June 12, 2023

REPORT #E23-465

Variable Speed Heat Pump Baseline and Key Assumptions Review

Prepared For NEEA:
Lauren Bates, Sr. Market Research and Evaluation Scientist

Prepared by:
Cynthia Kan, PhD
Josh Carey
Joel Zahlan, PhD

Cadmus Group
100 5th Avenue
Suite 100
Waltham, MA 02451

Northwest Energy Efficiency Alliance
PHONE
503-688-5400
EMAIL
info@neea.org

Table of Contents

Introduction

Northwest Energy Efficiency Alliance (NEEA) contracted with Cadmus to review its analysis of low-load efficient variable speed heat pumps (LLE VSHPs) for ducted residential systems in the Northwest. VSHPs can change their capacity (and efficiency) under a variety of operating conditions. Figure 1 shows an example of a variable speed system's performance specifications from the Northeast Energy Efficiency Partnerships' (NEEP's) heat pump list. Under low-load conditions (NEEA defines as 47°F outdoor temperature), the system can achieve a coefficient of performance (COP) of 2.34 up to 4.56.[1] At a given temperature, the tradeoff for increased efficiency is capacity (see yellow highlights). Going forward, low-load COP refers to a system's COP at minimum capacity at 47°F. For this review, NEEA has defined central ducted low-load efficient VSHPs as those that have a low-load COP of 4.5 or higher.

Figure 1. Example of VSHP Performance Specifications

Performance Specs

Heating / Cooling	Outdoor Dry Bulb	Indoor Dry Bulb	Unit	Min	Rated	Max
Cooling	95°F	80°F	Btu/h	9,382	41,000	49,892
			kW	0.68	4.1	5.56
			COP	4.04	2.93	2.63
Cooling	82°F	80°F	Btu/h	11,600	-	51,000
			kW	0.65	-	5.31
			COP	5.23	-	2.81
Heating	47°F	70°F	Btu/h	9,030	45,000	51,892
			kW	0.58	3.73	6.5
			COP	4.56	3.54	2.34

NEEA's research questions are outlined below by analysis area.

Unit Energy Savings (UES)

- *Are the data and methods used to determine LLE VSHP UES reasonable and sufficient for credible accounting of energy savings?*
  - *What data and methods are strongest for estimating UES (MN CEE study, MN CEE study plus follow-up analysis, or another)?*
  - *How well does the UES evidence apply to heating zone 2 (HZ2)?*
  - *What recommendations does the contractor have for defining an HZ2 UES?*
  - *How should UES for sales records without a "ship-to" zip code (which NEEA uses to determine heating zone) be handled (for example, using RTF climate weights, sales-weighted average,*

[1] COP is an instantaneous metric defined as energy output divided by energy input.

or other data/methods for extrapolating a UES for these units without an assigned heating zone)?

- *What refinements, if any, are needed to NEEA's data sources and methods?*

Incremental Cost

- *Are data sources and methods for determining the incremental first cost of the measure, and incremental operations and maintenance costs, reasonable and sufficient for credible estimates of cost-effectiveness?*
  - *Are data sources and methods for determining the incremental first cost of the measure, and incremental operations and maintenance costs reasonable and sufficient for credible estimates of cost-effectiveness?*
  - *How should data from multiple sources be integrated?*
- *What refinements, if any, are needed to NEEA's data sources and methods?*

Baseline Forecast

- *Is NEEA's naturally occurring baseline forecast a reasonable representation of market adoption without intervention by NEEA, utility programs, or its partners?*
- *What refinements, if any, are needed to NEEA's baseline forecast and what evidence supports these changes?*

Summary of Project Documents

NEEA provided Cadmus several documents to review.

- A VSHP product assessment and analysis prepared by Minnesota Center for Energy and Environment (MN CEE study)[2]
- A follow-up memo (unpublished) to the original MN CEE study analyzing low-load efficiency and additional climate regions
- A spreadsheet containing calculations for energy savings (VSHP_LLLE_UES.XLSX)
- A spreadsheet with recorded online storefront prices for VSHPs matched to MiniCapCOP47 statistics from the NEEP list (online_storefront_cost_data.XLSX)
- A VSHP spreadsheet tool used in the MN CEE report and follow-up calculations that compare the levelized cost of heating and cooling provided by variable-capacity heat pumps based on an 8,760-hour bin model (VCHP LCTool v1.24cd.XLSX)
- A word document summarizing the incremental cost research (VSHP_LLLE_Incremental Cost.DOCX)
- A word document describing the market baseline (VSHP_LLLE_Baseline)

[2] MN CEE. 2022. *Variable Speed Heat Pump Product Assessment and Analysis.* https://neea.org/img/documents/VSHP-Product-Assessment-Product-Council.pdf

Cadmus also used weather files from the Regional Technical Forum (RTF) in the analysis. Cadmus staff also discussed the documents listed above with NEEA's product manager and MN CEE staff.

