Low-Load Efficient Heat Pumps
A field data and product teardown exploration of why some heat pumps excel under part-load conditions

Christopher Dymond, Northwest Energy Efficiency Alliance
Cory Luker, Cadeo Group, LLC.
Ben Schoenbauer, Center for Energy and Environment
John Bush and Joe Vadder, OTS Energy, LLC
Robert Weber, US Department of Energy

ABSTRACT

Current metrics (HSPF2 and SEER2) for heat pumps do not provide sufficient differentiation to facilitate application-specific optimization. This research assesses a new metric and savings opportunity to differentiate heat pumps ideal for fuel systems and in mild or marine climates. To better identify heat pumps that are efficient under these low-load conditions—termed Low-Load Efficient (LLE) heat pumps—this study employs a comprehensive approach that integrates field observations, laboratory tests, and detailed equipment data. The approach uses high-resolution field performance data to compare different machines' energy consumption with different minimum output COP values. The field data contains a mixture of equipment types and climate conditions from the Northwest and Midwest. The equipment data relies on readily available extended product performance information reported by the manufacturers. In addition, the research includes evaluation of the hardware features that are necessary to enable superior low-load efficiency**.**

The findings from this work improves our understanding of what factors contributing to LLE, as well as informs how to choose the right heat pump for a specific climate or application. These results underscore the importance of control and transient behavior, factors which cannot be captured in a single, steady-state test condition. The practical application of this information can guide equipment choices where the heat pump operates most of the time between 35 °F and 55 °F. This is especially valuable for heat pumps with fossil fuel backup or those located in mild or marine climates.

Introduction

NEEA has identified low-load efficient (LLE) heat pumps as a strong product differentiator capable of driving cost-effective savings. This work began in 2020 in collaboration with the Center for Energy and Environment on a project which compared different archetypes of heat pumps that represent a range of capacity and coefficient of performance (COP) vs 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 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 Canadian Standards Association interim CSA EXP:07 test procedure[1] revealed the significant impact on an annualized rating metric (SCOP) when the equipment was tested under its own native controls and under heating and cooling loads commensurate with outdoor test chamber conditions. Heat pumps with superior part load efficiency were found to have controls which modulate compressor and fans to minimum necessary output without wild cycling behaviors (Harley 2022).

Figure 1 illustrates the operation 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. Superimposed on this performance graph are the weighted load hours in a very cold (Bozeman, Montana) climate. Figure 1 shows that even in a cold climate, there is a significant portion of the annual load where the heat pump operates at reduced fan and compressor speed, where efficiency is significantly higher. During hours when the house load is below the minimum operating capacity of the heat pump, it will need to cycle on and off, but do so at a higher efficiency.

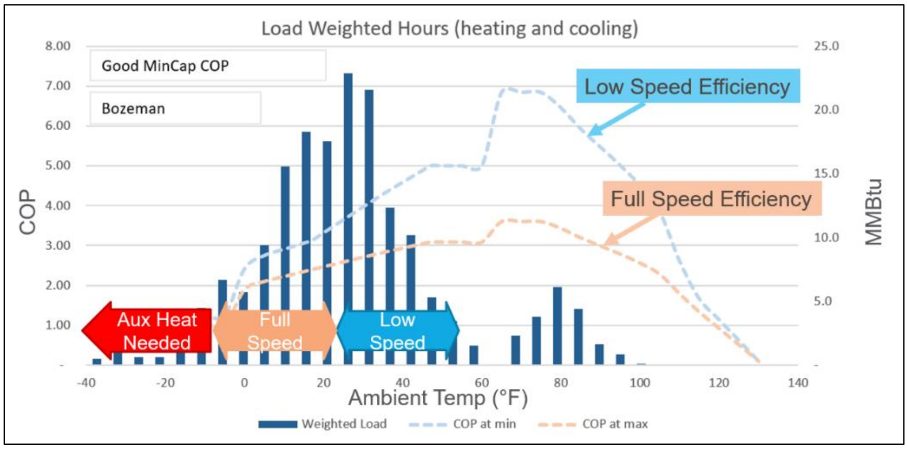

Figure 1 – Heat pump efficiency at both low and full speed and annual load vs ambient temperature.

NEEA has defined LLE heat pumps as with a COP at its minimum output capacity at 47 °F greater than or equal to 4.5. This COP data is readily available on the NEEP cold climate air source heat pump product list as the “COPMin47°F” value.[2] This value represents the COP of a heat pump at an outdoor air temperature of 47 °F while the heat pump operates at low compressor speed. For a single speed heat pump this value is synonymous with maximum capacity, but for two speed or variable speed heat pumps this speed as specified by the manufacturer at which the unit operates at low load test conditions. There may be differences

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

[2] In this paper we refer to this term as MinCapCOP47 to avoid any confusion that this is the COP at minimum capacity and not the minimum COP at 47°F.

between the NEEP MinCapCOP47 values and the AHRI test condition $H1_{Low}$ values, as manufacturers are not required to publish $H1_{Low}$ data. However, conversations with manufacturers suggest that such differences are not expected. NEEA has defined an LLE heat pump as any heat pump with a MinCapCOP47 not less than 4.5, a threshold that roughly delineates the top third of all heat pumps listed in the NEEP database.

Figure 2 is a graph of HSPF2 versus a MinCapCOP47 values for all M1 rated products on the NEEP database. The graph shows that the MinCapCOP47 can vary significantly for a given HSPF2 value. A product 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 the majority of the time in most climates.

