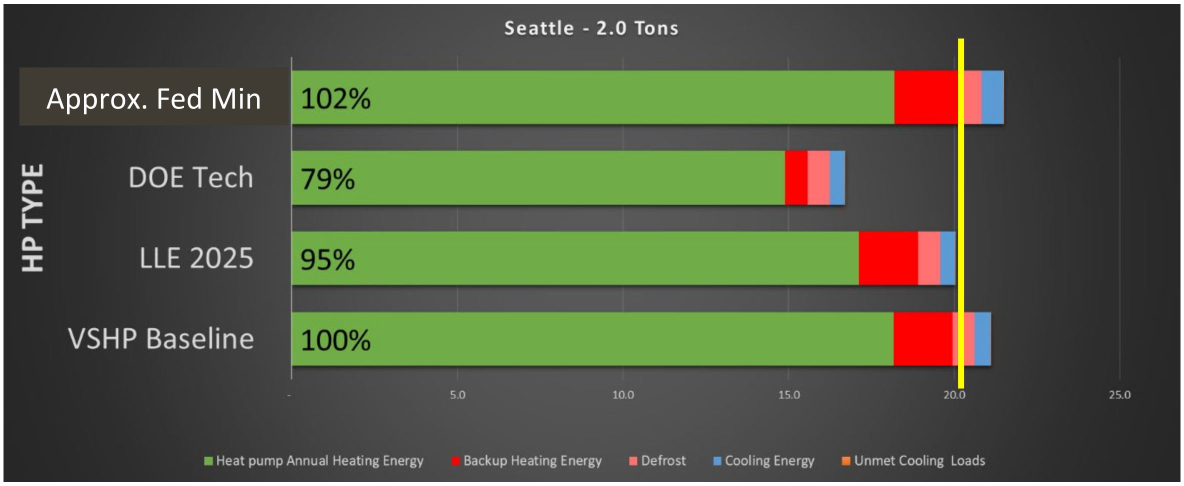

Figure 43: 2-ton heat pump energy consumption comparison in Seattle

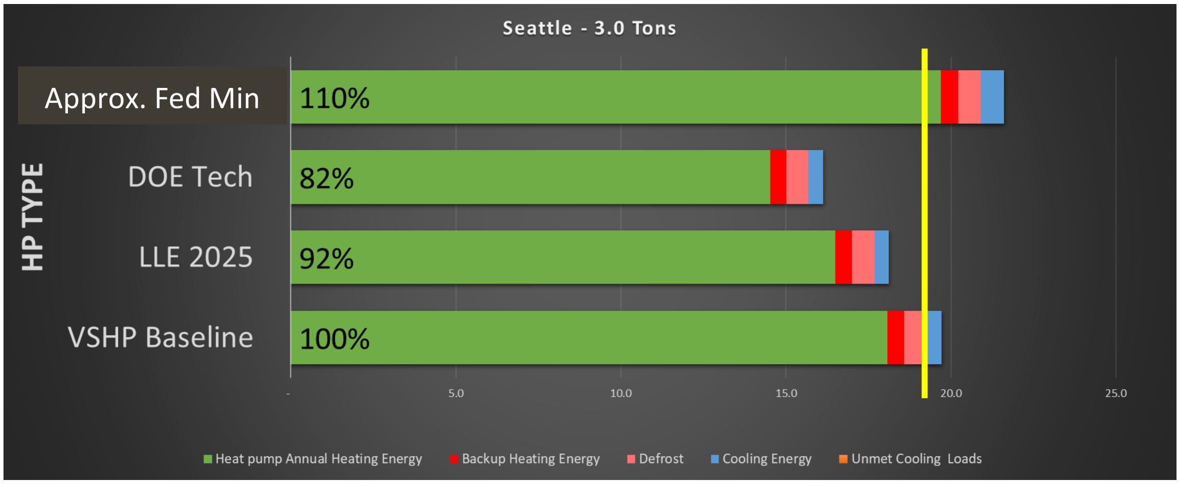

Figure 44: 3-ton heat pump energy consumption comparison in Seattle

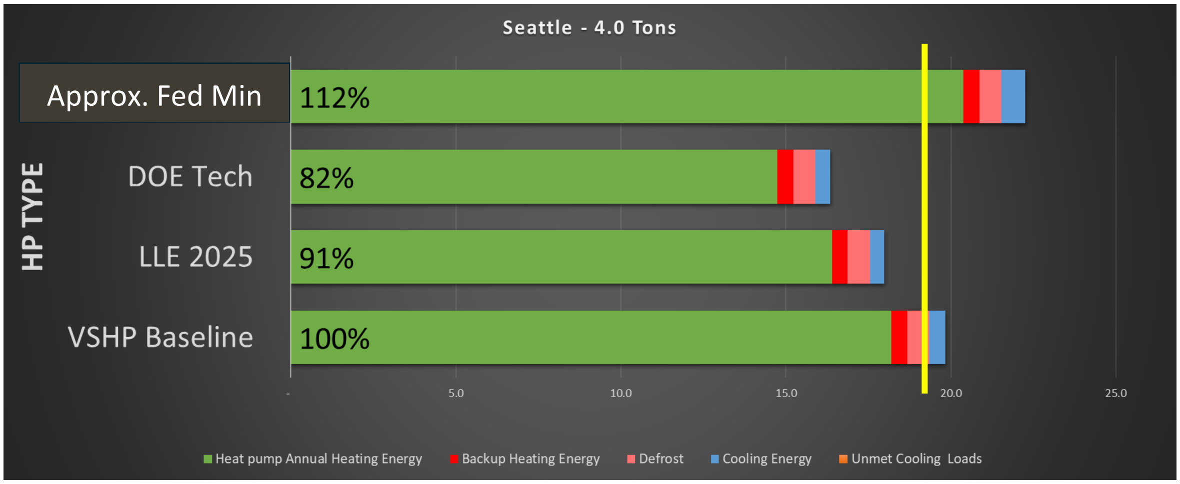

Figure 45: 4-ton heat pump energy consumption comparison in Seattle

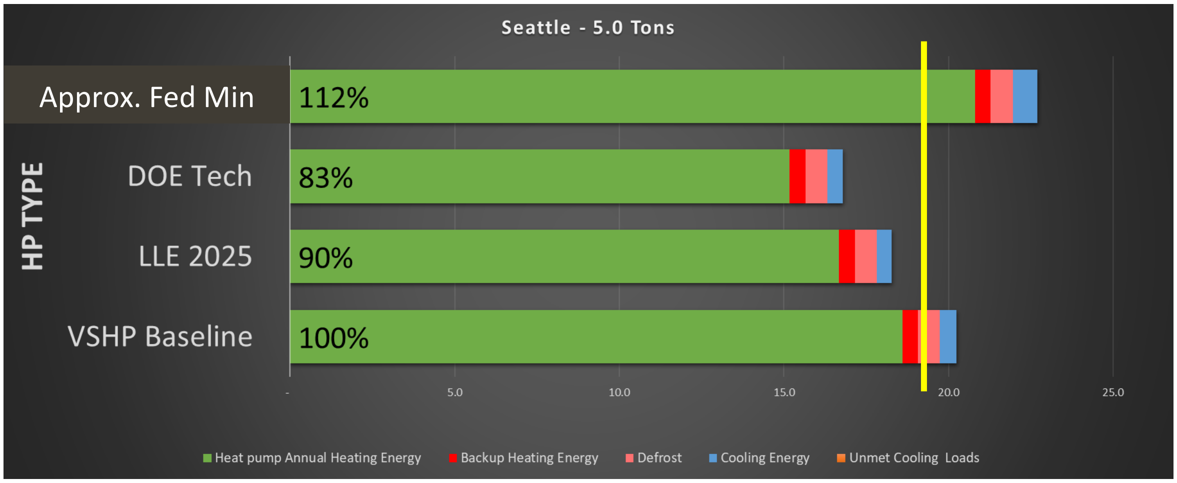

Figure 46: 5-ton heat pump energy consumption comparison in Seattle

In colder climates like Denver, CO and Minneapolis, MN, improving LLE will still reduce energy consumption, just not as significantly as in milder climate regions, because outdoor air temperatures will be colder than the temperature bands that take advantage of LLE heat pumps. Figure 47 through Figure 50 show energy consumption compared to VSHP Baseline for different-sized heat pumps in Denver and a 4-ton heat pump in Minneapolis.

