April 20, 2022

REPORT #E22-328

Variable Speed Heat Pump Product Assessment and Analysis

Prepared For NEEA:
Christopher Dymond,
Sr. Product Manager

Prepared by:
Isaac Smith, Residential Program Development Manager

Center for Energy and Environment
212 North 3rd Avenue, Suite 560
Minneapolis, MN 55401

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

Table of Contents

Table of Figures

Table of Tables

Glossary of Terms

Term	Definition
VCHP	Variable Capacity Heat Pump
VSHP	Variable Speed Heat Pump (a consumer-friendly descriptor for a VCHP)
SEER	Seasonal Energy Efficiency Ratio
HSPF	Heating Seasonal Performance Factor
NEEP	Northeast Energy Efficiency Partnerships
QPL	Qualified Product List
Levelized Cost of Ownership	The present value of the lifetime costs, which include install cost, maintenance, and operation (energy use) divided by the energy delivered over the system's lifetime
COP	Coefficient of Performance
HP	Heat Pump
AHRI	Air-Conditioning, Heating, and Refrigeration Institute
ER Backup	Electric Resistance Backup Heat
Weighted Heating Hours	House load in Btu times hours in temperature bin

Executive Summary

This project assesses currently available centrally ducted variable capacity heat pumps (VCHP[1]) 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 VCHPs 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 lifecycle levelized cost of heating and cooling (contact NEEA for a copy of the **VCHP Levelized Cost** Tool VCHP LCTool.xlsx). This tool enables users to compare different heat pump archetypes and to understand what performance metrics, attributes, and equipment features lead to better HP performance and the lowest levelized cost of ownership for the homeowner. The key findings from this project include the following.

1. ***While the centrally ducted HP market is vast, it can be distilled down to 14 manufacturers that produce equipment for 19 brands and 36 product lines.*** There are more than 5,800 centrally ducted VCHPs on NEEP's ASHP qualified product list—an overwhelming number of HP options and pairings. However, most of these systems are the same piece of equipment offered by multiple brands with various options for indoor unit pairings. This market can be greatly simplified by understanding these brand relationships and equipment offerings.
2. ***VCHP pricing is still largely driven by SEER values.*** VCHPs with the same SEER value tend to be priced within ±10% across brands. These same systems have different HSPF values, heating capacities, and coefficient of performance (COP), but these specifications don't noticeably impact price. However, an increase in SEER results in a clear increase in price. The link between cooling efficiency and price may reflect the market and utility rebate programs' tendency to overemphasize standard ratings such as SEER rather than equipment performance.
3. ***COP, not extended capacity or modulation, is the most important indicator of HP performance.*** VCHP archetypes with COP performance in the top 25% of the market had lower annual energy use and lower levelized cost of ownership in cold and mild

[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.

climates when compared to VCHP archetypes with excellent modulation range or extended capacity.

4. ***Minimum capacity COP between 35°F and 50°F is critical in almost all climates, even cold climates.*** HP performance in this temperature range drives lower annual energy use in all climates. This is a result of the sheer number of heating hours at these temperatures. Even when evaluating weighted heating hours, this temperature range is important in all climates, as shown in Table 12 and Appendix D: Weighted Heating Hours. HPs typically operate close to minimum capacity at these temperatures, so minimum capacity COP at 47°F is a valuable metric for determining HP performance and lower annual energy use.
5. ***Equipment cannot have both excellent COP metrics (top 10% of the market) and excellent extended capacity metrics (top 10% of the market); one is sacrificed for the other.*** While evaluating HP performance metrics, the research team discovered that manufacturers must make product development tradeoffs between high COPs and great extended capacity due to the inherent underlying physics of extracting more capacity at cold temperatures, which takes more energy and lowers the COP.
6. ***Upfront cost is a key driver of lowest levelized cost of ownership.*** The upfront cost of the equipment and installation greatly affects HP selection and sizing when optimizing for the lowest levelized cost of ownership. An HP that delivers lower annual energy use may not be justified if it entails a significant increase in equipment cost.
7. ***Oversizing HPs has diminishing returns on the lowest levelized cost of ownership.*** Slightly undersizing a heat pump typically offers the lowest lifecycle cost. For example, in a cold climate such as Bozeman, MT, sizing the heat pump for 5°F delivers some annual energy savings, but not enough to justify the increased equipment cost for the larger system. From a consumer cost perspective, even with extended capacity heat pumps, it is better to size a heat pump in Bozeman for 17°F and rely on electric strip heat for those limited hours when the heat pump cannot meet the load.
8. ***Building envelope and duct sealing upgrades are the best strategies to reduce peak demand.*** HPs with better extended capacity metrics or oversized HPs can produce peak demand savings, but the extra cost for these systems is better spent on envelope and duct sealing improvements. Improving the building envelope reduces annual energy use and the size of the HP needed, which lowers upfront and annual energy costs for the homeowner. These improvements also have a greater impact on peak demand than do oversizing the HP or installing an HP with better extended capacity.

Introduction

Variable capacity heat pumps (VCHPs) represent a significant market opportunity for energy savings in the Northwest. More than 500,000 homes in the Northwest currently have electric furnaces, and 1.5 million homes have central forced-air, single-stage heat pumps. The total technical potential for energy savings of these two target markets is estimated at over 330 average megawatts.

The challenge is determining which system provides the most cost-effective, near-term solutions for replacing existing single-stage heat pumps and electric furnaces. Simply specifying the equipment with the highest heating seasonal performance factor (HSPF) and seasonal energy efficiency rating (SEER) does not guarantee the best solution for customers and utilities.