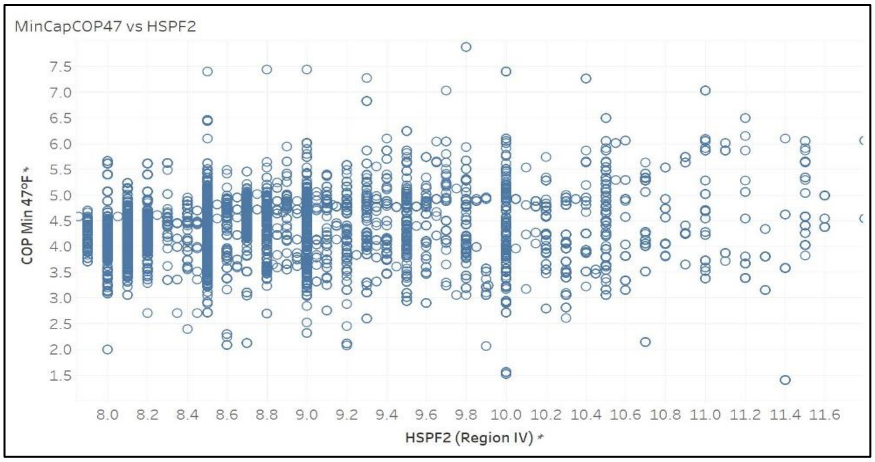

Figure 2 – COPMin47°F vs HSPF2 (source: NEEP ccASHP Database).

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 versus those with low values. Figure 3 shows 2021 wholesale price data of 11 different ducted heat pumps of the same rated capacity and comparable HSPF values. 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 than efficiency.

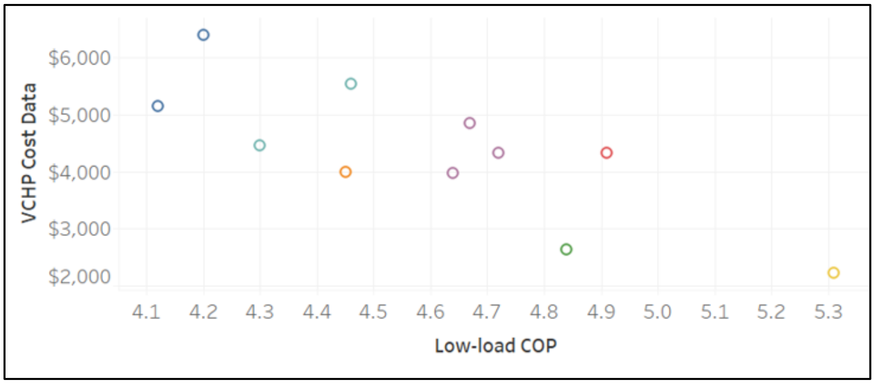

Figure 3 – Wholesale equipment cost of similar heat pumps vs MinCapCOP47.

Previous work (Smith, 2022) found evidence that MinCapCOP47 (based on AHRI 210/240 test condition $H1_{low}$ could be a strong performance indicator but several remaining questions (Table 1) need to be addressed before we can confidently state that the efficiency gains are real. The following sections seek to answer these questions. While the focus of this is on performance during the heating seasons, it should be noted that the same performance gains probably exist for cooling performance by using a AHRI 201/240 test condition C_{Low} values that reflects part load efficiency during low-cooling load hours.

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

Metrics Evaluation

Is $H1_{low}$ (i.e. MinCapCOP47) a good indicator of part load efficiency? The AHRI test condition $H1_{low}$ measures capacity and power draw when the heat pump is operating at its minimum rated output and the outdoor test chamber is at 47 °F. The resulting COP from these measurements should be the same as the MinCapCOP47. To establish if the AHRI test condition $H1_{low}$ (i.e. MinCapCOP47) provides a good representation of part load efficiency, we conducted phone interviews of engineers and product managers from six major US heat pump equipment manufacturers. All companies confirmed our understanding that the COP generated from the $H1_{low}$ test condition was a reasonable indicator of part load efficiency. Two manufacturers added that the values between companies may not be directly comparable because the products may have different turndown ratios[3]. For example, a heat pump with a capacity that is four times the minimum capacity may not be quantifying the same thing as a heat pump which has a maximum capacity that is only twice that of its minimum capacity. The potential impact of turn down ratio is interesting on ensuring apples to apples comparability between products should be addressed in future work.

The CEE Study (Smith, 2022) revealed that the sensitivity of annual performance to turn down ratio is only significant when the part load efficiency values are low. Equipment with good MinCapCOP47 values (i.e. above 4.5) are not as sensitive to turn down ratio because the short cycling behavior in a properly sized variable speed heat pump is very narrow when the loads are small and when the heat pump does cycle on and off, it does so with high efficiency.

One potential way to reconcile values at different turn down ratios would be to develop a normalized version of MinCapCOP47 to reflect the systems' performance under a consistent capacity rating. This could be accomplished using information available from $H1_{low}$ and $H1_{high}$ measurements and reasonable assumptions about cyclic degradation. The validity of any adjusted metric should be tested against lab or in-field performance. The other approach would be to request MinCapCOP47 data be provided at a consistent turn down ratio (e.g. a rated to minimum ratio of 3:1).

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[3] turndown ratio = Rated capacity at 47 divided by minimum capacity.

While tempting to draw the conclusion that $H1_{low}$ is an ideal indicator of part load efficiency, it is only a single test point measure and may not reflect the full range of part load efficiency that can occur from as low as 35 °F to as high as 60 °F. Because a properly sized variable speed heat pump should have most of its part load efficiency gains occur between 35 °F and 55°F, we believe $H1_{low}$ is a reasonable single test point of part load performance. Figure 4 below illustrates that for many US cities the fraction of the annual load is significant within this temperature range.

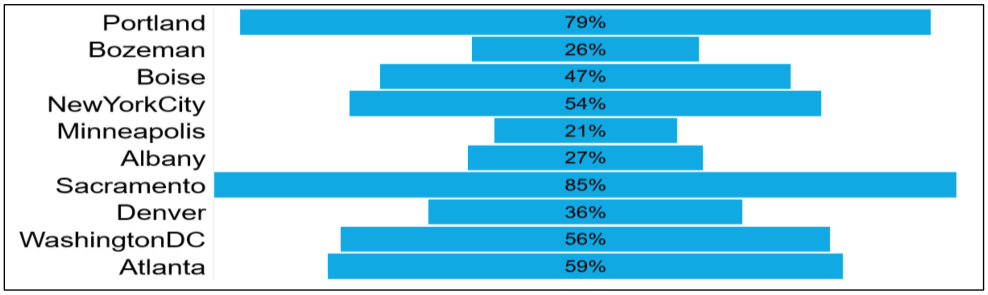

Figure 4 – Fraction of load that occurs when outdoor temperature is between 35 °F and 55 °F.