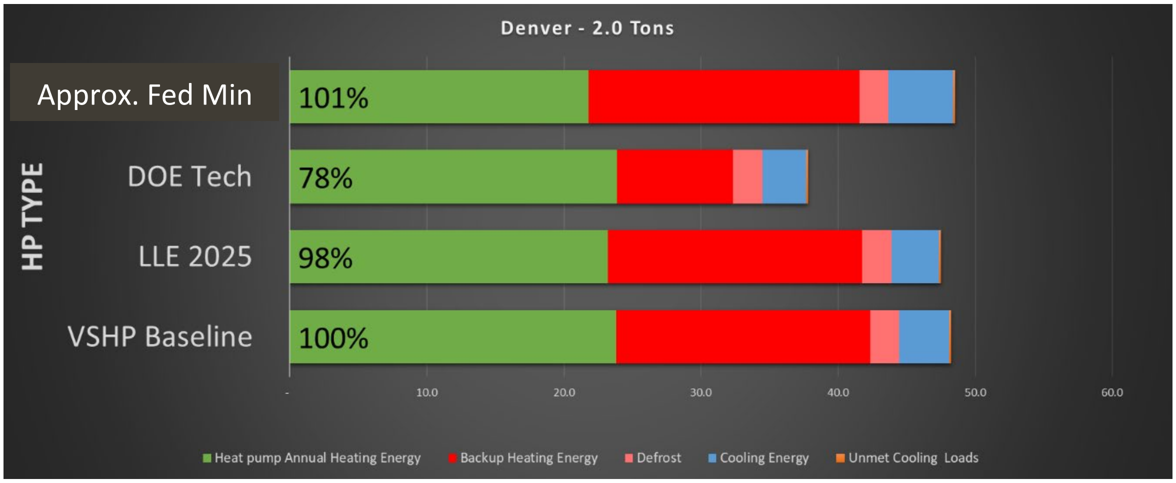

Figure 47: 2-ton heat pump energy consumption comparison in Denver

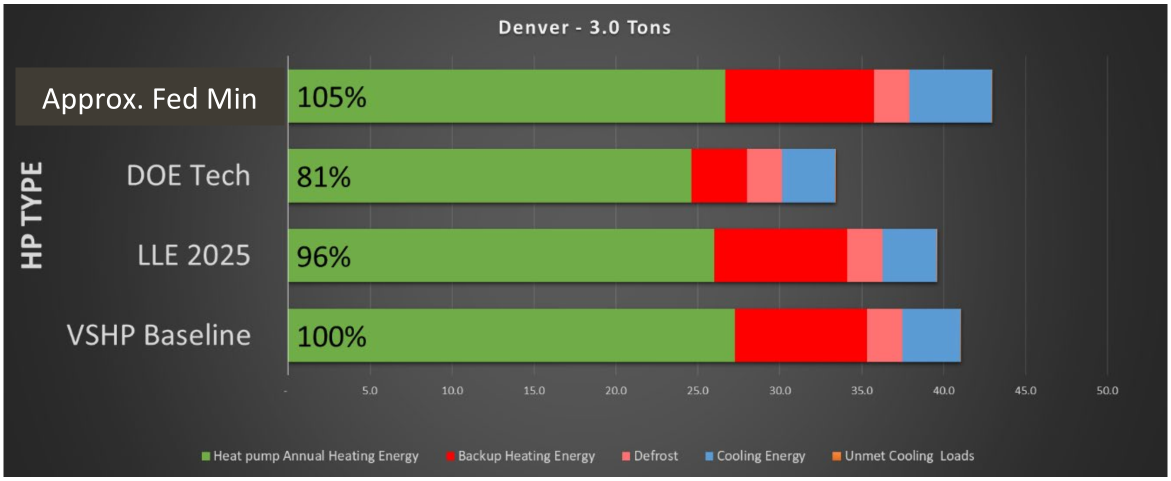

Figure 48: 3-ton heat pump energy consumption comparison in Denver

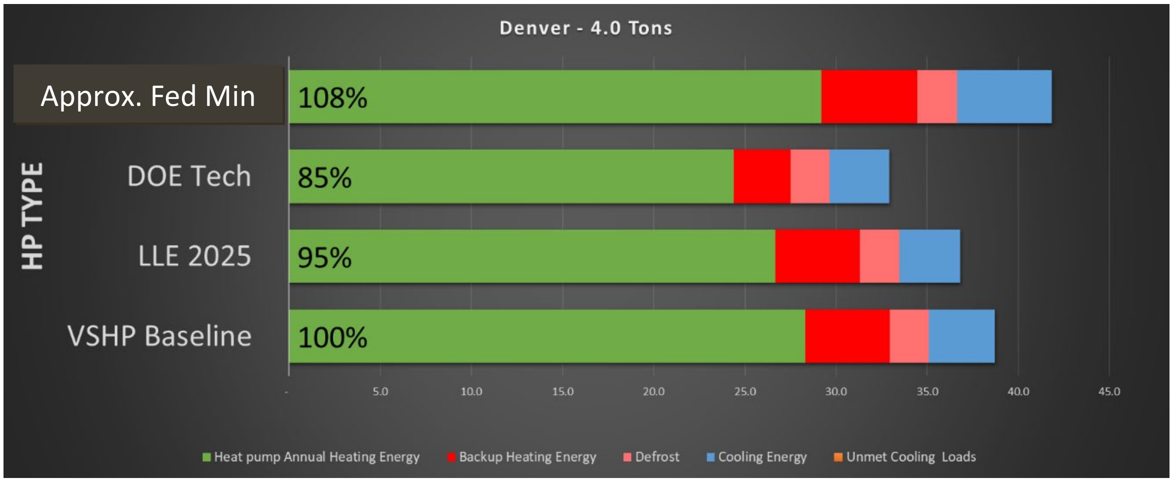

Figure 49: 4-ton heat pump energy consumption comparison in Denver

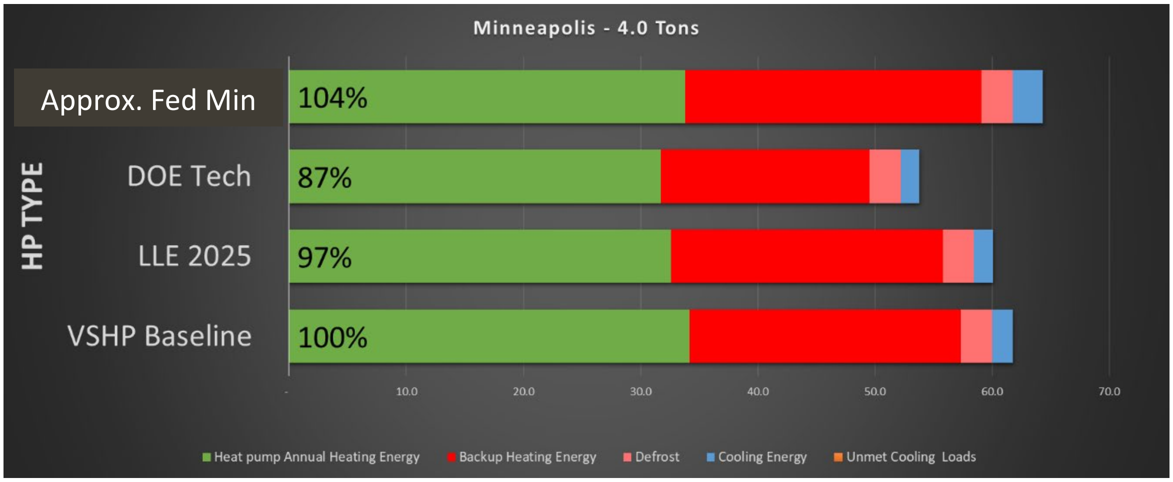

Figure 50: 4-ton heat pump energy consumption comparison in Minneapolis

2.2.1. Savings Potential Estimate

NEEA believes a 12.5% increase in MinCapCOP47 is achievable. If market average MinCapCOP47 is currently 4.0,[22] a 12.5% increase would mean that the market average would need to increase to a COP of 4.5. Such a shift in MinCapCOP47 has potential to save 2%–7% of the annual heating energy needed in a Northwest climate. In a typical home with a variable speed heat pump that uses roughly 3000 kWh/yr, this equates 60-210 kWh/yr. Applied to the 1.1 million heat pump-heated homes in the Northwest, this generates a technical potential energy savings in the range of 7.5–26.4 MW.

Table 5 compares projected energy usage reductions from the initial 2022 study to the updated archetypes of 2025. The 2022 values have been divided by 2 as they were based on a 25% increase in the minimum capacity COP at 47°F while the 2025 analysis is based on an LLE increase of only 12.5%. Several other changes were made to baseline heat pumps and the house used in the model, but the relative increase in performance should be comparable between the two modeling studies. In both cases the heat pump was assumed to be reasonably sized for the house load. In general, the refined modeling shows that savings still exist in moderate climates, but that in very cold climates like Minneapolis and Bozeman, the relative improvements from LLE are not very significant. It is worth noting that the benefit may be larger in the event that systems are oversized even for those climates (which is likely in some markets); the interactive effects of oversizing and low-load performance have not been fully explored.

Table 5: VCHP LCtool projected energy savings from LLE

City	2022 LLE[1]	2025 LLE[2]	Update Notes
Portland/Seattle	7.9%	6.6%	3 Ton
Boise	7.4%	3.4%	3 Ton
Bozeman	4.4%	2.0%	4 Ton
Sacramento	8.4%	4.6%	4 Ton
Denver	6.8%	4.1%	4 Ton
Minneapolis	3.8%	3.3%	4 Ton
New York City	8.6%	5.6%	4 Ton
Washington, DC[23]	8.2%	4.4%	3 Ton

[22] Variable Speed Heat Pump Product Assessment and Analysis (Note values in report for 25% increase), NEEA 2022, https://neea.org/resources/variable-speed-heat-pump-product-assessment-and-analysis

[23] Updated LCtool with COP curves modified from field and lab data. Efficiency was only increased by 12.5% in heating in temperature bins 34, 47 and 54. Size of HP was chosen for best annual heating and cooling.

2.3. Other Modeling Observations

2.3.1. Heat Pump Sizing

Proper sizing is important to extract the maximum benefit of low-load efficiency. If the heat pump is too small, it will not have enough capacity to operate at part load except in extremely mild conditions. If the heat pump is too large, it may be operating outside the effective benefit range of low-load operation. As the temperature drops some of the low-load benefit disappears. In addition, the oversized system will spend more of the year below its minimum capacity at cooler temperatures, thus dramatically increasing cycling penalties. A variable speed heat pump should be sized to run in its unloaded condition while still serving the majority annual load hours. The colder the design temperature, the larger the turndown ratio that is needed to ensure the system can still operate without short cycling during mild conditions.

2.3.2. Dual Fuel Systems

With rare exceptions, dual fuel heat pump systems do not allow the heat pump to operate simultaneously with the gas furnace. Customer cost savings from running a heat pump instead of running the gas furnace rely on the heat pump COP being high enough that the cost of electricity (per Btu) divided by the COP is better than the cost of the natural gas (per Btu). Practically speaking, this means that in most locations, heat pumps do not provide cheaper heat when operated below about 25°F–35°F. Customer savings and carbon savings have more to do with the crossover temperature and relative price of gas and electricity than the type of heat pump. Spending extra on a variable speed heat pump is not likely cost-effective if the heat pump is only used when outdoor ambient temperatures are above 35°F, though carbon-focused or demand-management programs may provide incentives that are tied to lower crossover temperatures, whether set as such throughout the winter or limited to demand response periods.

When a customer chooses to purchase a variable speed heat pump for a dual-fuel system, the type of variable speed does matter. A variable speed heat pump sized for cooling will in most climates be able to operate in an lower-load condition when ambient temperatures are between 35°F–55°F. This is an ideal range for an LLE heat pump; therefore, if a customer purchases a variable speed heat pump, one that is low-load efficient will likely result in substantially less electricity use as it will be within the LLE temperature band during most of its heating load hours.

2.3.3. Duct Loss

Duct loss is another factor that can significantly impact system performance during the heating season. Though this is external to the equipment, it is important to consider for ducted VSHP applications. The impact of duct loss varies by region. In cold climates where homes have basements, most ductwork is typically inside the envelope, so duct loss has less impact. However, many climates generally have ductwork outside of the building envelope in the attic or crawl space; in these cases, duct loss can have a significant impact. To account for this variation, the sensitivity analysis used 30%.

2.3.4. Turndown Ratio

Lab and field testing showed that not all heat pumps tested were able to turn down effectively or to achieve the turndown ratio as reported on the NEEP database. Inconsistent reporting makes the turndown ratio difficult to use as a core metric. The turndown ratio is not a testing or reporting point required by AHRI, and NEEP provides no standardized guidelines; however, the introduction of a requirement for the CVP will ensure manufacturers report the real, achievable turn-down values within a reasonable tolerance.

Modeling results indicated that while turndown ratio can have an impact on a heat pump's performance, the impact is minimal if the heat pump turns down to between 3:1 and 5:1 output and has a COP greater than 4.5 (i.e., it is a good LLE system).

2.4. NEEA Future Modeling

NEEA is currently developing an updated energy model of low-load efficiency. This work relies on carefully screened NEEA performance data and calibration of an energy model to lab and field data. An addendum to this report with the updated energy savings estimates should be published by mid-2026.