This project was solely funded by the Northwest Energy Efficiency Alliance (NEEA) to develop an understanding of VSHP products and an analysis tool to identify the key products and system characteristics that provide the best value to consumers and utilities. This report outlines key findings from VCHP market research, product intelligence research, and VCHP modeling tool analysis completed for this project. NEEA staff played a significant role in the technical development of the “VCHP LCTool” and provided an advisory group to assist with calibration of the tool and development of the analysis criteria used in this report.

Technology Definition

VCHPs are heat pumps with a variable capacity compressor that modulates to meet the heating or cooling load of the building. This diverse product category includes many different systems, efficiency levels, features, and application types. This project focused on single-zone, centrally ducted VCHPs, as shown in Figure 1. These systems consist of a single outdoor unit paired with an air handler to distribute tempered air throughout the building. The term VCHP refers to this system type and application for this paper's purposes.

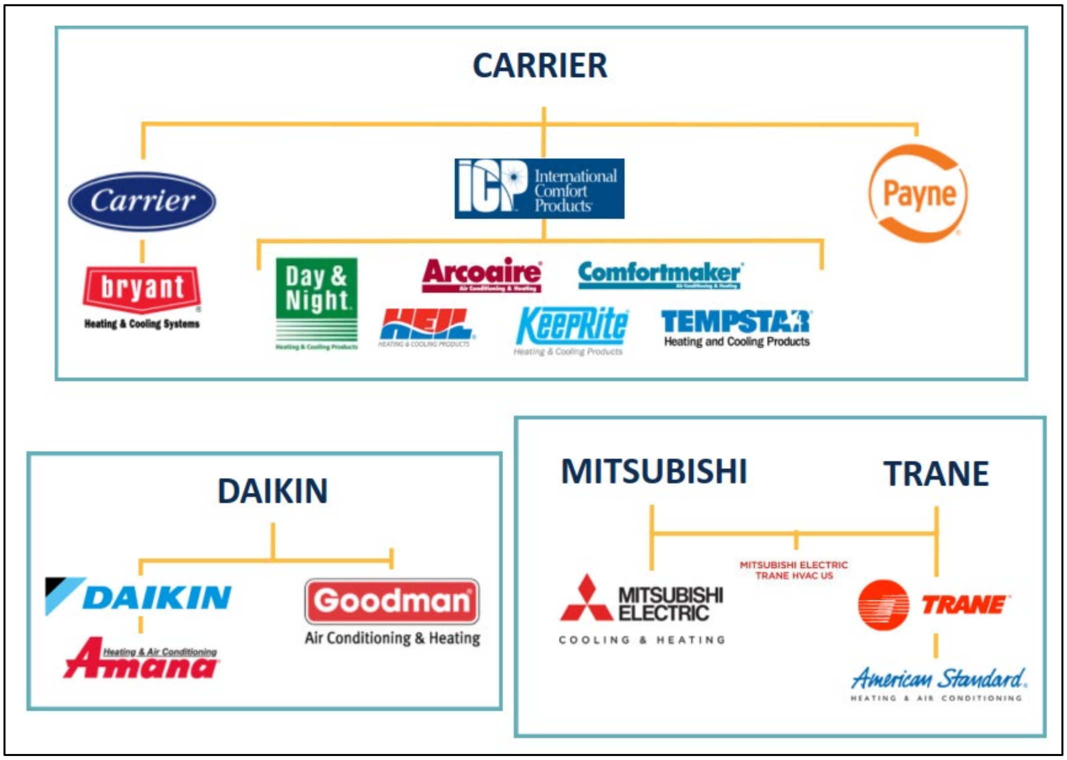
Figure 1. Single-Zone, Centrally Ducted VCHP

VCHP Market

The VCHP market is complex and consists of many manufacturers, brands, and product lines that can be paired together in seemingly infinite ways. The 5,800 VCHP systems on Northeast Energy Efficiency Partnerships' (NEEP's) air source heat pump product list (QPL) demonstrate this issue. That number represents only the subset of the product category designated for use in cold climates. However, this market can be distilled to 14 manufacturers that produce equipment for 19 brands with a total of 36 product lines.

Additionally, brands commonly offer the same VCHP equipment under a different brand or label. For example, Carrier and Bryant offer the same 16 VCHPs, sold under different product lines and model numbers within each brand. To help simplify and visualize these relationships, this paper includes a manufacturer family tree (see Appendix A: Manufacturer Family Tree). This visualization simplifies a complex market and demonstrates the relationships among manufacturers and brands. A subset of the manufacturer family tree is shown below in Figure 2.

Figure 2. Subset of Manufacturer Family Tree



Top VCHP Manufacturers

The research team collected information on each VCHP manufacturer through a market survey that included secondary research and interviews with a selection of manufacturers. The team identified the top manufacturers based on their product offerings, company size, and likely market share. Information on each of the top manufacturers is provided in more detail below. View additional details on each manufacturer in the VCHP Product Assessment database (see Appendix B:).

Carrier HVAC

Carrier HVAC, a division of the HVAC, refrigeration, and security system manufacturer Carrier Global, is one of the largest ducted heat pump system producers in the United States. With almost a dozen brands, Carrier offers low-efficiency budget lines, midrange systems, and some of the highest efficiency ducted equipment available, with the highest costs among residential ducted systems in the US. Carrier's premier HVAC brands, Carrier and Bryant, offer nearly identical lines of high-efficiency, inverter-driven heat pumps, of which the premium model boasts unequaled efficiency among ducted systems on the US market. These brands also offer a line of ductless systems. International Comfort Products, a subsidiary of Carrier, sells midrange and budget alternatives to Carrier and Bryant products through many brands with identical lines of heat pumps, including Comfortmaker, Day & Night, and Arcoaire. Payne, another Carrier brand, offers a handful of budget heat pumps.