Is the impact of MinCapCOP47 adequately captured by HSPF2? If MinCapCOP47°F is already reflected in the seasonal heating rating then it might not be needed, or only be meaningful for specific applications or climates where equipment operates significantly more often in part load operation than in full load operation. To understand the impact of MinCapCOP47°F has on HSPF2 values we used the AHRI online calculation tool for HSPF2 using a range of $H1_{low}$ values.

Table 2 presents a sensitivity analysis of $H1_{low}$ measurements using the AHRI HSPF2 calculator.[4] The heating capacity at the $H1_{low}$ condition was held constant and the $H1_{low}$ power consumption was changed to produce a range of COP values consistent with values found in the NEEP database. The sensitivity analysis shows that $H1_{low}$ values have a limited impact of the HSPF2 rating. The result shows that increasing MinCapCOP47F from 3.78 to 4.54 (20% increase) only improves HSPF2 by 2%. Previously mentioned modeling work found that such an increase in part load efficiency would result in result in seasonal performance gains 3-4 times this amount in IECC climate zone 4 and 4-7 times this amount in mild climates or when the heat pump is not used during cold hours such as in a dual-fuel furnace configuration.

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

Test	Capacity @ 47°F min ($H1_{low}$) (Btu/hr)	Power Consumption @ 47°F min ($H1_{low}$) (Watts)	MinCap COP47°F	% Difference MinCapCOP47 °F Relative to Baseline	HSPF2	Relative difference to Baseline
1	7,740	800	2.84	-25%	7.76	-4%
2	7,740	700	3.24	-14%	7.92	-2%
3	7,740	600	3.78	Baseline	8.08	Baseline
4	7,740	500	4.54	20%	8.23	+2%
5	7,740	400	5.67	50%	8.38	+4%

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

Lab Data

Compelling evidence that MinCapCOP47 is a strong indicator of part load efficiency comes from lab test data conducted at the UL Laboratory in Plano Texas. Testing using CSA EXP07:19 (CSA 2019) and subsequent version CSA EXP07:23 (CSA 2023) provide a means of observing heat pump operation under its own native controls. During testing of over 19 heat pumps since the publication of CSA EXP07:19 data revealed the importance of good part load operation has on system performance.

Figures 5A and 5B provide show the impact on performance between two systems whose performance differences were driven by changes in their control algorithms. Figures 5A and 5B provide two examples of power consumption of nearly identical heat pumps. Both were manufactured by the same company, of the same size and from the same advertised product series, but differed after the manufacturer made changes to the controls software and minor changes to the hardware. The 2019 unit was tested in 2019 using EXP07:19 during the initial round of 13 tests at the UL lab, and the 2020 unit was tested roughly nine months later after the manufacturer was shown the results of the first round of testing and requested NEEA conduct the same testing of their updated product.

The part load COP of the 2020 model was consistently more than 50% better across all tests where the heat pump operated under part-load conditions. This resulted in a seasonal performance increase of 69% in heating and a 60% increase in cooling while the rated HSPF and SEER values only increased by 8%. Visually it is easy to see in the strong cycling behavior of the 2019 model compared to the much more controlled modulation of the 2020 model. The 2019 model (figure 5A) cycled between roughly 80% capacity and off, whereas the 2020 model (figure 5B) modulated power consumption and operated for a longer period with roughly a half-degree wider oscillation in indoor dry bulb (ID DB) temperature. The specific COPs generated during Figures 5A and 5B were 2.03 and 3.37 respectively, a 66% increase in performance.

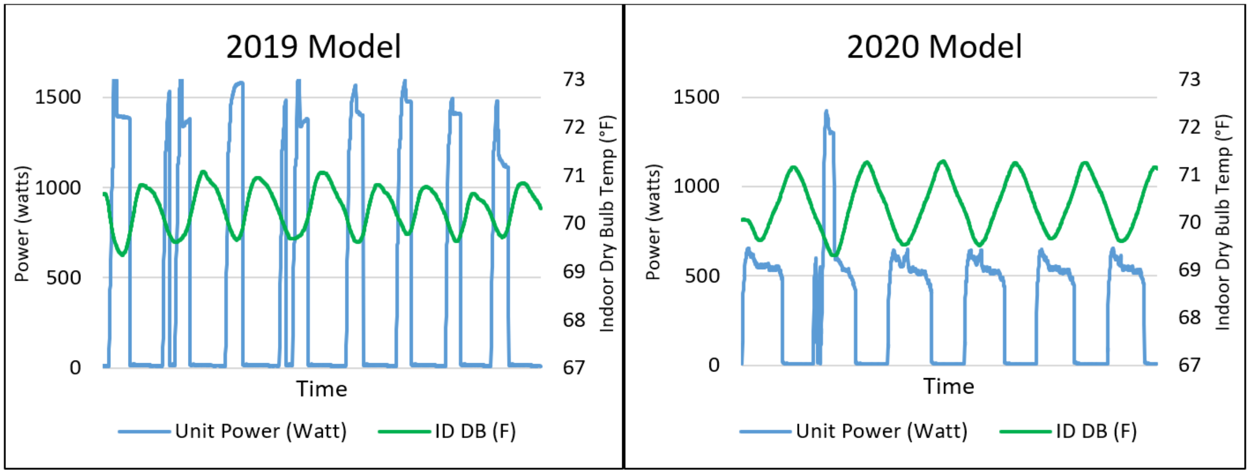

Figure 5A and 5B – Cycling Behavior on poor (left) and good (right) LLE heat pumps.

This data also suggests part load testing should be conducted as a load-based test where the machine operates under its own native controls rather than at a fixed speed. Future work may be warranted to investigate if load-based testing or a controls verification protocol is needed to confirm if heat pump is actually able to achieve good performance under its own controls. This however is beyond the scope of this paper.