Appendix A: BPA field test data graphs

These graphs are included as references without discussion. BPA is generating a more comprehensive report on the field data. These graphs contain filtered data of run time COP in the temperature range where LLE occurs against the normalized rated capacity of the heat pump.

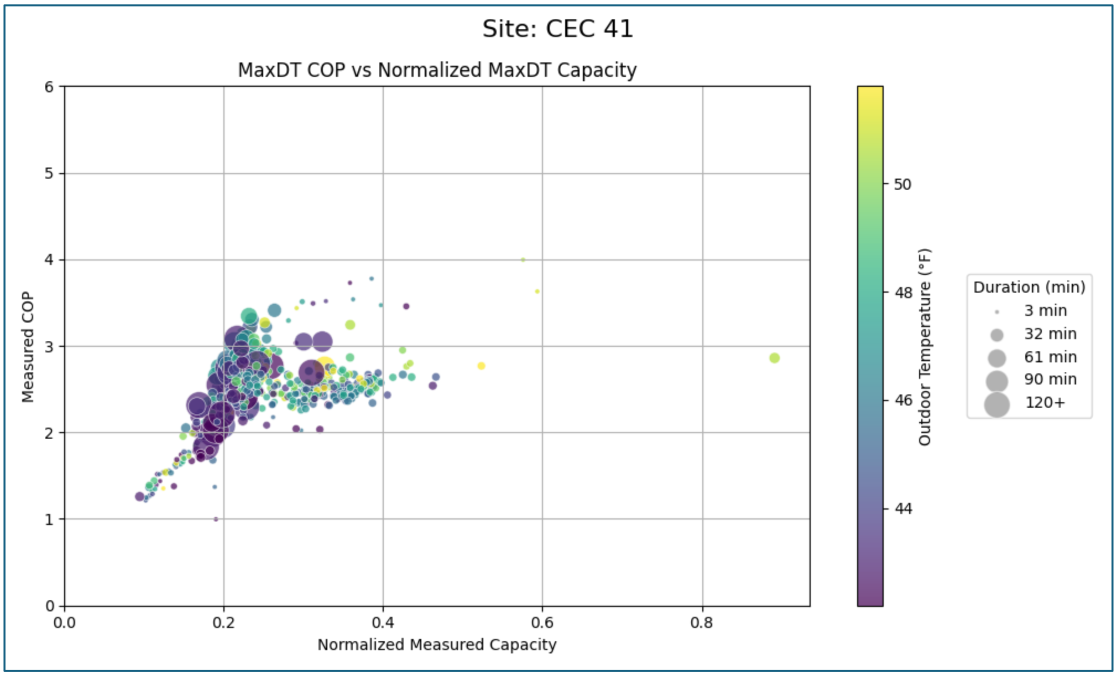

Figure 51 Field-tested heat pump CEC 41 measured COP vs. normalized measured capacity for outdoor air temperature 42°F – 52°F.

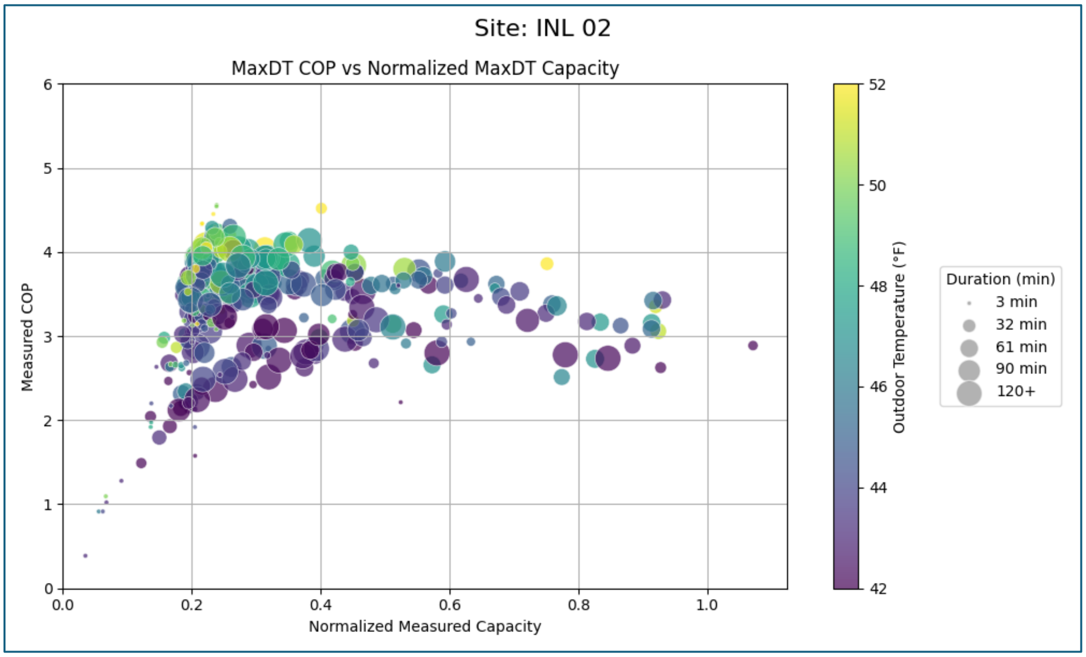

Figure 52 Field-tested heat pump INL 02 measured COP vs. normalized measured capacity for outdoor air temperature 42°F – 52°F.

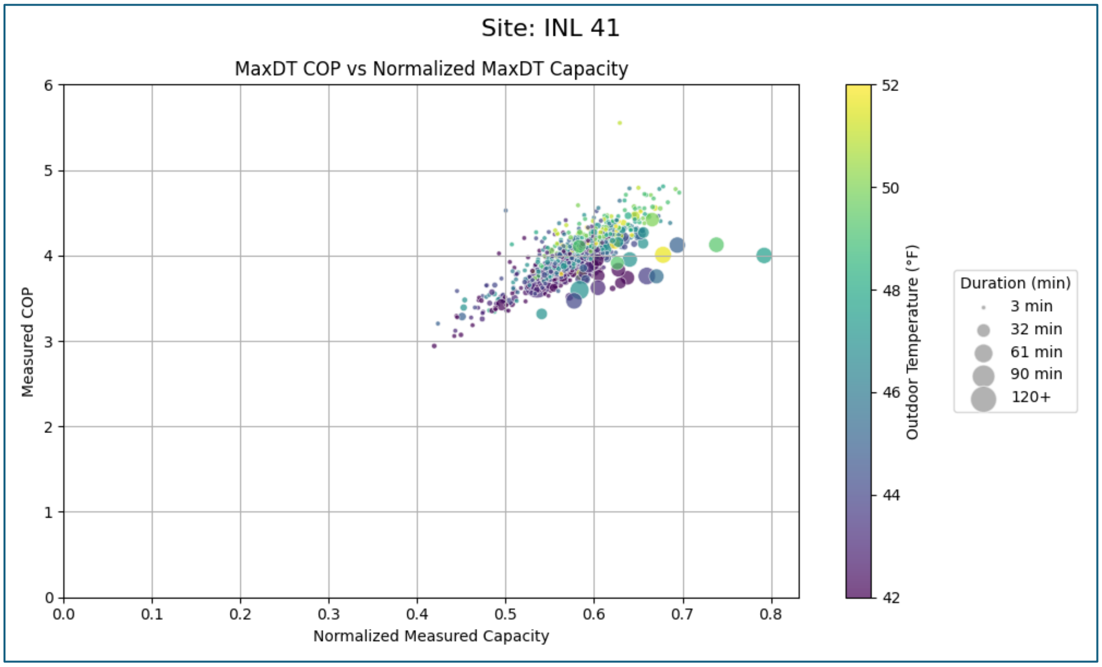

Figure 53 Field-tested heat pump INL 41 measured COP vs. normalized measured capacity for outdoor air temperature 42°F – 52°F.

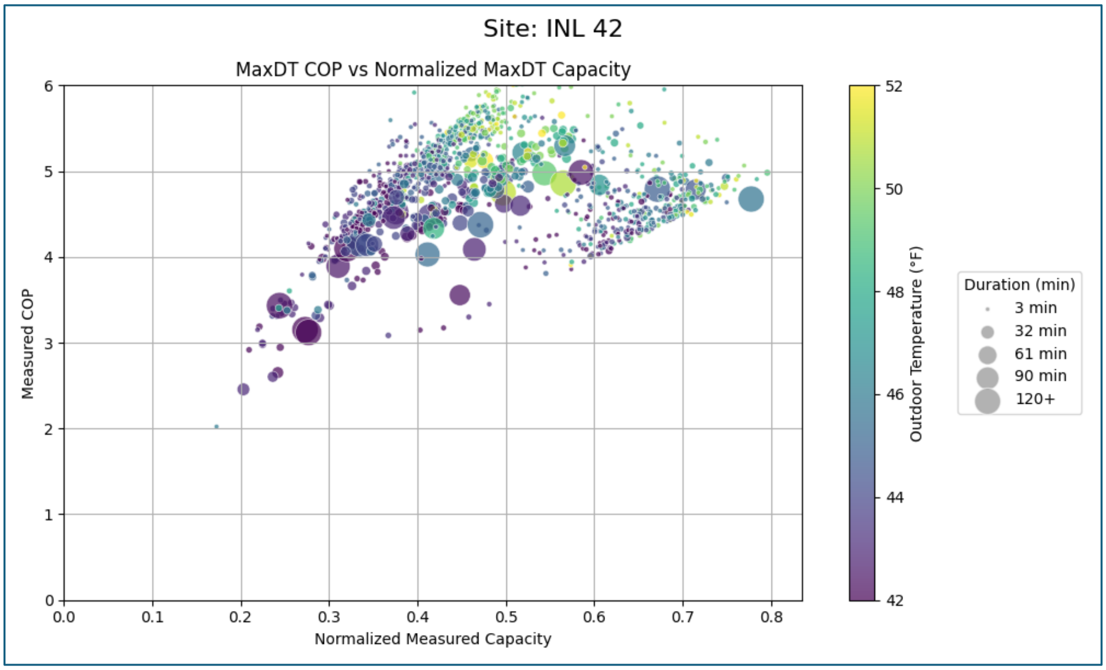

Figure 54 Field-tested heat pump INL 42 measured COP vs. normalized measured capacity for outdoor air temperature 42°F – 52°F.