Unit Energy Savings Assumptions

Which Values for Unit Energy Savings Should be Used

MN CEE modeled various VSHPs and their costs and energy consumption. MN CEE also produced a second follow-up analysis using the same modeling tool with similar results. NEEA asked Cadmus to recommend an approach for setting savings rates--using the published study alone, the follow-up analysis alone, or a combination of the two.

The UES analysis is calculated based on the analysis of VSHPs on NEEP's heat pump list 4.0.

Baseline LLE based on average value on NEEP's list: **COP of 4.00**

Efficient LLE based on top 25% of products: **COP of 5.00**

The MN CEE study includes modeling results for HZ1 and HZ3, but not HZ2.

Cadmus Response. Before discussing the UES values, Cadmus first summarizes our findings from reviewing the MN CEE study and related files. Recommendations are in bold text.

The heat pump model developed for the MN CEE study shows reasonable behavior compared to field data (see Appendix C of the MN CEE study). It applies an hourly COP based on the heating load and minimum and maximum system capacity, assuming the heat pump operates at the lowest capacity that meets the load (ideal behavior). **NEEA should check this modeling assumption against actual installed VSHP systems (if data are available) or ask manufacturers if this behavior is consistent with the way their systems are controlled.** Cadmus has collected field data on numerous heat pump systems and found units that do not operate as expected. For a metering study in Vermont , Cadmus found that the average cold climate heat pump system used backup heating when the heating load was smaller than the system capacity.[3]

Furthermore, Cadmus recommends that NEEA verify with manufacturers whether the minimum capacity COP specifications in the NEEP database are based on actual performance or if values were extrapolated.[4] If the minimum capacity COP specifications were extrapolated, NEEA should either verify the extrapolation is representative of actual performance (by talking to manufacturers) or consider dropping those points from the analysis if they appear unrealistic. For example, in Figure 1 of the unpublished memo, there are LLE values exceeding 7.0, which is a very high COP.

Field studies are expensive, time-consuming, and will require a large sample size to detect energy savings given the large variation expected in these systems. **Cadmus recommends NEEA consider a**

---

[3] Example is from an unpublished analysis workbook.

[4] NEEA's product manager mentioned that manufacturers are required to test COP at maximum capacity and rated capacity, but not minimum capacity.

limited field test of the performance impacts of low-load efficiency by adding on to an existing field study. NEEA is currently testing heat pumps by connecting two systems to the same building and then alternating systems every other week. NEEA could augment that field setup by testing two similar VSHPs with different low-load efficiency, and then seeing if a significant difference in energy consumption is detected once weather is factored in.

Assuming NEEA has confidence in the reported low-load COP specifications used in the MN CEE studies, Cadmus recommends NEEA publish and use the MN CEE follow-up study for planning UES.[5] The follow-up study includes UES values for Boise (technically in HZ1, but on the cooler end of the range) that provide a conservative estimate for HZ2 and, since many factors impact the energy consumption of a VSHP, the follow-up memo methodology isolates the performance metric of interest and may be easier to explain to funders and manufacturers. **Specifically, Cadmus recommends the rounded values below to indicate less precision.** The section following the table explains why we recommend using Boise's UES results for HZ2.

Table 1. Recommended UES by Heating Zone

Heating Zone	CEE Modeled Results Location	kWh Savings
HZ1	Portland (HZ1)	920
HZ2	Boise (HZ1)	1,190
HZ3	Bozeman (HZ3)	1,240

A key finding of the MN CEE analysis is that the performance above 15 °F is a key driver in annual energy use. Therefore, to determine a UES for HZ2, Cadmus looked at weather data for a representative city in HZ2 and selected the modeled location that was the best fit.[6]

Cadmus binned hourly outdoor temperatures from the RTF's climate files for Bozeman (HZ3, cooling zone 1 [CZ1]), Boise (HZ1,CZ3), Portland (HZ1,CZ1), and Spokane (HZ2,CZ2).[7] Cadmus used Spokane as the representative location for HZ2 since Spokane is in HZ2,CZ2, the most populated climate zone among HZ2. Figure 2 shows Spokane (grey bars) most closely follows Boise (yellow bars) across most temperature bins. Since Boise is in HZ1, using UES results for Boise as a proxy for HZ2 will result in a conservative estimate.