Field Data

One source of field data which can provide illustrative examples of good and bad LLE performance is the ongoing High Performance, High Capacity (HPHC) heat pump project being led by Bonneville Power Administration (BPA) and scheduled to finish in 2025. The project includes central ducted and multizone split system selected for a variety of criteria, including low temperature capacity, rated COP at 17F and expected low-load efficiency performance. Three examples were selected from that project to show here, illustrating examples of good and bad low-load efficiency performance. All of the below data is one-minute interval data.

The first example heat pump, in Figure 6, has a high claimed MinCapCOP47 of 4.92 at a minimum capacity of 17,300 Btu/h. During the period of time shown in the figure, the outdoor temperature is 49 °F. The average COP during this time is 4.73, and the average delivered capacity, when the system is running, is 19,365 Btu/h. This period of time includes recovery from a thermostat setback at the beginning of the time, followed by some steady low-load operation. The system shows desirable traits: the lag between compressor turn-on and fan power turn-on is short, capacity is reached quickly, and the system appears to run steadily at minimum capacity once recovery has been achieved.

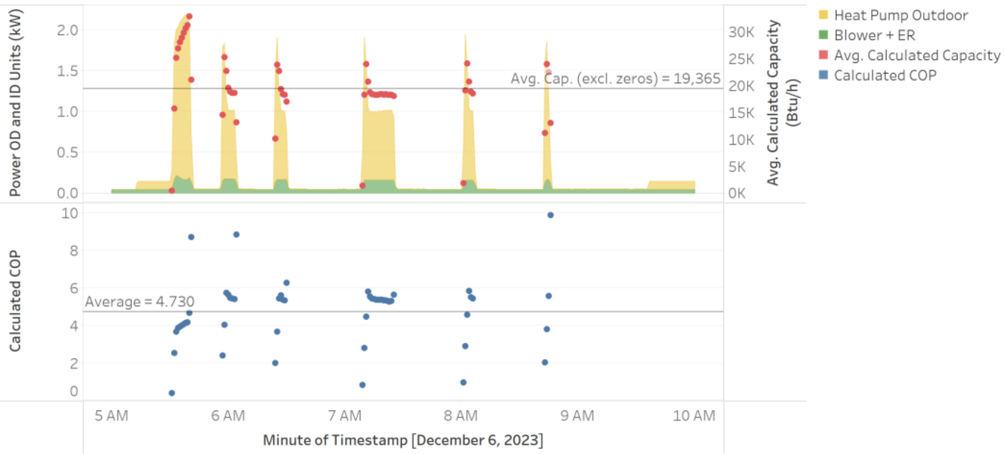

Figure 6 – BPA HPHC field testing example 1 – high claimed MinCapCOP47.

The second example in Figure 7 shows a case where the system has a low claimed part load COP, which is shown in the measured data. This system has a claimed MinCapCOP47 of 3.87 at a minimum capacity of 14,300 Btu/h. The data shown is for the same hours, and the site is in the same city as above. This system shows reasonable control behavior, but suffers from a very slow capacity ramp-up, in addition to only settling at a mediocre COP. The average COP during this time window was under 3.0. The system power appears stable around the manufacturer's listed minimum power at this condition (1.08 kW), but is slowly increasing as capacity increases. One possible explanation is that the system control is slow to reach the target refrigerant pressures (potentially explaining the slow rise of capacity).

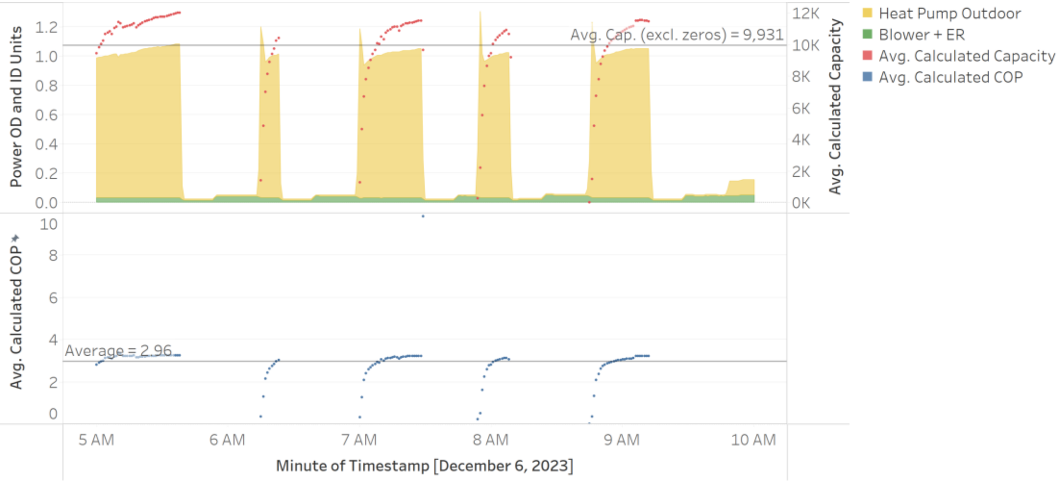

Figure 7 – BPA HPHC field testing example 2 – low claimed MinCapCOP47.

The final example in Figure 8 shows a case where system control behavior clearly negatively impacts performance. This system has a claimed MinCapCOP47 of 3.86 at a minimum capacity of 12,000 Btu/h. This site is in a different city in the same region, but the average temperature during this time period is about the same, 48 °F. In this case, the behavior which is observed is totally different: the system turns on and ramps up capacity continuously until the heat call ends. The duration of each run cycle is quite short, and the average capacity is over 14,000 Btu/h, reaching as high as 26,000 Btu/h, despite the load clearly being quite low. Anecdotally, this system exhibits similar behavior at low-outdoor-temperature, high load conditions, too: turning on and ramping up continuously until the heat call is over.