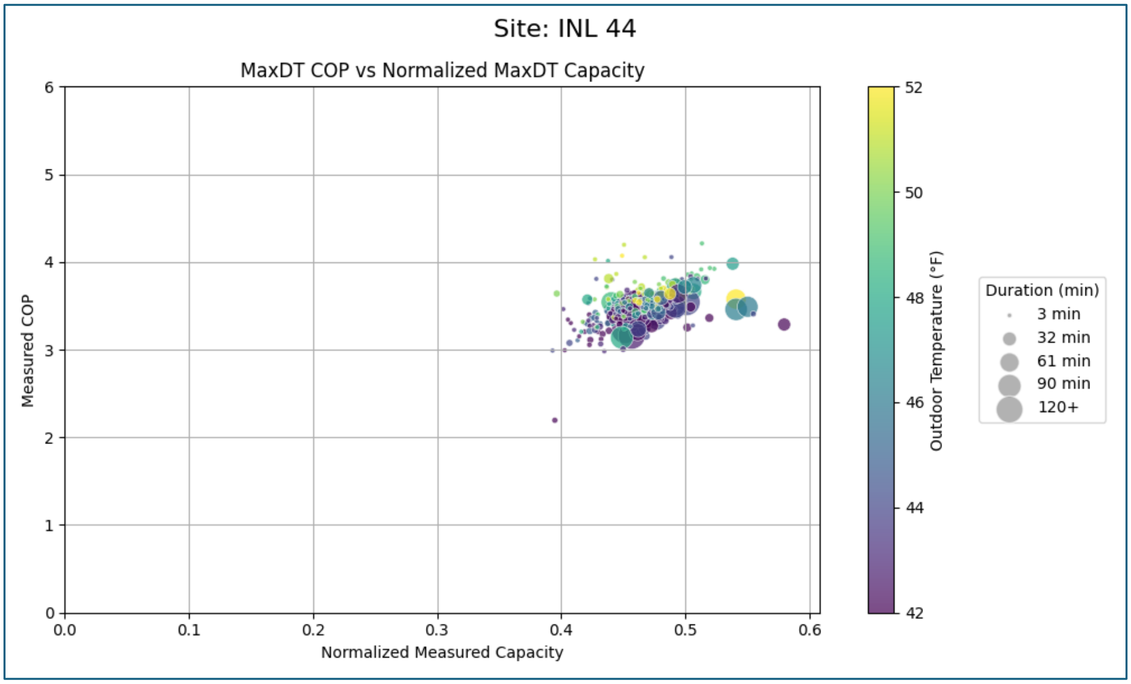

Figure 55 Field-tested heat pump INL 44 measured COP vs. normalized measured capacity for outdoor air temperature 42°F – 52°F.

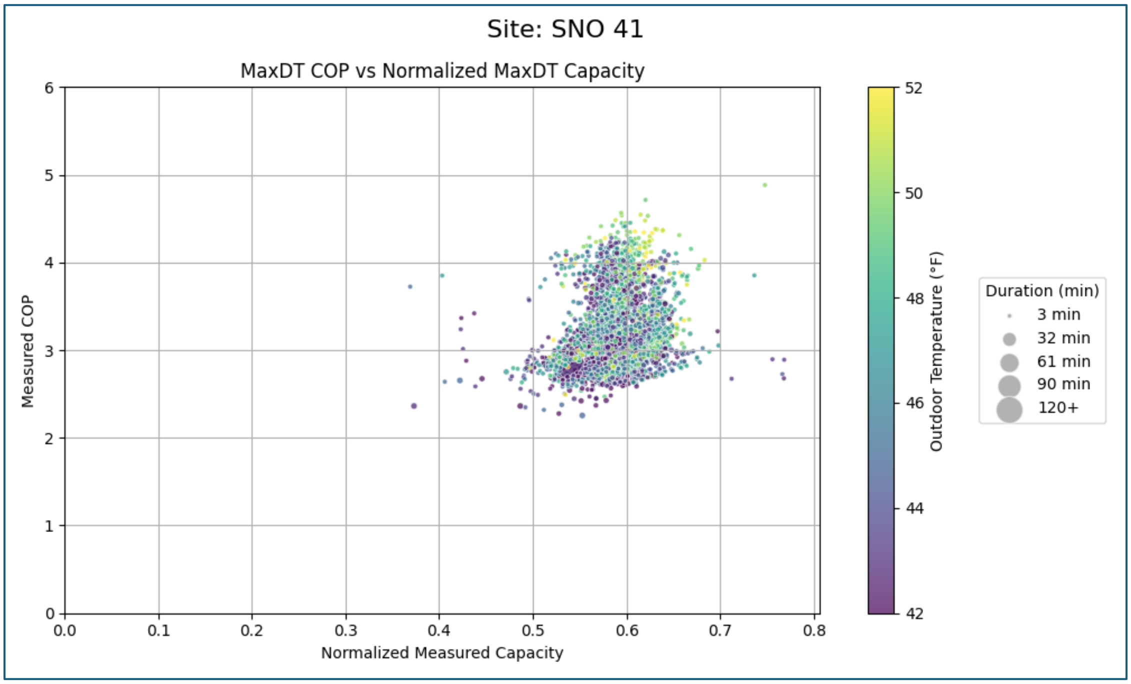

Figure 56 Field-tested heat pump SNO 41 measured COP vs. normalized measured capacity for outdoor air temperature 42°F – 52°F.

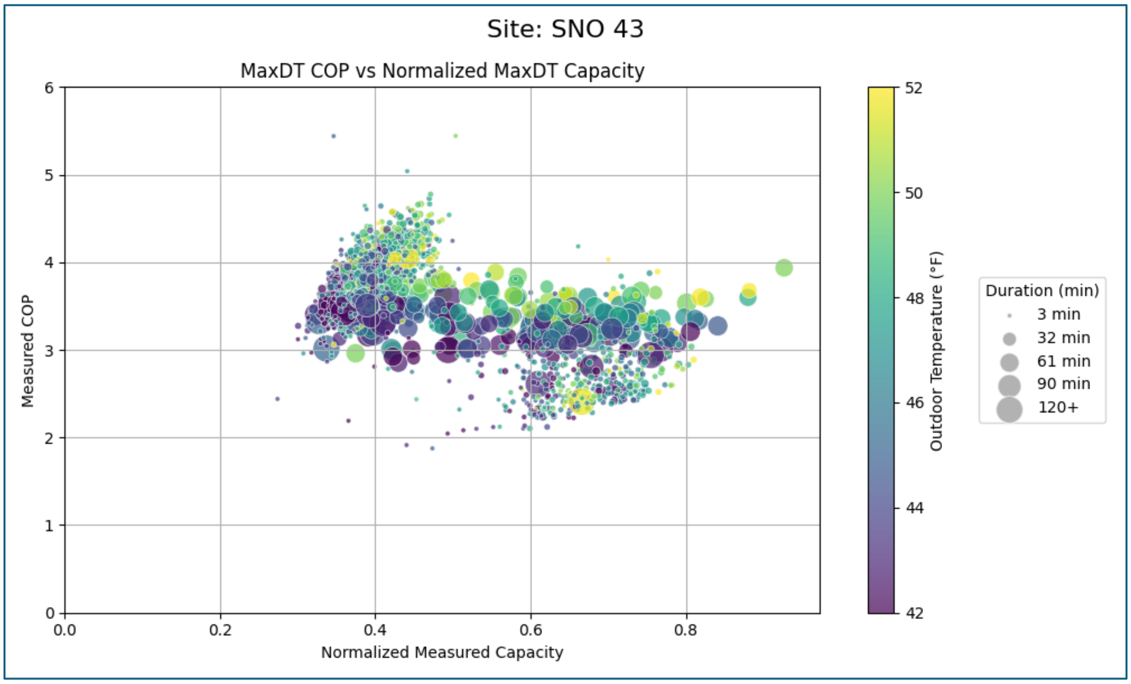

Figure 57 Field-tested heat pump SNO 43 measured COP vs. normalized measured capacity for outdoor air temperature 42°F – 52°F.

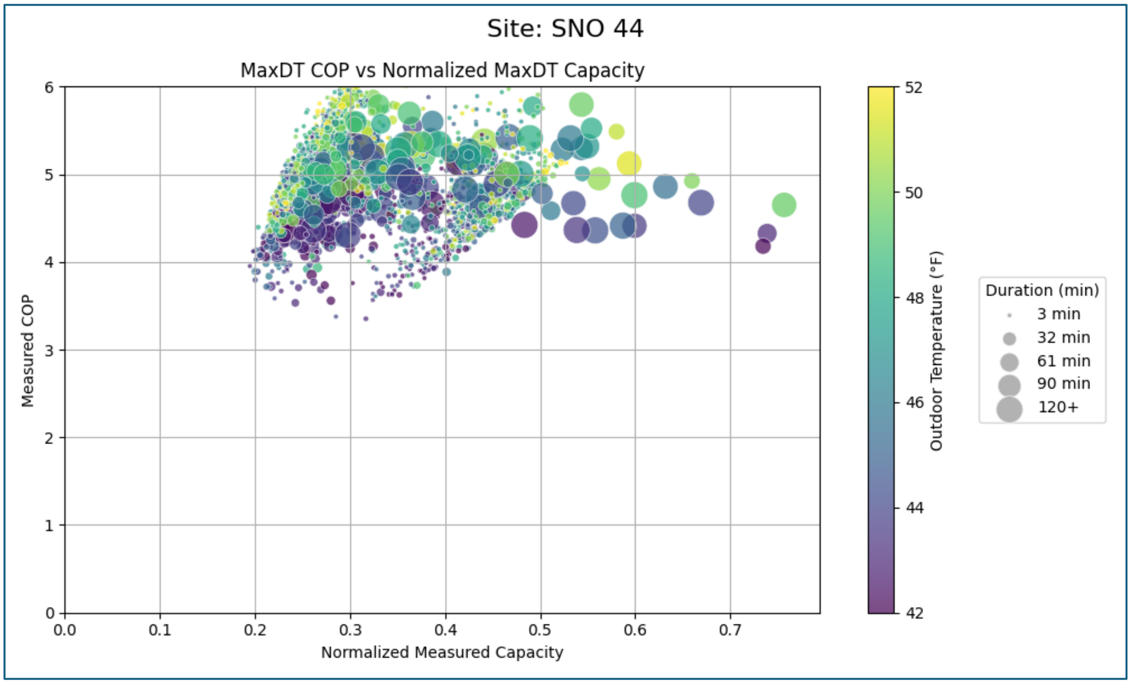

Figure 58 Field-tested heat pump SNO 44 measured COP vs. normalized measured capacity for outdoor air temperature 42°F – 52°F.