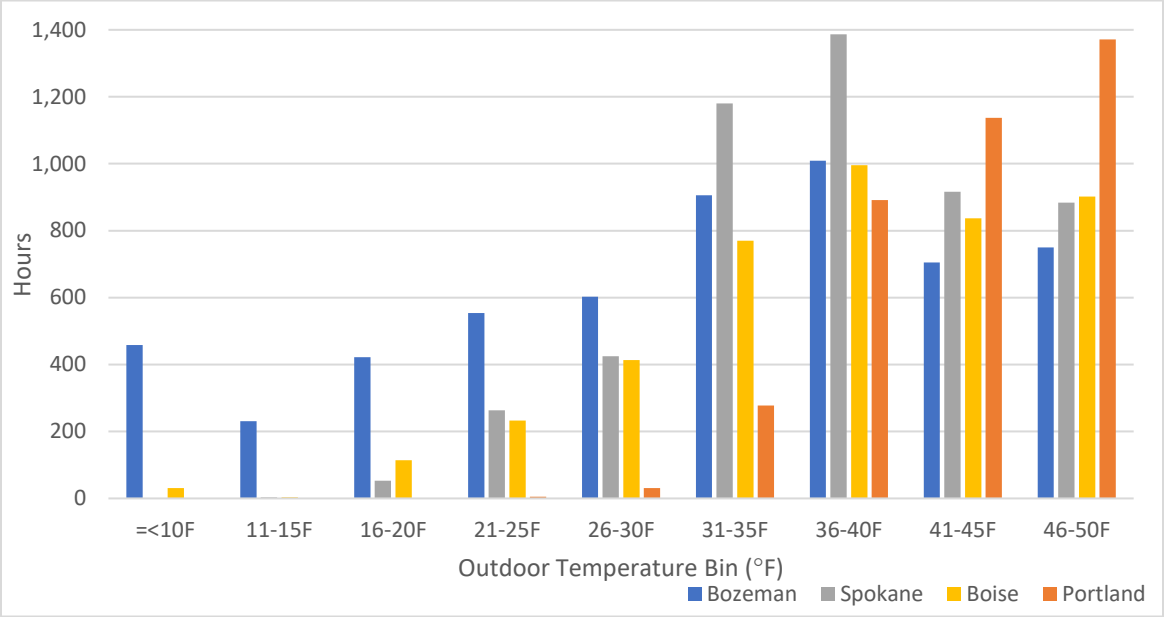
---

5 The memo will first need to be made into a publication quality document. In its current state, it needs editing and is lacking context such as dates when cost data were collected or sample sizes and definitions.

6 MN CEE has modeling results for Portland, Boise, Bozeman, Sacramento, Denver, Minneapolis, New York City, and Washington DC.

7 RTF. Accessed April 2023. "Climate Files." https://rtf.nwcouncil.org/work-products/supporting-documents/climate-files/

Figure 2. TMY3 Hours at Outdoor Temperatures



How to Link Sales Data to UES

- NEEA's HVAC sales data includes ship-to location for 25% of sales, but 100% have ship-from location. Records with ship-to data will be assigned a corresponding heating zone and savings rate. Savings rates for remaining sales need to be extrapolated.
- NEEA has considered three extrapolation approaches and is interested in recommendations for which method to use and if other data/methods should be considered.
- NEEA's current sales data cover approximately one-third of Northwest shipments.

Cadmus Response. Cadmus reviewed NEEA's three proposed methods and recommends modifying method 3: use a sales-weighted average among non-missing records that is updated when NEEA obtains new sales data. Table 2 shows the recommended extrapolation approach.

To check if the reported data are representative, NEEA can interview the largest known nonparticipating suppliers (in NEEA's annual data collection) to determine their annual sales and whether their ship-to regions are similar to the known dataset. However, NEEA is not confident that nonparticipating suppliers would be responsive to further inquiries. NEEA expects to have data from additional suppliers for 2022 and could replicate the analysis using the augmented data to see if results continue to be similar. NEEA could also survey program administrators that offer VSHP rebates to see where the measures are being installed, assuming there are programs in all climate zones.