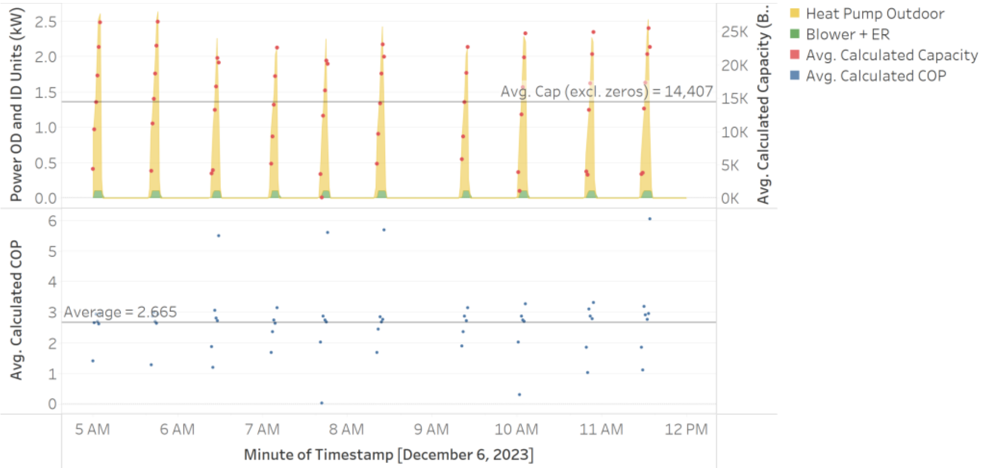

Figure 8 – BPA HPHC field testing example 3 – Does not meet claimed MinCapCOP47 performance.

The ongoing HPHC project has several dozen sites, and more of them have good low load performance than bad. The above examples are intended to illustrate some important examples. The first shows a system which rapidly reaches capacity, runs at a steady, low power, and meets a high claimed COP. The second shows a system which runs steadily at minimum power but is very slow to reach capacity, hurting actual capacity and efficiency. The third shows a system which starts at low power but ramps rapidly, resulting in short and inefficient cycles rather than long, steady, efficient heat cycles. These results underscore the importance of control and transient behavior, factors which cannot be captured in a single, steady-state test condition.

Analysis in the HPHC project, still ongoing at the time of writing this paper, has included further efforts to understand whether systems are regularly meeting or missing their claimed performance numbers at minimum capacity, 47°F outdoor condition. One observation which has emerged is that some manufacturers appear to have generally better agreement between measured and claimed performance than others. Figure 9 and 10 below show examples of good and bad agreement respectfully. The histograms show average calculated capacity, COP, and heat pump power for all run cycles greater than 3 minutes in duration, while the outdoor temperature was between 40-54°F. The red dashed line shows the NEEP database claimed capacity, power and COP, while the histogram shows field measurements.

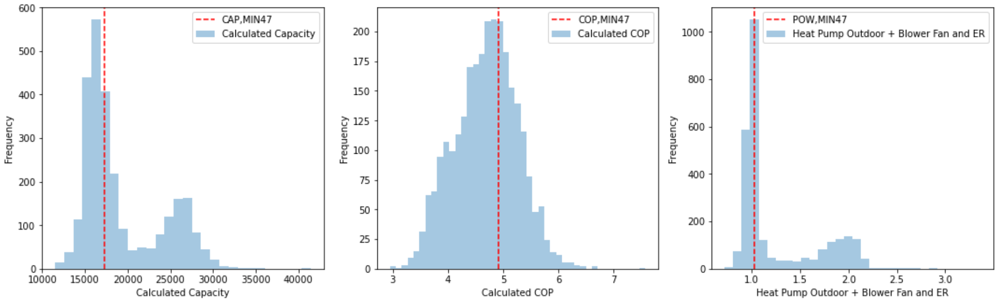

Figure 9 – Frequency of measured capacity, power and COP for BPA HPHC field testing example #1.

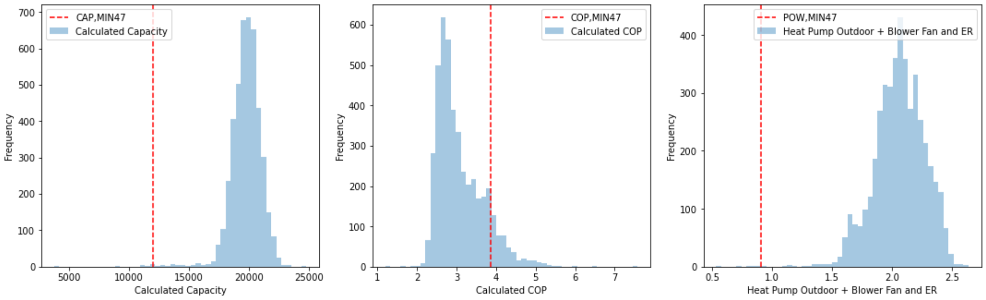

Figure 10 – Frequency of measured capacity, power and COP for BPA HPHC field testing example #2.

These two examples are representative of the emerging findings among the other sites in the BPA field data. Further findings in this area will be the subject of more analysis and reporting as the project progresses. In addition, NEEA is currently conducting lab testing which hopefully will provide better insight on why some systems appear not to hit their reported target MinCapCOP47 values.

Source of Savings Investigation.

The investigation, which aimed to identify technologies and design decisions that contribute to exceptional low load efficiency in heat pumps, consisted of two parts. The first part involved in depth interviews with engineers from heat pump and compressor manufacturers as well as a researcher from Oak Ridge National Laboratory (ORNL). The second part conducted a “paper teardown" of 25 heat pumps across seven manufacturers to test a variety of hypotheses of the root causes of LLE. This involved detailed review of data from product specifications and service manuals. By assessing trends in NEEP values for MinCapCOP47 associated with various technologies and design decisions, we could test theories discussed during the OEM discussions about features that lead to improved low load efficiency.

The paper teardown analysis focused exclusively on 36 kBtu (3-ton) inverter-driven, single-zone ducted heat pumps. Each OEM's product line was reviewed across two to three quality tiers. Indoor/outdoor pair selections strictly followed OEM guidelines. Care was taken to avoid unusual parings of indoor and outdoor units or data that was suspect. This narrow focus aimed to minimize variables impacting low load efficiency analysis. Results are organized into five sections: compressor design, metering devices, heat exchanger design, indoor/outdoor fans, and control algorithms. This structure offers a detailed look at factors affecting heat pump performance under low load conditions, based on OEM interviews and paper teardown findings.