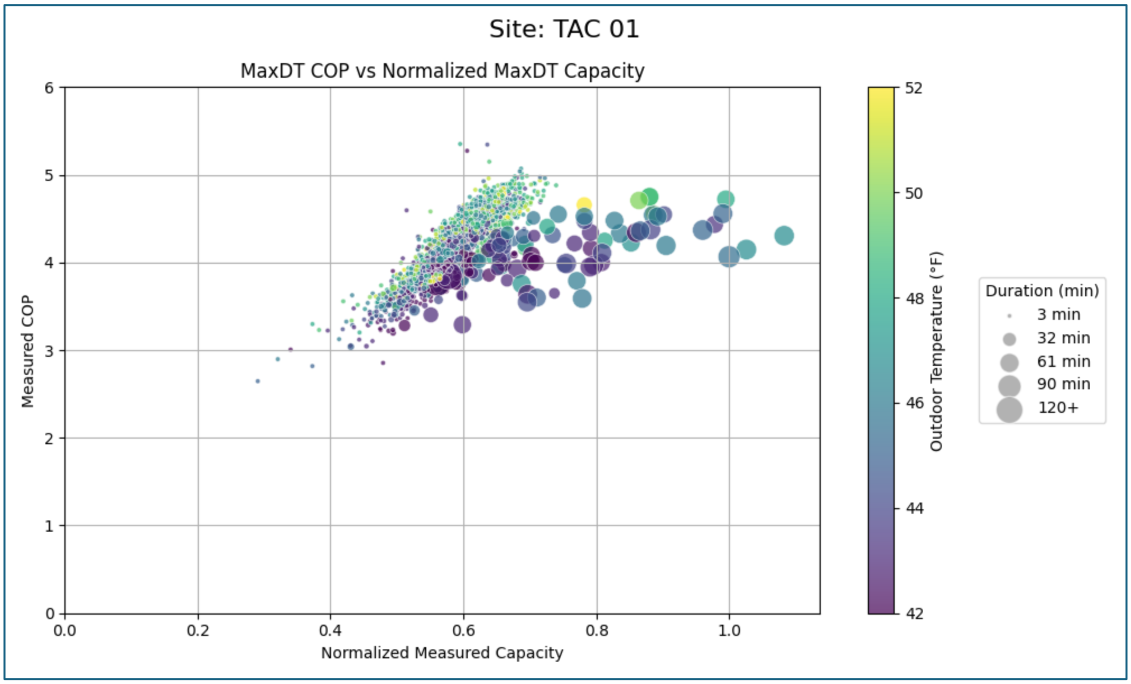

Figure 59 Field-tested heat pump TAC 01 measured COP vs. normalized measured capacity for outdoor air temperature 42°F – 52°F.

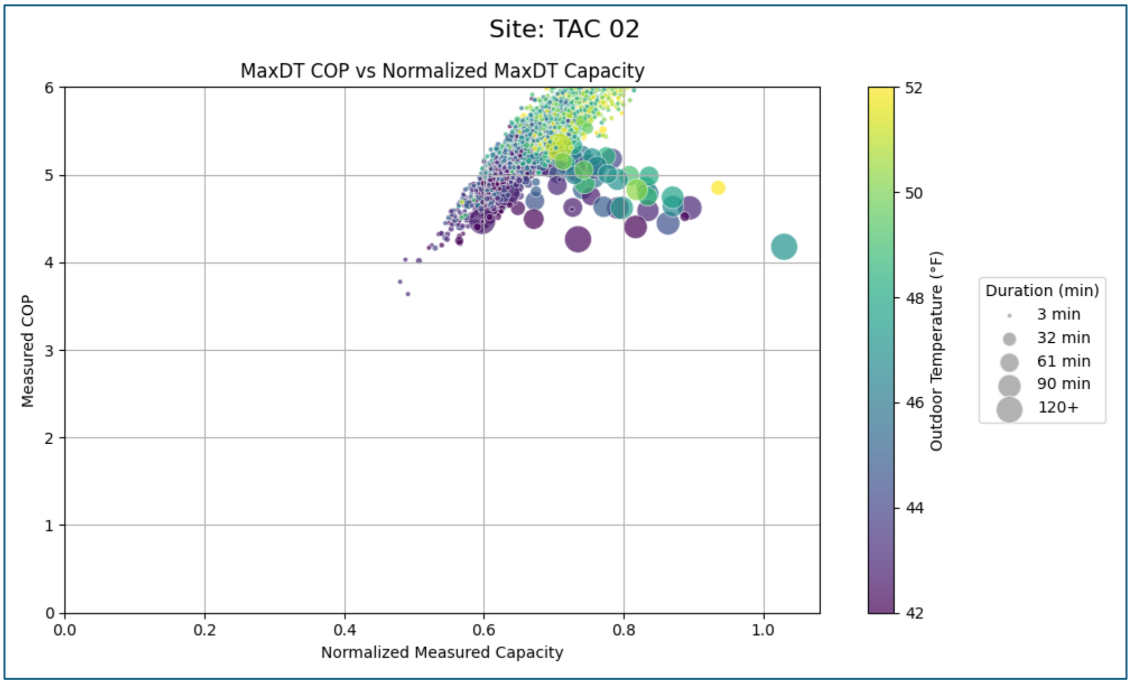

Figure 60 Field-tested heat pump TAC 02 measured COP vs. normalized measured capacity for outdoor air temperature 42°F – 52°F.

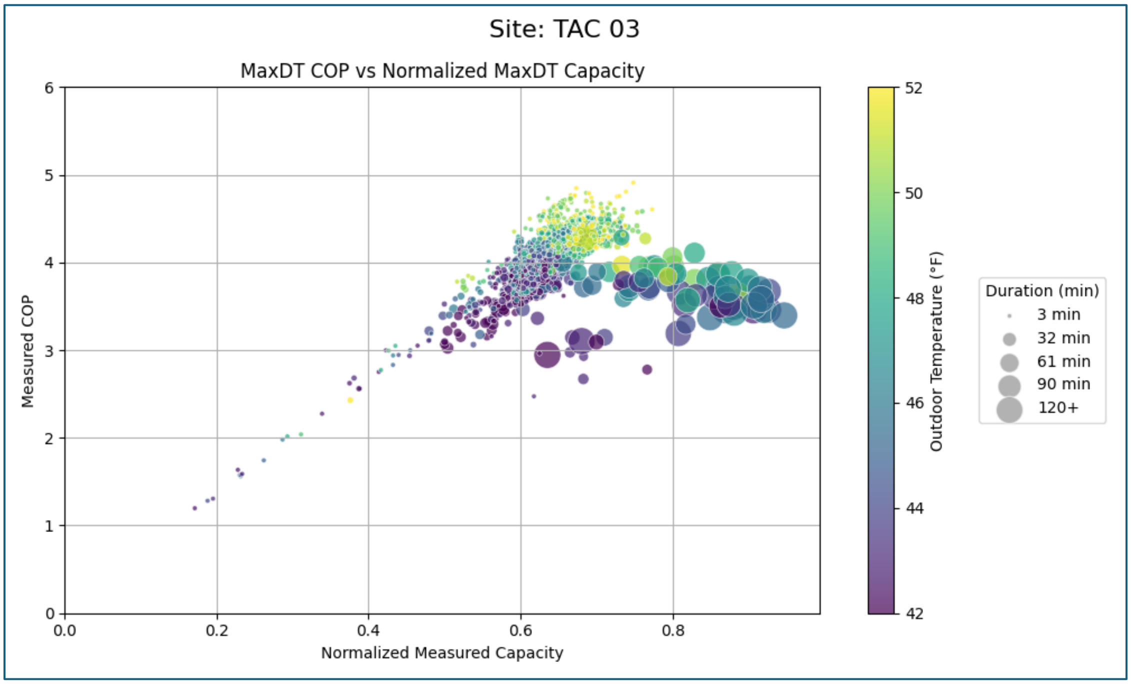

Figure 61 Field-tested heat pump TAC 03 measured COP vs. normalized measured capacity for outdoor air temperature 42°F – 52°F.

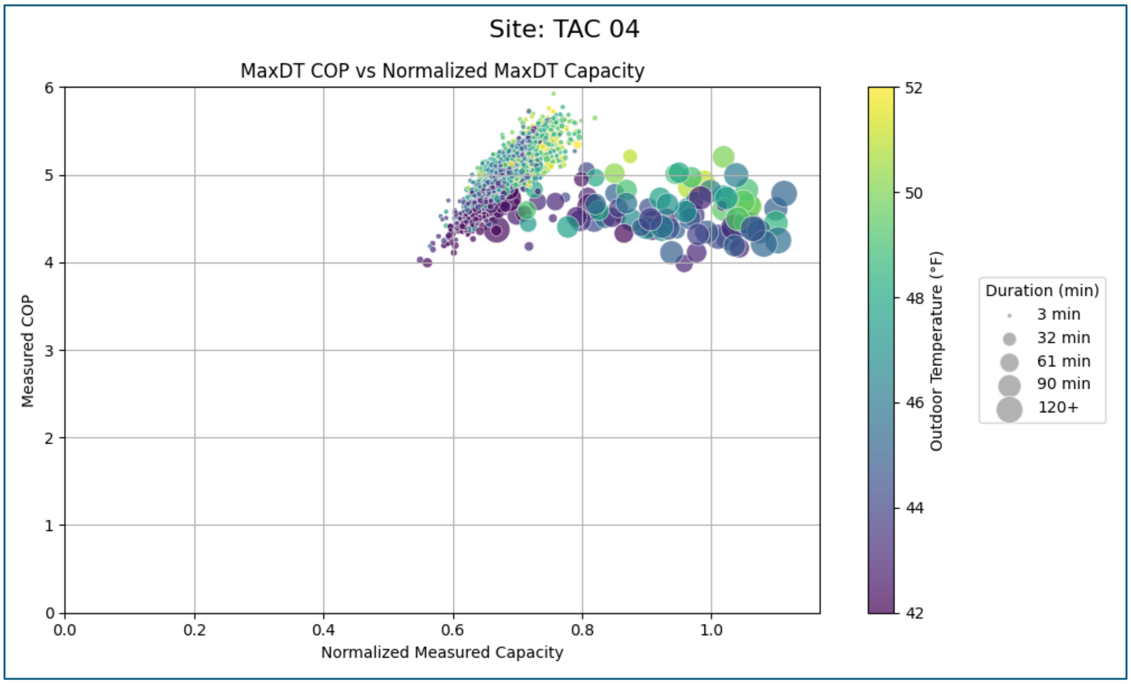

Figure 62 Field-tested heat pump TAC 04 measured COP vs. normalized measured capacity for outdoor air temperature 42°F – 52°F.