Carrier Global, and its HVAC division, are headquartered in Palm Beach Gardens, Florida. Carrier's US workforce is among the largest for major ducted heat pump manufacturers. The company has factories throughout the country, and its residential heat pumps are manufactured in its Tennessee facility.

Daikin North America

Daikin is the world's largest manufacturer of HVAC products and has attempted to grow its market share in the United States in recent years. Its two primary brands, Daikin and Amana, offer nearly identical lines of high-efficiency, inverter-driven heat pumps, as well as furnaces and other HVAC equipment. The Daikin brand also offers a line of high-efficiency ductless heat pumps, a mixed-ducted heat pump system (VRV LIFE), and compact, whole-home ducted systems (Daikin Fit and SkyAir). Goodman, another Daikin brand, offers midrange and budget ducted heat pumps that differ in performance specifications compared to Daikin and Amana product lines.

Daikin's North American headquarters and primary manufacturing plant are located near Dallas, Texas. Daikin has a larger US workforce than Carrier, but a higher proportion of its US employees work under Daikin Applied, the company's commercial HVAC division, making their residential HVAC workforce comparable in size.

Lennox International

Lennox is a United States-based HVAC system manufacturer. Lennox offers several lines of heat pumps at varying efficiencies and price points, including three inverter-driven variable capacity systems with some of the highest efficiencies on the market. The manufacturer sells some of the same ducted equipment through Armstrong Air, though this brand only offers one VCHP system. Like Carrier's subsidiary International Comfort Products, Lennox International also owns Allied Air, which manufactures budget heat pumps sold under several brands, including Ducane, AirEase, and Concord.

Lennox International is headquartered in Richardson, Texas, and manufactures HVAC equipment in Iowa and Saltillo, Mexico. Allied Air equipment is manufactured in South Carolina. In contrast to its competitors, Lennox focuses almost entirely on manufacturing HVAC equipment and has a smaller total number of employees than other major ducted heat pump manufacturers. However, its US workforce of 11,500 is not drastically smaller than Carrier's or Daikin's HVAC divisions.

Mitsubishi Electric Cooling & Heating

Mitsubishi Electric Cooling & Heating, a division of the Japan-based global electronics manufacturer, specializes in high-efficiency air source heat pumps for residential and commercial applications. Unlike other HVAC manufacturers, Mitsubishi Electric Cooling & Heating produces only heat pumps but offers a range of configurations and a unique degree of system customization. In contrast to conventional heat pump products, for which each condensing unit pairs with a few compatible indoor units, Mitsubishi offers a more flexible modular system. It designs these products so that a few universal outdoor units can be paired with a variety of indoor units, both ductless and ducted. In addition, rather than offer the same higher-capacity outdoor condenser models like its competitors (who usually offer models of up to four to five tons), Mitsubishi designs lower-capacity outdoor units that easily combine into a single system to increase total capacity.

Ductless mini-split systems dominate Mitsubishi's lineup and are viewed as premium products among ductless systems. Though less popular than its ductless counterparts, Mitsubishi condensers can be paired with ducted air handlers. Due to Mitsubishi's innovative compatibility, some systems can be configured with both ducted and ductless indoor units in a single heating and cooling system. Mitsubishi heat pump products are all high-efficiency, inverter-driven units; unlike other manufacturers, Mitsubishi does not offer a lower-efficiency budget line.

The Mitsubishi Electric Cooling & Heating US headquarters and main US distribution facility are in Suwanee, Georgia. Among HVAC manufacturers with comparable market share in the United States, Mitsubishi is alone in importing all products rather than manufacturing them in the country. Heat pumps come from its consumer product production facility in Thailand. To aid its US HVAC distribution, Mitsubishi entered a partnership with Ireland-based Trane Technologies (a subsidiary of Ingersoll-Rand) in 2018 to form Mitsubishi Electric Trane HVAC US (METUS). This relationship is largely for distribution and branding purposes. It allows Mitsubishi to co-brand products with Trane to leverage Trane's distribution channels and registered contractors to sell Mitsubishi-manufactured products. This partnership does not operate in reverse, as Mitsubishi does not co-brand or distribute Trane-manufactured products. Including the staff of METUS, Mitsubishi has only about 1,200 US employees, making it by far the smallest heat pump manufacturer with major US distribution.

Future Product Opportunities

The market survey and manufacturer interviews also revealed a significant product and market opportunity: the replacement of existing air conditioners with heat pumps. Historically, this has been a difficult sell because most heat pumps require an upgrade to the existing furnace or air handler, and customers are not willing to pay extra to replace both. Bosch's relatively new Bova line addresses this barrier by offering an outdoor unit with an A-coil that can be paired with any existing furnace. This product has gained significant market share in areas where contractors are familiar with the product's capability and ease of installation. These contractors highlight the benefits of modulation and efficiency and upsell it to homeowners looking for an air conditioner replacement.

Mitsubishi is also launching a product in this category in early 2022. The project team worked with Mitsubishi on a pre-commercial pilot of this product and interviewed contractors and homeowners that had it installed in the Northwest. Findings from this research and a more detailed overview of this product category are not published as they fall under a non-disclosure agreement between NEEA and Mitsubishi.