Compressor Design Considerations.

Compressors are the heart of heat pump systems and account for 70-90% of total energy consumption of a heat pump. Compressors operate most efficiently within a specific pressure and flow rate range, typically optimized for full load conditions. Fixed losses, while small, increase as a percentage of total power at lower loads. Heat pumps with high fixed losses therefore would likely have poor part load efficiency.

OEMs agreed that increased compressor turndown can improve overall efficiency. At low compressor speeds the system behaves as if the heat exchangers are oversized. This results in improve the heat exchanger ability to capture or reject heat which all agreed is the primary driver of heat pump efficiency. In addition, reducing compressor speed can reduce the losses that occur when a machine cycles on and off and refrigerant pressure and heat exchanger temperatures have to be returned to nominal operating conditions. There are limits to this however to compressor turn down as it is important to ensure adequate oil pressure and flow in the refrigerant lines to circulate oil back to the compressor. Manufacturers limit the turn down ratios or engage oil return cycles which run the compressor briefly at high speed briefly to enhance oil return. OEMs also agreed that rotary compressors maintain better efficiency than scroll compressors at lower pressures but because operating pressures do not change much between low speed and high speed in a normal heat pump refrigeration cycle this difference is not likely very significant across typical ranges of operation.

The paper teardown assessment of compressor design evaluated compressor type and compressor turndown ratio.

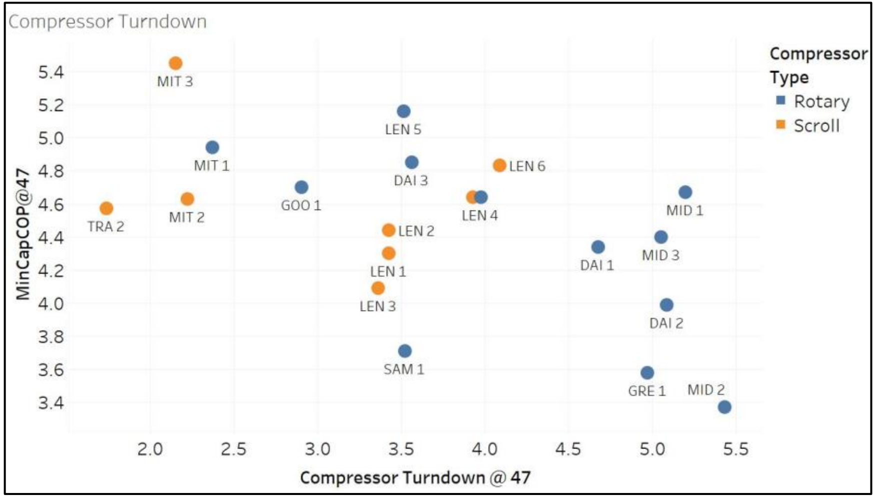

Figure 11 presents a scatter plot that compares MinCapCOP47 values by compressor type (rotary or scroll) and turndown ratio for all units assessed. The graph illustrates a wide range of MinCapCOP47 values for both compressors types, suggesting that compressor type is not a dominating factor in determining low load efficiency. A focused examination of the three Mitsubishi ducted units, including one with a rotary compressor and two with scroll compressors, effectively underscores this point. Despite similar rated capacities and turndown ratios among the three Mitsubishi units, there is no discernible advantage in terms of MinCapCOP47 for rotary compressors. Additionally, the Lennox Signature SL25XPV, equipped with a scroll compressor featuring an impressive 4.1:1 turndown has a claimed MinCapCOP47 of 4.83.

These findings suggest that both scroll and rotary compressors are very capable of high efficiency at high turn down ratios. Figure 11 also shows that there is no clear 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.

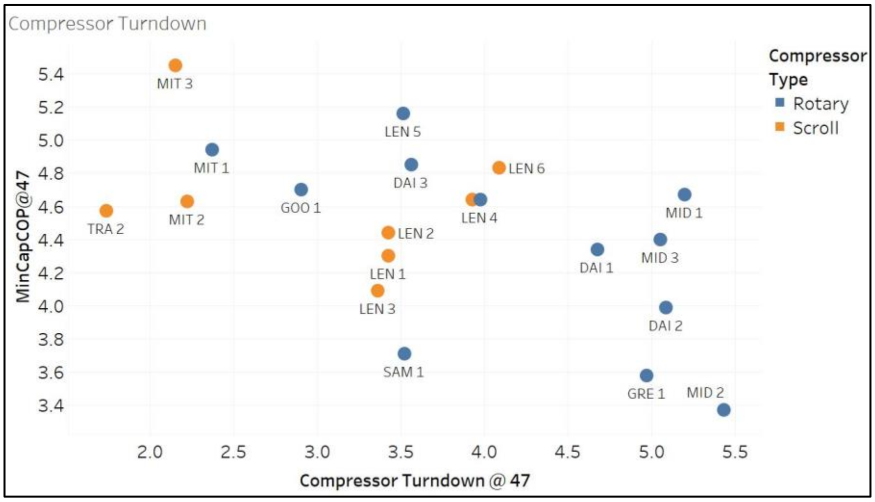

Figure 11 – MinCapCOP47 as a Function of Compressor Type and Turndown.

Metering Device Considerations

Modern heat pumps use two main types of metering devices: the thermostatic expansion valve (TXV) and the electronic expansion valve (EEV). Positioned upstream of the evaporator coil, these devices regulate the flow of refrigerant, thereby controlling pressure and temperature across the heat exchanger. By adjusting the size of the valve opening, they manage the superheat across the evaporator coil, optimizing refrigerant heat absorption.

OEMs explained that when appropriately sized and configured, TXVs can perform comparably to EEVs. However, TXVs encounter challenges under low load conditions, where their ability to accurately regulate flow is limited. Operating outside their design range may lead to excessive hunting, resulting in cyclical fluctuations in suction superheat levels. Conversely, EEVs, especially in systems with broad capacity ranges, offer distinct advantages.