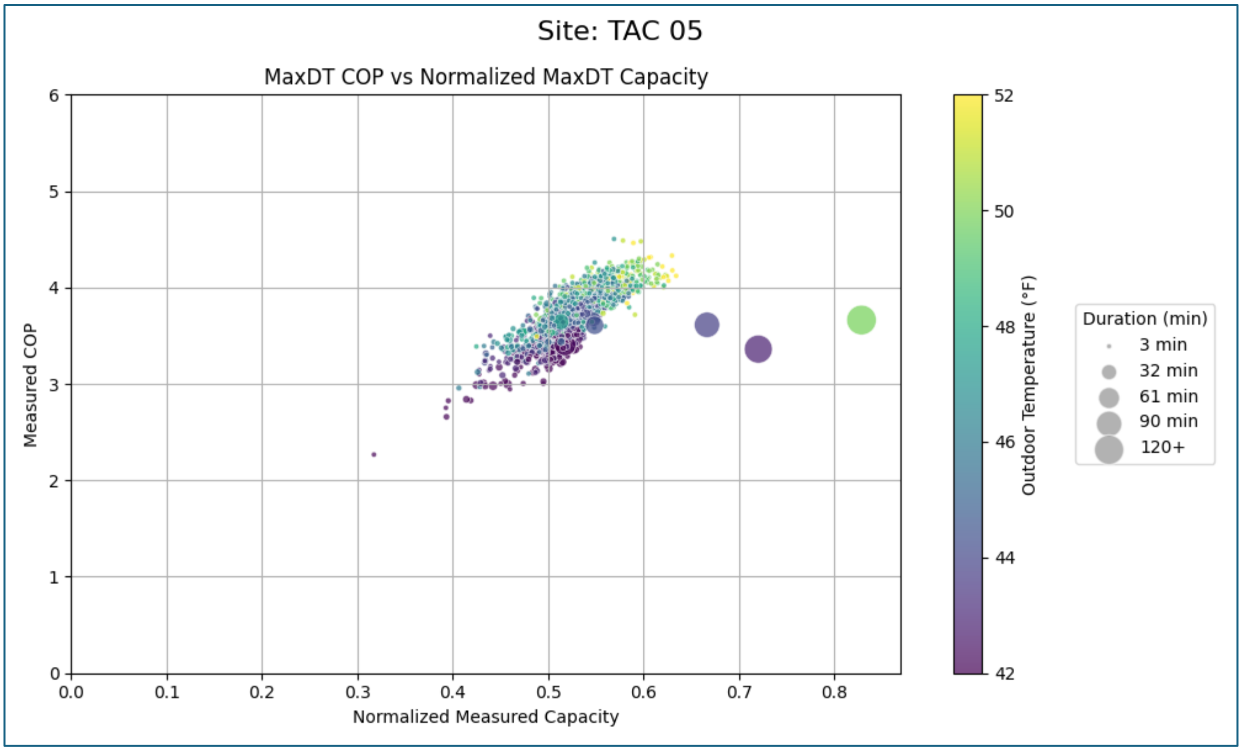

Figure 63 Field-tested heat pump TAC 05 measured COP vs. normalized measured capacity for outdoor air temperature 42°F – 52°F.

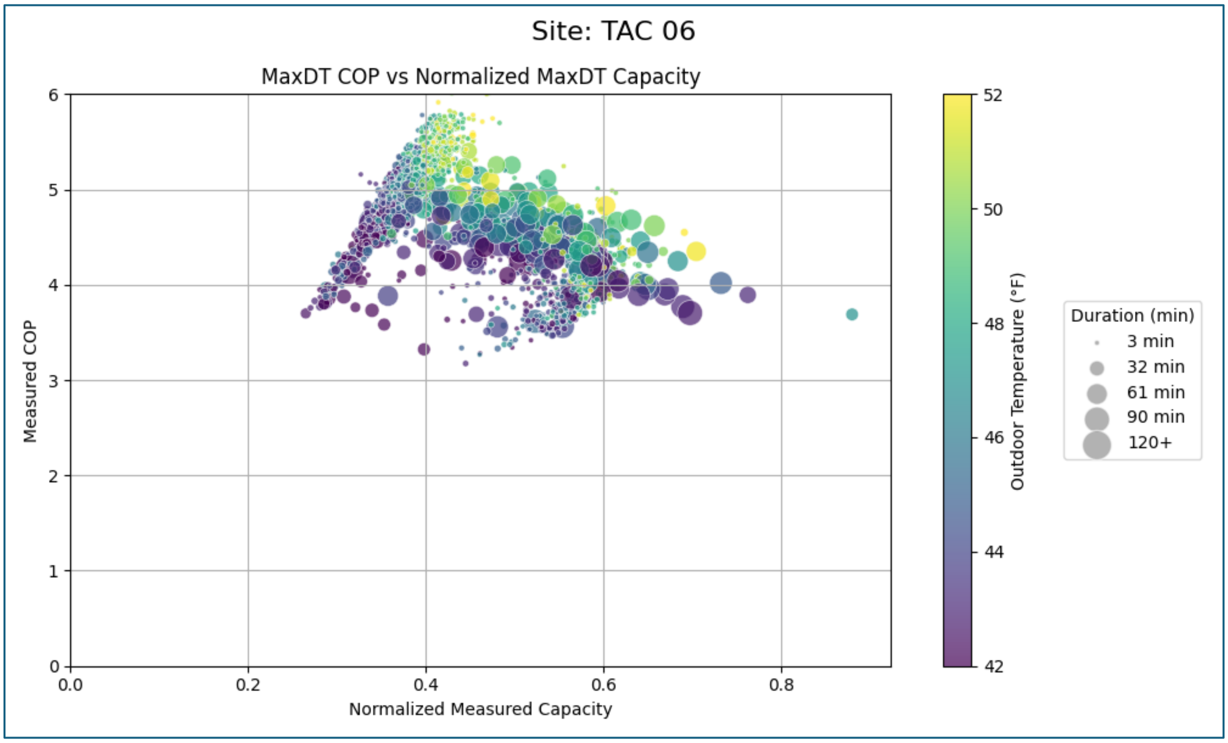

Figure 64 Field-tested heat pump TAC 06 measured COP vs. normalized measured capacity for outdoor air temperature 42°F – 52°F.

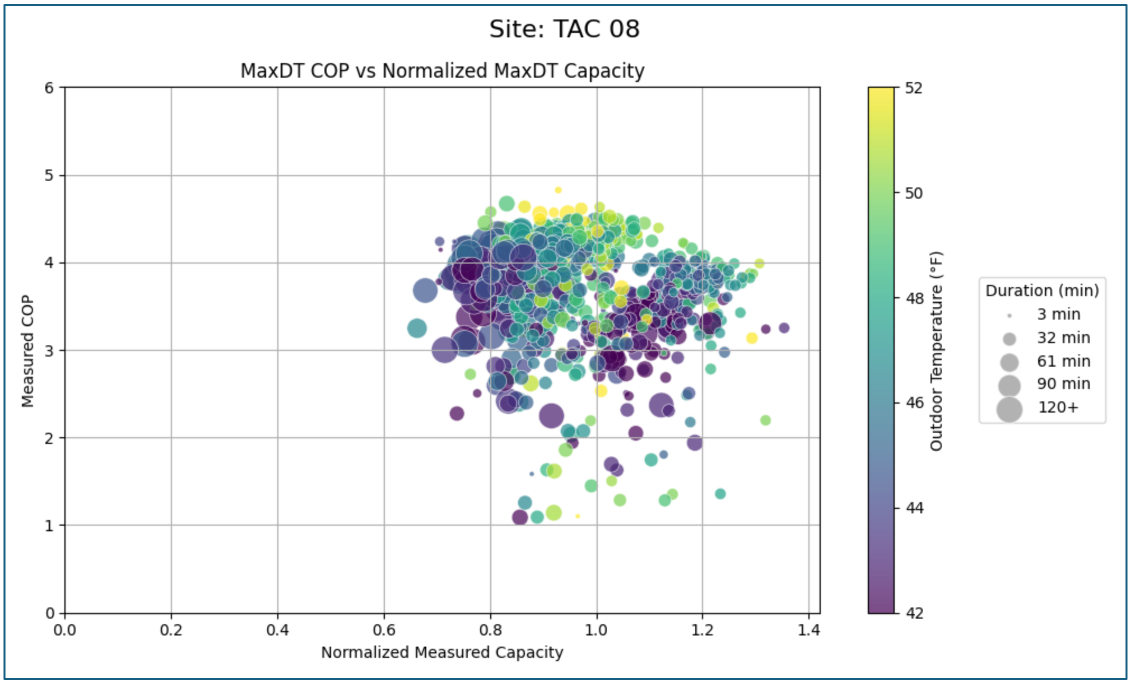

Figure 65 Field-tested heat pump TAC 08 measured COP vs. normalized measured capacity for outdoor air temperature 42°F – 52°F.

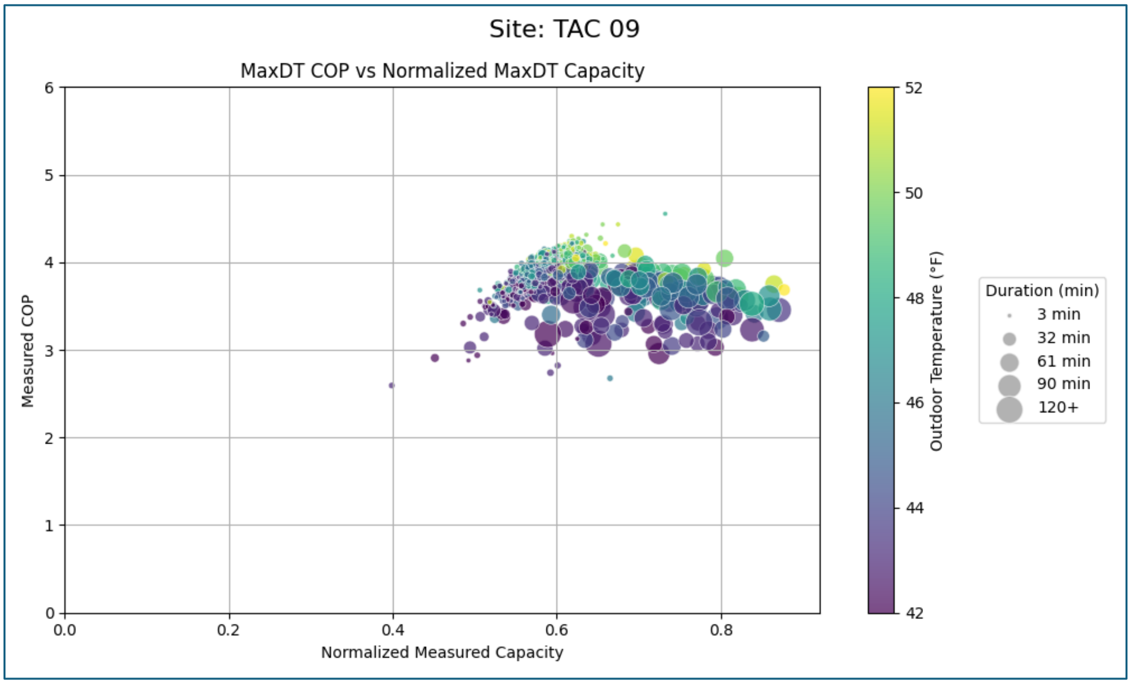

Figure 66 Field-tested heat pump TAC 09 measured COP vs. normalized measured capacity for outdoor air temperature 42°F – 52°F.