Manufacturer Database

The VCHP manufacturer database developed for this project (see Appendix B) provides a detailed expansion of the manufacturer family tree. It outlines the corporate owner, brands, and product lines within each family. The database has information on the company and where its equipment is manufactured, as well as details on each product line. This includes modulation or number of stages, unit nomenclature, SEER, HSPF, product sizes, and whether it is on NEEP's QPL. The database denotes whether each VCHP can be paired with a gas furnace and whether the product has an A-coil potential paring. The complete database can be found in Appendix B**.** Figure 3 shows the Carrier portion of the database.

Figure 3. Carrier Portion of Manufacturer Database

Corporate Owner	Brand	Product Line	OEM	Modulation (# Stages or VC)	Unit	SEER	HSPF	Sizes	Cold Climate HP (80% capacity at 5F)	NEEP QPL Listed (VC systems)
Carrier (United Technologies)	Carrier	Infinty	Carrier US Tennessee Facility (residential condensing units and heat pumps)	VC	25VNA4	24	13	2-5 tons	Yes	Yes
				VC	25VNA0	20.5	13	2-5 tons	Yes	Yes
				5	25VNA8	19	11	2-5 tons		
				2	25HNB6	17.5	9.5	2-5 tons		
				2	25HNB6**C	17.5	9.5	2-5 tons		
		Performance		2	25HCB6	17	9.5	2-5 tons		
				1	25HCC5	16	9	2-5 tons		
				1	25HHA4	14	8.2	2-5 tons		
				1	25HPB6	16	9.5	2-5 tons		
		Comfort		1	25HBC5	15	8.5	2-5 tons		
				1	25HCE4	14	8.2	2-5 tons		
	Comfortmaker (International Comfort Products)	Ion		VC	CVH8	19	11	2-5 tons	No	Yes
				2	CCH6	17.5	9.5	2-5 tons		
				1	CSH6	16	9	2-5 tons		
				1	CSH5	16	9	2-5 tons		
				1	CSH4	14	8.2	2-5 tons		
		Performance		1	N4H6	17.5	9.5	2-5 tons		
				1	NXH5	15	8.5	2-5 tons		
				1	NXH6	15	8.5	2-5 tons		
				1	NH4H4	14	8.2	2-5 tons		
				1	NH4H4**C	14	8.2	2-5 tons		
				1	N4H4	14	8.2	2-5 tons		
	Payne	Heat Pumps		2	PH16NA	17	9.5	2-5 tons		
				1	PH16NC	16	9	2-5 tons		
				1	PH15NB	15.5	9	2-5 tons		
				1	PH14NB	14	8.2	2-5 tons		

Pricing

Based on interviews with manufacturers, the best way to find consistent pricing information is to look up equipment costs through online marketplaces. These online storefronts offer distributors a low-cost way to sell equipment. These prices typically represent the base cost at which manufacturers allow their equipment to be sold, known as the minimum allowable price. These data, as well as the source for each price, are included in the manufacturer database with a focus on variable capacity equipment.

The price analysis from online distributors highlights several trends in heat pump pricing. Compressor modulation (single-stage versus two-stage versus variable capacity) significantly affects the price among ducted heat pumps. On average, a variable capacity ducted system costs about 20% more than a two-stage system of similar efficiency from the same brand. Heat pump brand also accounts for variation in VCHP price. Not all price disparity can be associated with variable capacity, as some brands have consistently higher prices for all types of units. For example, though Carrier offers some of the highest efficiency VCHPs on the market, even its lower efficiency systems consistently cost more than comparable variable capacity systems from other major brands, such as Daikin and Trane. After Carrier, Trane produces the most expensive heat pumps, followed by Lennox and Daikin/Amana.