The paper's teardown assessment aimed to test the hypothesis that heat pumps equipped with EEVs exhibit higher MinCapCOP47 values compared to those with TXVs due to the former's superior control of superheat during low load conditions. Figure 12 presents a plot correlating MinCapCOP47 values with metering device type and compressor turndown ratio for all analyzed systems. The graph demonstrates a wide range of MinCapCOP47 values for both metering device types suggesting that while EEVs may enable better control, they were not necessary for good MinCapCOP47 values.

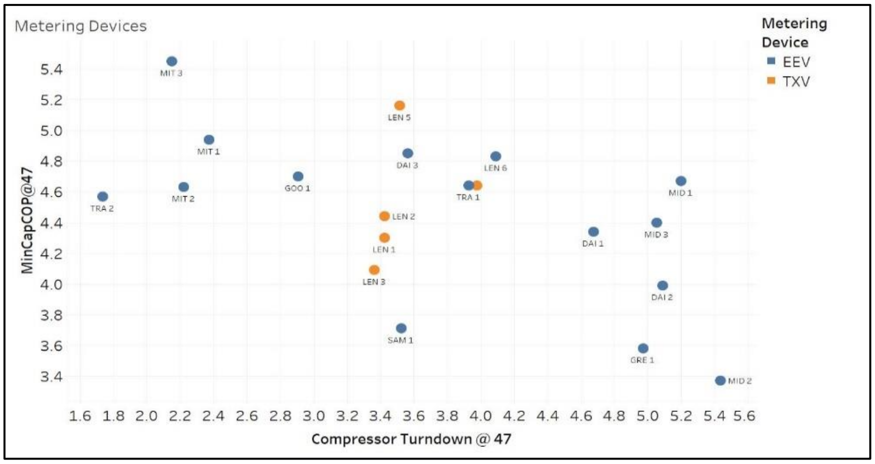

Figure 12 MinCapCOP47 as a Function of Metering Device Type and Turndown.

Heat Exchanger Design Considerations

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. OEMs explained and confirmed that larger outdoor heat exchanger size increases the opportunity to have better efficiency at low loads, but only if the system is designed to take advantage of the larger heat exchanger. Analysis by Yusub et. Al (link) found that condenser path operation can increase part load heat transfer rate within the heat exchanger by 18 to 43 percent relative to rated conditions.

OEMs explained that reducing discharge pressure of the compressor reduces the input power required by the compressor which could increase efficiency, but that this reduction is constrained by the need to keep the system's discharge pressure high enough for both the phase change cycle to be effective and to ensure flow rate is high enough within the heat exchanger to maintain turbulent flow and ensure good heat transfer effectiveness. 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 pressure drop across the heat exchanger and reduced power consumption, but doing so could cause the flow during low speed to become laminar within the heat exchanger thereby dramatically reducing its effectiveness.

Figure 13 shows MinCapCOP47 values as a function of total heat exchanger sizes for both indoor and outdoor units. This graph provides some indication that better part load efficiency can be achieved with large heat exchangers, however there are ample examples of lower performance with large heat exchangers.

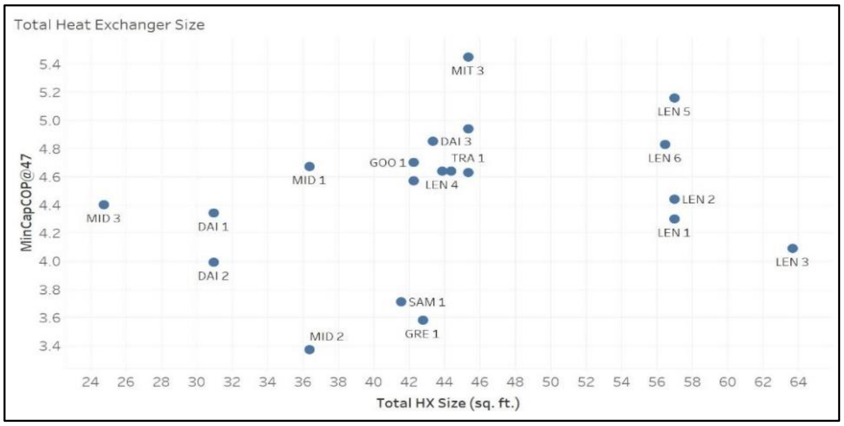

Figure 13 – MinCapCOP47 as a function of the ratio of heat exchanger size.

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. More than one OEM explained that there is always a compromise with heat exchanger design due to the need for both heating and cooling operation. If a vapor compression cycle is optimized for one, it will probably not be optimized for the other.

Figure 14 shows a plot of MinCapCOP47 versus heat exchanger ratio from the paper teardown. Figure 14 suggests that heat exchange ratio may be a limiting factor in determining low load efficiency and that there is some a general trend with larger ratios having superior MinCapCOP47 values.

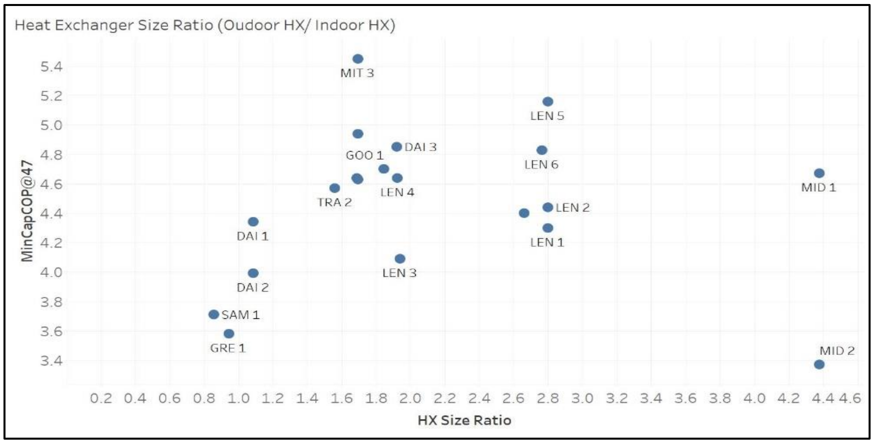

Figure 14 – MinCapCOP47 as a function of the ratio of outdoor to indoor heat exchanger area.