Table 2. Cadmus Recommended Application of HZ UES

Datapoint Disposition	Estimated Share of Northwest Shipments	UES Heating Zone
Has ship-to/ship-from	1/3 x 25% = 8%	Apply ship-to location heating zone UES. NEEA estimates 82% of these units have a matching ship-to/ship-from heating zone.
Has ship-from	1/3 x 75% = 25%	For 82% of these units, apply the same heating zone UES as ship-from. The remainder of units should apply the heating zone UES based on analyzing known ship-to/ship-from data. The benefit of this approach is that it uses all the ship-from data.
Not reported	67%	Extrapolate based on results from the above steps. Validate reasonableness through interviews with non-reporting suppliers or analyzing the new 2022 supplier data.

Incremental First Cost

NEEA's incremental cost memo includes three results for incremental first cost, summarized in Table 3.

Table 3. Comparison of Incremental First-Cost Methodology

Source	Methodology	Results
MN CEE published report (data collected in 2021)	Modeled heat pump costs based on a web scrape of the minimum advertised price online of 36 systems and contractor pricing covering four original equipment manufacturers. Modeled by archetype for a consistent design temperature.	$115 incremental cost for Portland (installed cost, likely driven by the difference in size since modeled archetypes were sized for a specific design temperature).
MN CEE unpublished memo	Same dataset, looking only at equipment costs for 3-ton units. Small sample size.	Memo figure shows a negative correlation between equipment cost and low-load COP.
NEEA's analysis of online listed price (December 2022)	Regression analysis based on 36 data points; not all major brands are represented. Standard errors are large due to the small sample size.	$2.94 incremental first cost (less than 1% of the typical online advertised equipment price)

NEEA did not provide evidence that the measure's incremental operations and maintenance (O&M) costs differed from a reference unit.

Cadmus Response. Based on Cadmus' discussion with NEEA staff, we expect O&M costs to be the same as a reference unit. **NEEA should explicitly note in the incremental cost documentation that no incremental O&M costs are expected.**

The key takeaways from Cadmus' review of the materials and discussions with NEEA staff are that NEEA staff are not confident that the data collected in 2021 for the MN CEE study is representative of today's costs, but they are confident the incremental cost is small compared to the total cost of a heat pump.

NEEA staff say the current heat pump market is driven by high demand and that HVAC contractors can name their price. This makes it a challenge to use installed cost for determining incremental cost.

NEEA's analysis of online equipment prices is more recent, is independent of contractor pricing practices, and results in nearly zero incremental cost when controlling for differences in brand, capacity, and the seasonal energy efficiency ratio. The sample size is small and standard errors are large, so **Cadmus recommends adding more data points and re-running the analysis to see if the results continue to be stable or using a range of values for the incremental cost**. Furthermore, NEEA's product manager says that to achieve a good low-load efficiency, an electronic expansion valve is required. The cost of an electronic expansion valve (NEEA staff estimate at $10) is negligible compared to the cost of the other system components. As such, Cadmus expects no significant incremental first costs. **Until NEEA is able to augment its analysis with additional data points, NEEA could use a range of costs from $3 to $10.**

Baseline Forecast

NEEA provided a memo showing how staff forecasted the naturally occurring baseline. It provides an overview of NEEA's heat pump intervention history and discussion of barriers, followed by analysis of sales data used to establish a baseline trend for the LLE market share.

Cadmus Response. NEEA makes a compelling set of arguments in support of its naturally occurring baseline, which is forecasted for two years and then held constant for 15 years. Cadmus recommends the following enhancements:

- NEEA claims awareness of variable speed technology is growing due to many organizations working on cold climate heat pumps. However, NEEA states there is no notable effort to promote low load efficient VSHPs outside of NEEA. **Strengthen this claim with evidence from NEEA's early interactions with supply chain actors about awareness of variable speed technology and low-load efficiency. Since NEEA is regularly in contact with supply chain partners, it could include awareness questions in its next outreach survey or set of interviews**.
- NEEA's sales data represents about one-third of all products sold in the Northwest, so it would be ideal to **confirm this dataset is also representative of units that are not reported to NEEA**. **See previous recommendation about analyzing the augmented 2022 supplier data when available.**
- The autoregressive integrated moving average modeling is highly sophisticated but does not factor in monthly sales volume. Explaining this analysis to a layperson may be challenging. **Consider using a simple linear regression on the observed data in Table 3 of the baseline memo. Results from the linear extrapolation are shown in Table 4 and are similar to the time series forecast**.
- **Round forecasts to the nearest percent to avoid implying overprecision**.

Table 4. Comparison of Time Series and Linear Extrapolation Market Share Forecasts

Year	Time Series Forecast	Linear Extrapolation
2022	20.0%	19%
2023 and beyond	16.3%	18%