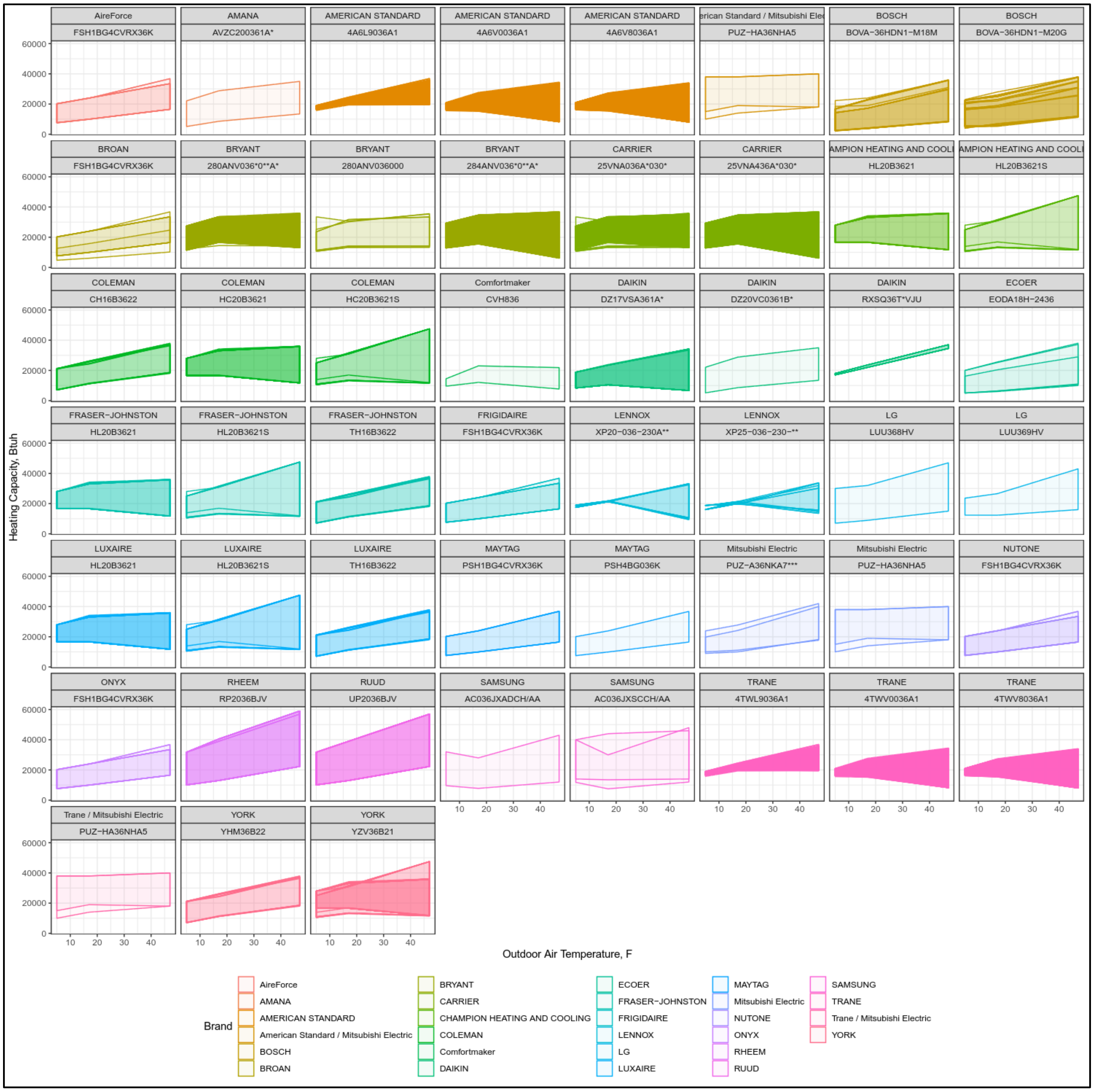
Analysis of price differences within the VCHP product category also provides insights. The price data suggest that cooling efficiency impacts system price more than the impacts of heating capacity or performance. For example, the price of all 21-SEER VCHPs varied at most by ±10% from the mean, even though these systems have different heating capacities and performance levels. In contrast, the average 23-plus-SEER VCHP costs 28% more than the average 21-SEER VCHP, showing a clear link between SEER and price.

VCHP Archetypes

An early evaluation of the coefficient of performance (COP) and capacity curves of every VCHP system in NEEP's QPL revealed the range of VCHP system performance. Figure 4 illustrates this range; each graph shows the system capacity versus outdoor air temperature for three-ton systems on NEEP's QPL. This initial analysis led to the development of HP archetypes that represent the variety of performance on the market today and the performance metrics that define these archetypes.

The data shown in figure 4 was produced from the NEEP database from 2021. NEEP provides public access to individual heat pump product data at https://ashp.neep.org/#!/. Subscribing funders of the database can download complete copies of the data if desired.

Figure 4. VCHP Capacity Curves



Archetype Metrics

The research team developed heat pump performance metrics to quantify and compare VCHP performance across a wide range of available products. These metrics quantify HP performance using data currently available from the manufacturers, listed on NEEP's QPL, or both. The team developed these metrics for three key areas that help define and differentiate heat pump performance: modulation, capacity, and COP.

Modulation

Modulation defines a system's ability to vary its capacity between maximum and minimum across a range of outdoor air temperatures. Modulation is important at moderate temperatures when a home's heating load is low. Heat pumps with better modulation reduce on and off cycles during low-load conditions, resulting in better system efficiency.

The "**modulation ratio**" defined below provides a single metric that focuses on the size or tonnage of the system and the minimum capacity output at a moderate temperature of 47°F. Rated capacity at 95°F is used as a proxy for the system's size or tonnage because this is the most common and consistent way that manufacturers report the tonnage of a system. The team considered, but did not use, maximum or rated capacity at 47°F because maximum capacity at 47°F is not reported as consistently and therefore may be easier for manufacturers to modify, thus creating the illusion of better modulation. Minimum capacity at 47°F is reported through AHRI and indicates a system's ability to modulate to low capacities at moderate temperatures. The modulation ratio metric allows one to easily compare the ability of all three-ton systems (or any other size) to modulate down to low-capacity outputs at moderate temperatures.

Modulation Ratio = Rated Capacity at 95°F / Minimum Capacity at 47°F

Capacity

Capacity is a measurement of the system's ability to maintain maximum capacity output at low temperatures. The "**capacity ratio**" metric defined below also uses rated capacity at 95°F as a proxy for the system size or tonnage. This is compared to the maximum capacity output at 5°F to determine the system's ability to maintain its rated capacity, or tonnage, at low temperatures.

The "**capacity slope**" metric outlined below is used to determine whether a system has a steep drop in capacity at lower temperatures. This can affect a system's overall performance at low temperatures because more backup heat is needed if the system's maximum capacity output cannot meet the home’s heating load. Systems with better capacity ratios and capacity slopes reduce the need for backup heat.

Capacity Ratio = Maximum Capacity at 5°F / Rated Capacity at 95°F

Capacity Slope = Maximum Capacity at 5°F / Maximum Capacity at 17°F

Coefficient of Performance (COP)

COP is an important metric that measures how efficiently a heat pump delivers energy. Manufacturers report a system’s COP through AHRI testing at 47°F and 17°F, so these values are readily available. The “**low-load COP**” metric outlined below indicates a system’s ability to deliver heat efficiently at moderate temperatures and low loads. This metric is key because most climates have substantial heating hours at moderate temperatures.