Indoor and Outdoor Fan Considerations

Fan energy plays an important role in total energy use, especially during part load conditions. This is because the power needed decreases exponentially with decrease air flow rate for a given pressure drop. Thus, if a system appropriately modulates the fan speed, there will 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 field operation suggest inconsistent implementation of fan controls among OEMs, limiting the exploitation of fan power curve unloading potential.

Assessing fan impacts efficiency and fan turndown ratio on LLE was not possible through the physical teardown. However, 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 1/3rd of the flow rate, a savings of around 500 watts when compared to a constant speed fan motors operating at part load conditions.

Control Algorithm 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 affect the variable speed components, variable speed compressors and fans, as well as EEVs.

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 and energy is lost regaining pressure and heat exchanger temperatures.

OEMs also emphasized that controls can take you away from a good design, but they can’t overcome 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 we interviewed pointed out that a large heat exchanger may sound better, but become far less effective when refrigerant flow becomes laminar and the heat exchanger effectiveness plumets.

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. Figure 15 shows that higher MinCapCOP47 values 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.

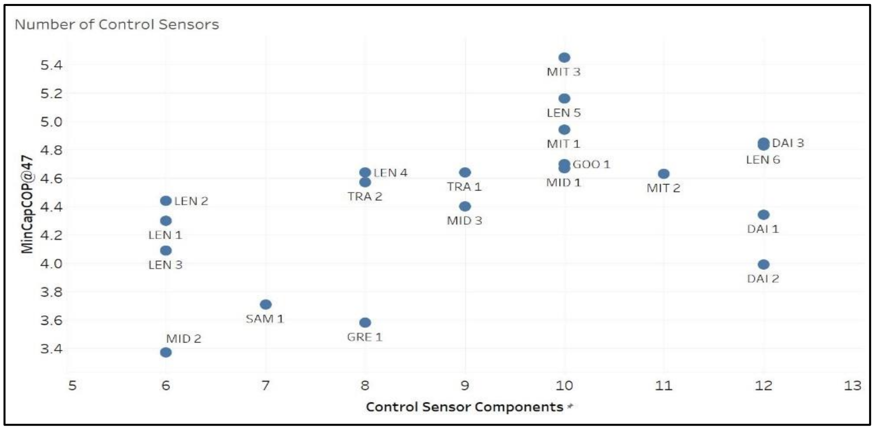

Figure 15 – MinCapCOP47 as a control sensor components.

Conclusion

Part load efficiency is an important component to heat pump seasonal performance. While the current metrics of HSPF2 and SEER2 include bin-hours that include results from the $H1_{low}$ test point, there does not appear that there is a strong relationship between this test point and annual heat pump performance. Strong part load efficiency is especially important for heat pumps installed in mild climates and when supplementary heating systems do most of the heating such as with dual fuel gas furnaces.

No clear evidence was found that strong part load efficiency would drive equipment manufacturing costs. There are clearly some design approaches that would increase cost of achieving higher MinCapCOP47 values but there are plenty of examples where it can be achieved without added cost. This investigation identified two likely two sources improved part load efficiency. First and most likely is accurate control of the refrigerant cycle and fans during under part load conditions. The second is the outdoor heat exchanger size which limit the maximum part load efficiency that a heat pump can achieve.

We found that manufacturers were largely unaware of the in-field performance benefits of strong part load efficiency. We speculate that this is largely because they are focused on SEER and HSPF ratings and other key market design considerations such as equipment longevity, price and supply chain driven issues. Future recommended investigations should explore more lab testing to confirm if the static test value of $H1_{low}$ is a reliable differentiator, or if a controls verification procedure or load based testing is needed. In addition, further investigation may be needed to determine MinCapCOP47 values should be normalized to a consistent turndown ratio.

References

Air Conditioning, Heating and Refrigeration Institute (AHRI). 210/240- 2024 Performance Rating of Unitary Air Conditioning & Air-Source Heat Pump Equipment. https://www.ahrinet.org/search-standards/ahri-210240-i-p-performance-rating-unitary-air-conditioning-and-air-source-heat-pump-equipment

Canadian Standards Association (CSA). CSA SPE-07:23 Load-based and climate-specific testing and rating procedures for heat pumps and air conditioners. https://www.csagroup.org/store/product/CSA%20SPE-07%3A23/

Harley, B., M. Alatorre, C. Dymond, and G. Hamer. 2022. CSA EXP07: Ongoing Progress, Lessons Learned, And Future Work In Load-based Testing of Residential Heat Pumps. (https://docs.lib.purdue.edu/iracc/2456/)

Kwak Y., S. Hwang, and J. Hwan Jeong. 2020. Effect of part load operating conditions of an air conditioner on the number of refrigerant paths and heat transfer performance of a condenser Energy Conversion and Management. Volume 203 (https://www.sciencedirect.com/science/article/pii/S0196890419312634)

Ossorio, R., E. Navarro-Peris, and J. Marchante. 2023. A novel methodology to assist manufacturers in the heat exchanger sizing for variable-speed heat pumps based on part load conditions and economic assessment. Thermal Science and Engineering Progress. Volume 46. (https://www.sciencedirect.com/science/article/pii/S2451904923005826)

Smith I. 2022. Variable Speed Heat Pump Product Assessment and Analysis. Energy Conversion and Management. (https://neea.org/resources/variable-speed-heat-pump-product-assessment-and-analysis)

U.S. Department of Energy (DOE). Appendix M to Subpart B of Part 430, Title 10, Uniform Test Method for Measuring the Energy Consumption of Central Air Conditioners and Heat Pumps. https://www.ecfr.gov/current/title-10/chapter-II/subchapter-D/part-430/subpart-B/appendix-Appendix%20M%20to%20Subpart%20B%20of%20Part%20430.