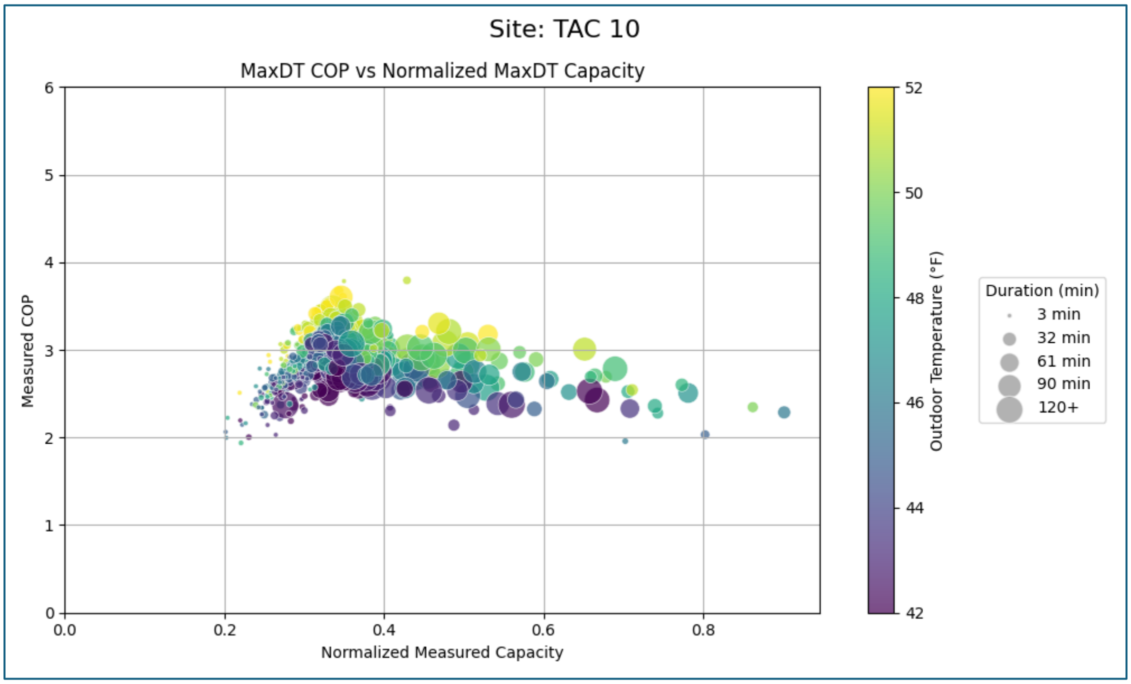

Figure 67 Field-tested heat pump TAC 10 measured COP vs. normalized measured capacity for outdoor air temperature 42°F – 52°F.

Appendix B: Rating Representativeness Project data graphs

These graphs are included as references without discussion as other presentations (e.g., NEEA Product Council, Purdue University, NEEP Representativeness study) provide detailed discussions.

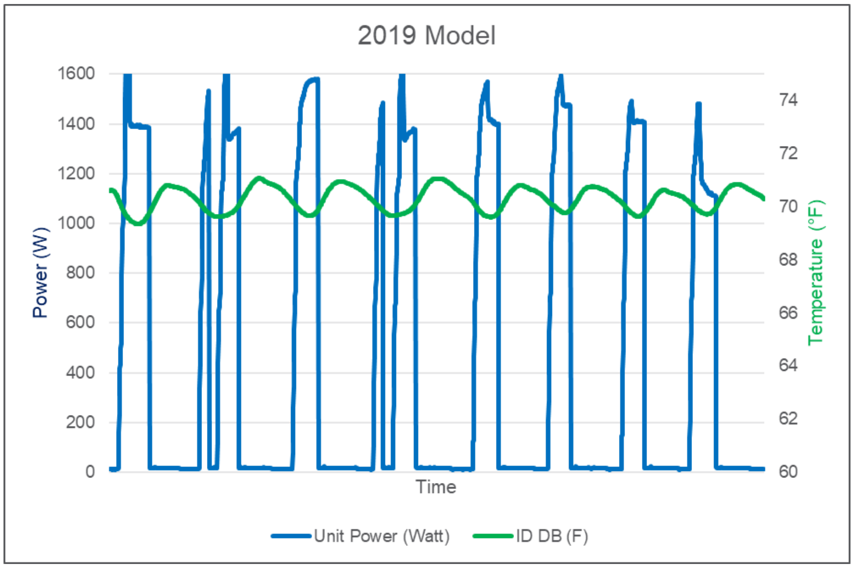

Figure 68: Load-based testing of ductless unit when Tamb = 47°F

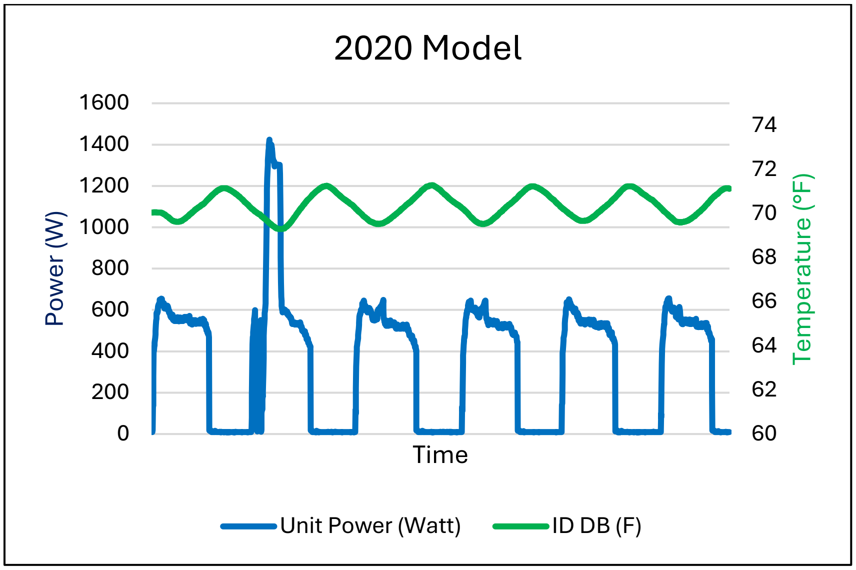

Figure 69: Load-based testing of ductless unit when Tamb = 47°F (same make and model as in Figure 68, but post-update to control algorithm in new model year)

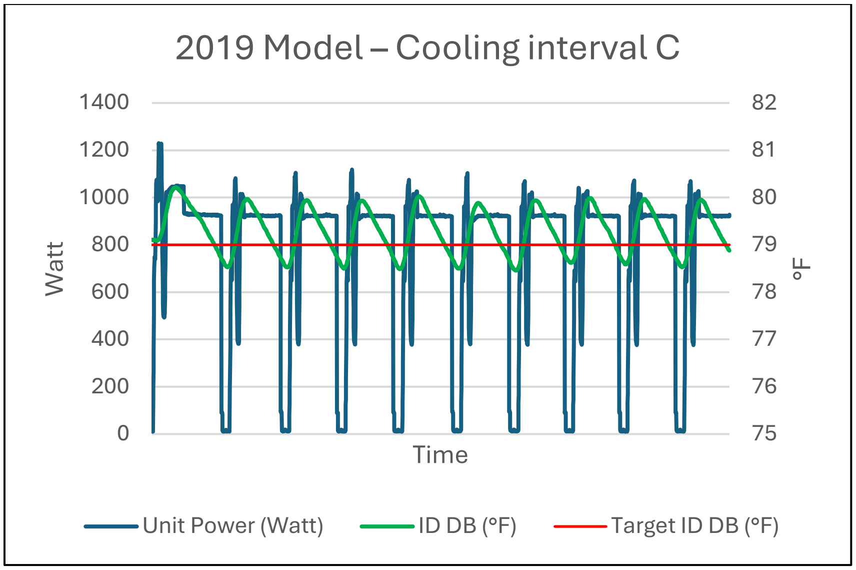

Figure 70 Load based testing of ductless unit when Tamb = 90F

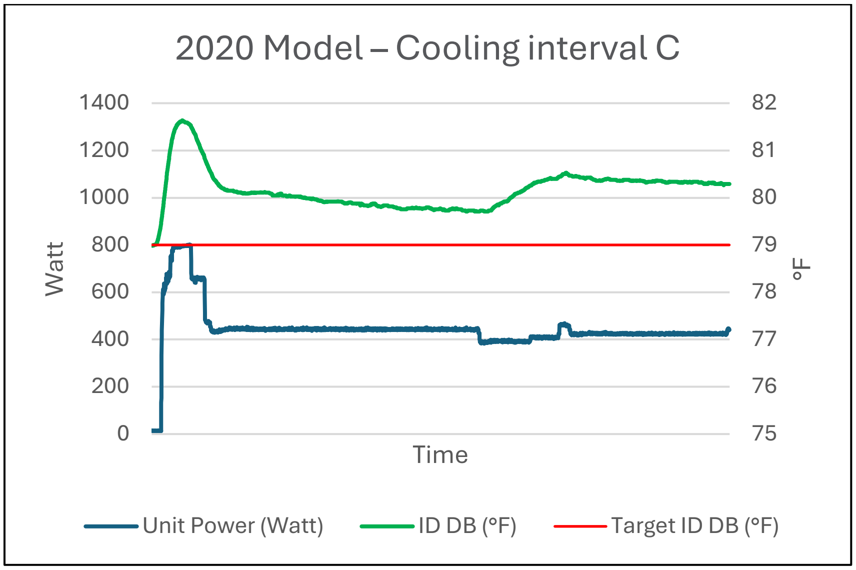

Figure 71 Load based testing of ductless unit when Tamb = 90F (same make and model as Figure 4-3, but post update to control algorithm in new model year)

The following six figures display the same information format shown in Appendix A, but for data collected on the six systems tested in the Rating Representativeness study.

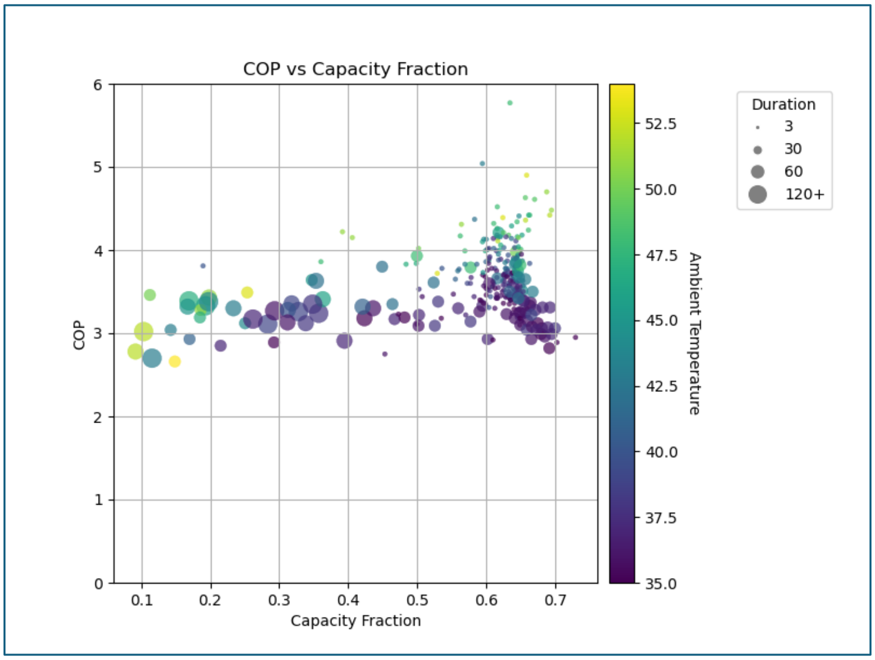

Figure 72 Rating Representativeness field study heat pump Unit A measured COP vs. normalized measured capacity for outdoor air temperature 35°F – 55°F.