The “**high-load COP**” metric indicates a system’s ability to deliver heat efficiently at low temperatures. This metric uses AHRI reported values for maximum capacity output at 17°F. NEEP’s QPL also reports maximum capacity COP at 5°F, but 17°F was chosen for this metric because AHRI has more stringent reporting requirements and these two values correlated strongly. The result is that a system with a good COP at max capacity 17°F also had a good COP at max capacity at 5°F.

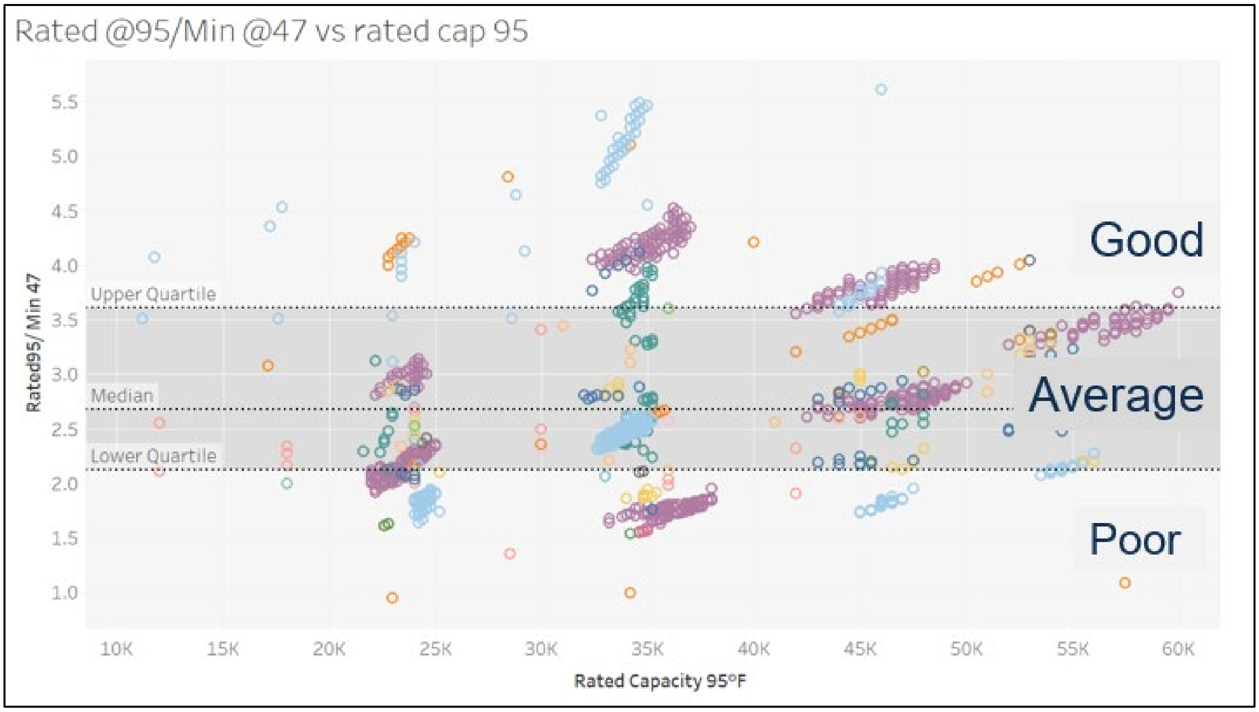
Low-load COP = COP at minimum capacity at 47°F

High-load COP = COP at maximum capacity at 17°F

Archetype Metrics Market Analysis

The archetype metrics outlined above were applied to the VCHP products on NEEP’s QPL to determine the values that represent good, average, and poor performance for each metric. Good is defined as the top 25% of products, average as the middle 50%, and poor as the bottom 25%. Figure 5 visualizes this analysis.

Figure 5. Modulation Ratio Analysis



The team completed this analysis for each metric, and the values in Table 1 show the results. These values reveal the relative performance of products on the market and help separate and define excellent performance for each metric. *Notably, no single product is excellent, or even good, at every metric.* This analysis revealed the difficulty, if not impossibility, of designing a product that maintains capacity well and has good COP metrics; one must be sacrificed to achieve the other. These are key decisions that manufacturers are likely to make during product design. The modeling tool and this analysis facilitate a better understanding of the metrics with the most significant impacts on performance.

Table 1. Archetype Metrics

	ModRatio	CapRatio	CapSlope	LowLoadCOP	HighLoadCOP
	Rated @ 95 / Min capacity 47	Capacity Max5 / Rated @ 95	Capacity Max5/Max17	COP at minimum output @ 47	COP at maximum output @ 17
Excellent: top 10%	4.3	1.0	0.97	5.2	2.8
Good: top 25%	3.60	0.83	0.88	5.0	2.6
Market Mean Value	2.7	0.59	0.79	4.0	2.4
Poor: bottom 25%	2.2	0.54	0.75	3.8	2.1
Worst: bottom 10%	1.00	0.50	0.50	3.5	1.0

Archetypes

The research team developed heat pump archetypes for this analysis using the above data. Each archetype represents a system that exemplifies performance in one key category based on the metrics above. These archetypes also represent the variety of systems available on the market today; they include a reference VCHP, as well as market average one-stage and two-stage archetypes for comparison. These systems were modeled as archetypes and do not correlate to specific makes and models, but each archetype has at least one product that fits the archetype definition. Therefore, the archetypes are realistic and not simply arbitrary systems that do not exist on the market. Archetype names are intended to be descriptive of the core performance characteristics, as follows:

- Reference VCHP: average performance of variable capacity heat pumps
- Capacity Champ: superior low temperature capacity heat pump, not just good COP
- COP King: excellent COP across a wide range of performance
- Modulator: average performance, with high ModRatio
- Mild Master: superior performance during low load (mild climate) conditions
- Average Two: average performance of two speed heat pumps
- Average One: average performance of single speed heat pumps

Table 2. Heat Pump Archetypes

	ModRatio	CapRatio	CapSlope	LowLoadCOP	HighLoadCOP
Archetype	Rated @ 95 / Min capacity 47	Capacity Max5 / Rated @ 95	Capacity Max5/Max17	COP at minimum output @ 47	COP at maximum output @ 17
Reference VCHP	3.00	0.60	0.80	4.00	2.40
Capacity Champ	2.50	1.00	1.00	4.00	2.40
COP King	2.50	0.60	0.80	5.40	2.80
Modulator	5.00	0.60	0.80	4.00	2.40
Mild Master	3.50	0.50	0.80	5.00	2.60
Average Two	1.30	0.50	0.50	3.80	3.00
Average One	1.00	0.50	0.50	3.60	2.40

Incorporating these archetypes into the modeling tool allows us to explore the impacts of these metrics, or heat pump capabilities, on energy use, cost, and peak demand across different climates and house types, as described in the tool features outlined in the next section.

VCHP Levelized Cost Tool

The modeling tool developed for this project ("VCHP LCTool.xlsx") enables the user to generate levelized heating and cooling costs for different types of heat pumps under different climates, operating ranges, rates, and system costs. This allows a user to compare the relative merit of the performance metrics outlined above under various climates, use cases, energy price scenarios, and controls. The tool uses an 8,760-hour energy balance model that calculates the energy consumption and heating or cooling delivered for every hour of the year. **Appendix C: VCHP Tool Calibration** details how the tool calculates performance and energy use and how it was calibrated. The following sections describe the core calculational components (modules) within the tool.

House Types

The tool includes five generic house types that range in size, shape, and heating load. These include a sprawling ranch, a two-story home, a new home, an old home, and a solar-sensitive home. The tool also allows users to enter their home characteristics related to UA (U-value*area), infiltration, ventilation, and volume, among other features.

Location

The tool includes eight locations from across the country, with a focus on the Northwest. The tool uses typical annual meteorological data (TMY3, third iteration), organized by the National Renewable Energy Laboratory (NREL). These data are generated by creating a distribution plot of 15 years of weather data and selecting the most representative instance of each month over that 15-year period. The actual weather data from each of those representative months are then aggregated into TMY3 data and included in the tool for each city.

Utility and Customer Rates

The tool is designed to model and compare two rate structures: a customer rate and a utility rate. Each rate structure has five predefined rate options: flat, hourly, daily, winter, and summer. The utility rate structure has an additional option of "super," which allows the user to choose a specific day, a number of hours, and a rate for a price change. These rate structures allow the user to compare the costs associated with the utility and the customer for the modeled scenario.

VCHP Selection

The tool includes two heat pump options for selecting equipment—NEEP's QPL and the previously-described VCHP archetypes. Any system on NEEP's QPL can be selected using its Air-Conditioning, Heating, and Refrigeration Institute (AHRI) index number. Selecting equipment from the NEEP QPL requires the user to choose a system that is properly sized for the heating and cooling load of the selected house type. Conversely, the VCHP archetypes are automatically sized to meet the home's heating load at the heating design temperature or a user-selected temperature, described further in the sizing section below.

Capabilities

Sizing

The VCHP modeling tool is designed to scale the size of the VCHP archetypes to meet the heating load for the home at the design heating temperature (99^{th} percentile of outside air temperature (OAT)). The user can then adjust the size of the heat pump in two ways. One is through a sizing factor, which allows the user to oversize or undersize the heat pump by entering a percentage; the other is by entering a design temperature to which the user would like the heat pump to be sized. For example, a user could enter 30°F, and the heat pump would be sized to meet the home's heating load at that temperature. The user can also choose the tonnage of the VCHP archetypes, which allows for a simple comparison of all archetypes of the same size rather than sizing based on a design temperature. These options enable the user to modify the size of the heat pump and evaluate the impact on performance, cost, and energy use.

Pricing

The team developed the pricing model within the tool through work with an experienced heat pump contractor. This model includes the cost of equipment, labor, parts, permits, overhead, and profit. The equipment costs were generated from a secret shopper exercise completed by the heat pump contractor for various VCHP products. These data were then applied to HP archetypes (see Table 2), with the Capacity Champ and COP King defined as premium products with a higher equipment cost. The remaining VCHPs were the next tier down in cost, followed by the two-stage and one-stage archetypes. The equipment costs are then adjusted based on the size of the HP, and the sales price is calculated at that point. An option also exists for the user to enter equipment cost into the tool.

Outputs

The tool generates a myriad of outputs related to the energy use, performance, and cost for each model run. These are saved in an iteration database within the tool that can compare runs and analyze results. An overview of some key outputs from the tool is outlined below.

Table 3. Overview of Key Outputs

Category	Outputs
Energy Use	• Total energy use • Heating energy use • Cooling energy use • ER backup energy use • Defrost energy use • Peak demand for 1 hour • Summer Peak • Winter Peak
Heat Pump Performance	• Heating COP • Cooling COP • HP balance point • Hours above max capacity • Hours below minimum capacity
Cost	• Total customer and utility costs • Cost of heating • Cost of cooling • Levelized cost of heating (present value) • Levelized cost of cooling (present value)

VCHP Analysis

The VCHP tool is designed to complete a multitude of modeling runs through which the detailed inputs and outputs can be compared. The user selects a specific set of design and operating conditions, runs the model, and then adjusts these inputs, creating additional iterations. These modeling runs are saved in an iteration database so that they can be compared across the detailed outputs from the model. The team completed an initial analysis for a cold climate—Bozeman, MT, and a mild climate—Portland, OR. This analysis compares the energy use, levelized cost, and peak demand for every HP archetype across various HP sizes.