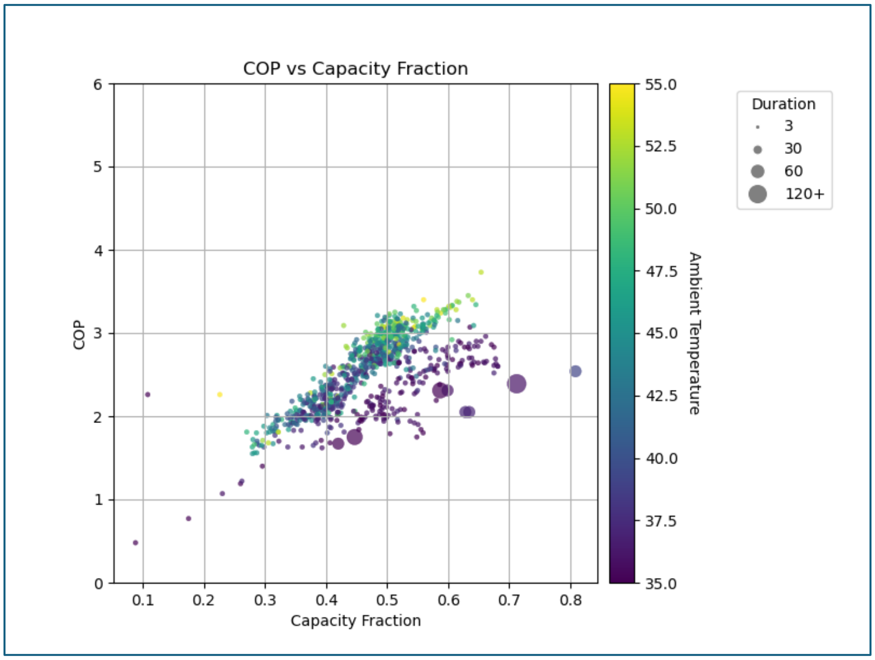

Figure 73 Rating Representativeness field study heat pump Unit B measured COP vs. normalized measured capacity for outdoor air temperature 35°F – 55°F.

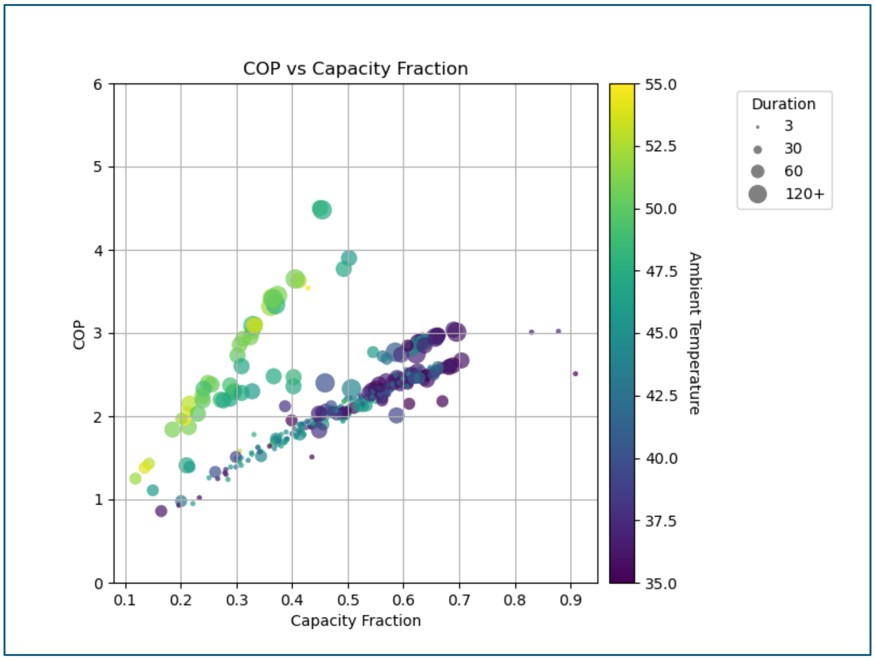

Figure 74 Rating Representativeness field study heat pump Unit C measured COP vs. normalized measured capacity for outdoor air temperature 35°F – 55°F.

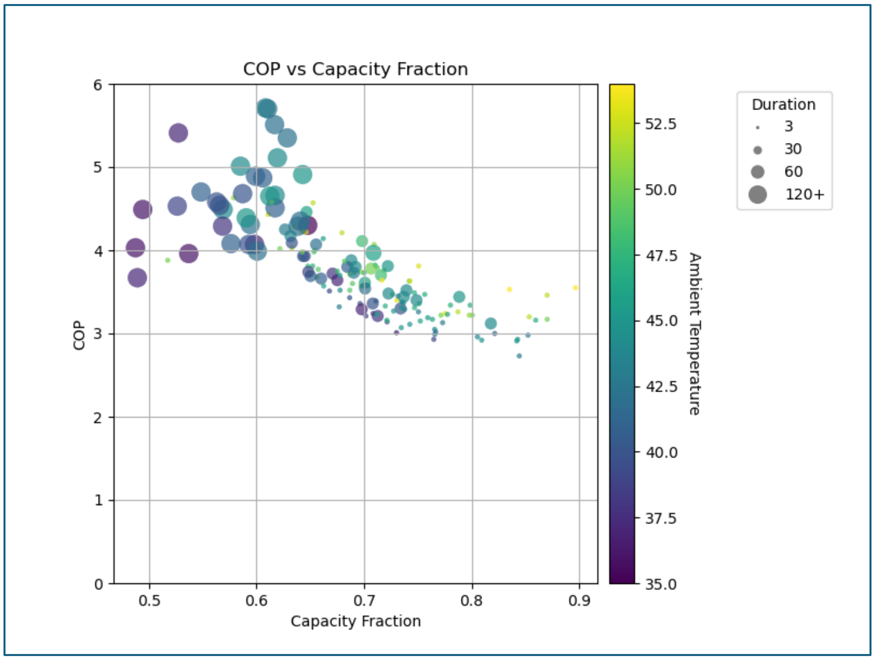

Figure 75 Rating Representativeness field study heat pump Unit D measured COP vs. normalized measured capacity for outdoor air temperature 35°F – 55°F.

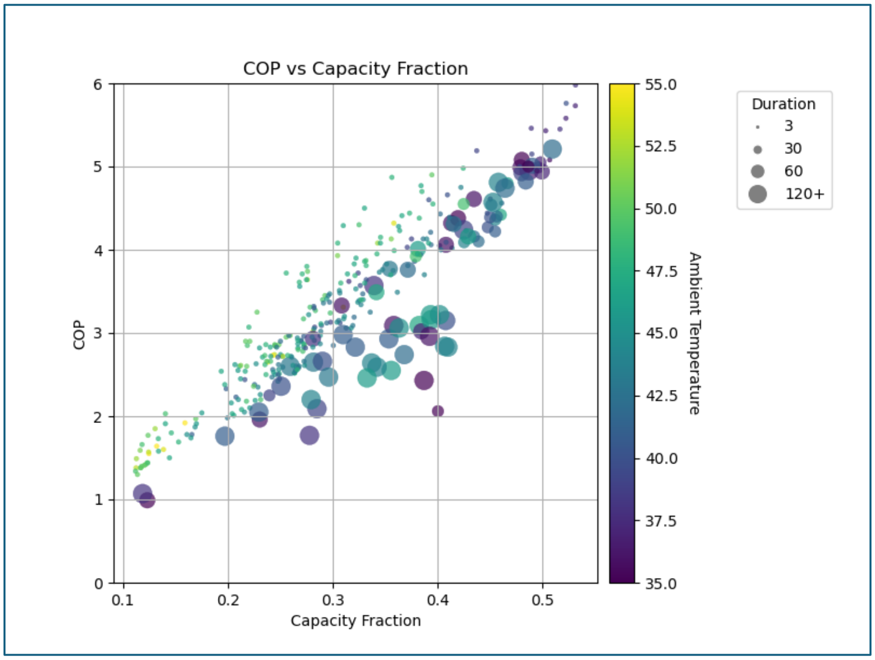

Figure 76 Rating Representativeness field study heat pump Unit E measured COP vs. normalized measured capacity for outdoor air temperature 35°F – 55°F.

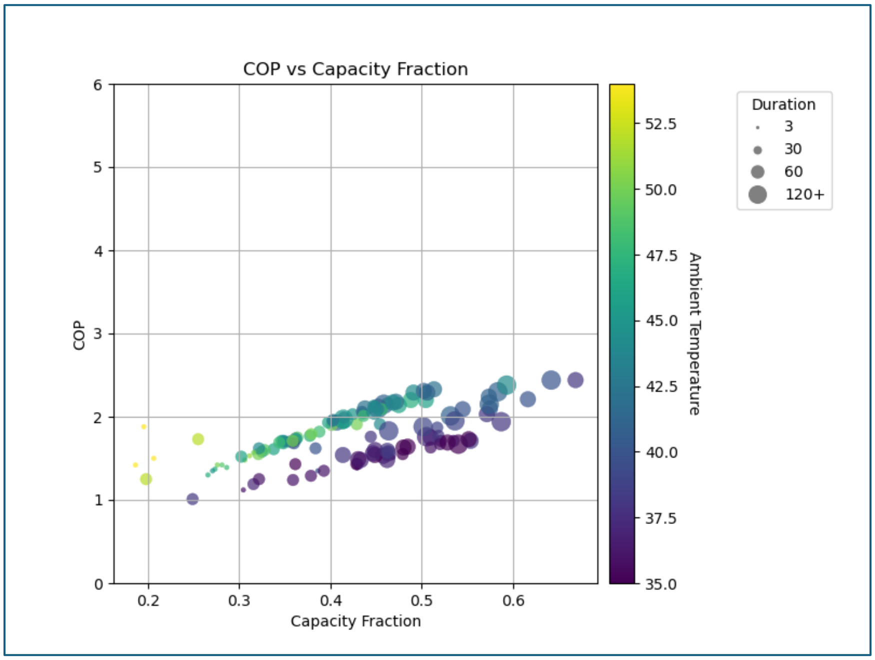

Figure 77 Rating Representativeness field study heat pump Unit F measured COP vs. normalized measured capacity for outdoor air temperature 35°F – 55°F.

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