Cold Climate—Bozeman, MT

Methodology

The cold climate modeling runs were designed to compare each of the seven HP archetypes across a variety of sizes. For this analysis, the house type, customer rates, and additional performance factors (described below) remained fixed. The HP archetypes and their defining performance metrics can then be compared to determine which HP metrics result in lower energy use, reduced peak, and lowest levelized cost of ownership.

Each HP archetype was sized to meet the heating load at four design temperatures: -6°F, 5°F, 17°F, and 30°F. These will help determine which design temperature leads to the lowest levelized cost and lowest energy use while evaluating the benefits of better capacity metrics. For example, the Capacity Champ archetype can meet the home's heating load at 5°F with a 3.5-ton system, while every other HP archetype requires a 6-ton system or larger. The results from these modeling runs are presented below in sections on energy use, levelized cost, sizing, and a summary of findings.

Energy Use

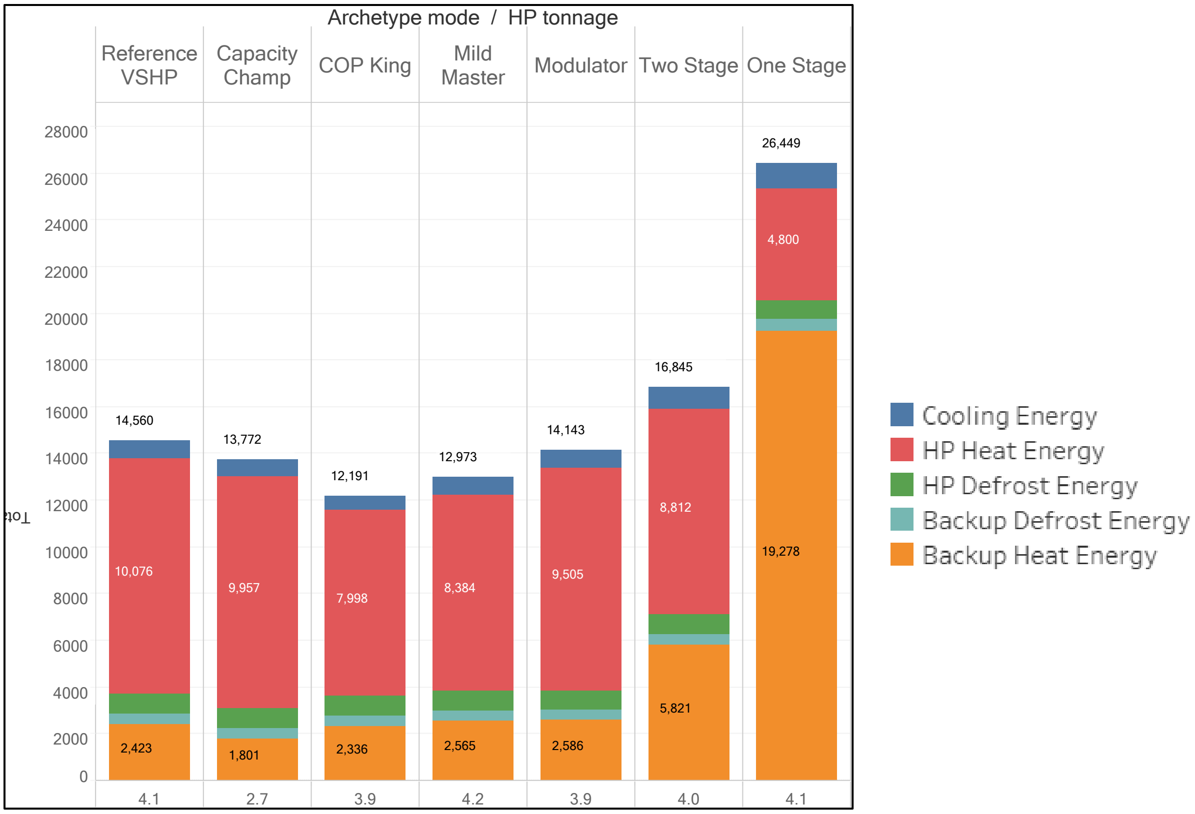
The table below compares the total energy use for each HP archetype. These systems were sized to meet the heating load at 17°F, which resulted in the lowest levelized cost of ownership (discussed further in the Levelized Cost section). Each archetype's energy use is compared to the Reference VCHP.

Table 4. Bozeman Total Energy Use Results

Archetype	Total Energy Use (kWh)	Energy Use Comparison	Percent Difference	Sales Price
Reference VCHP	14,560			$11,344
Capacity Champ	13,772	(788)	-5%	$11,777
COP King	12,191	(2,369)	-16%	$12,688
Mild Master	12,973	(1,587)	-11%	$11,432
Modulator	14,143	(417)	-3%	$11,195
Two-stage	16,845	2,285	16%	$9,432
One-stage	26,449	11,889	82%	$8,247

The COP King had the lowest annual energy use of all the archetypes, using 16% or 2,369 kWhs less energy than the Reference VCHP. The Mild Master had the second lowest total energy use, with the One-stage system using the most energy by a large margin. Figure 6 illustrates the results of additional analysis of annual energy use for these archetypes.

Figure 6. Total Energy Use by Source—Bozeman, MT

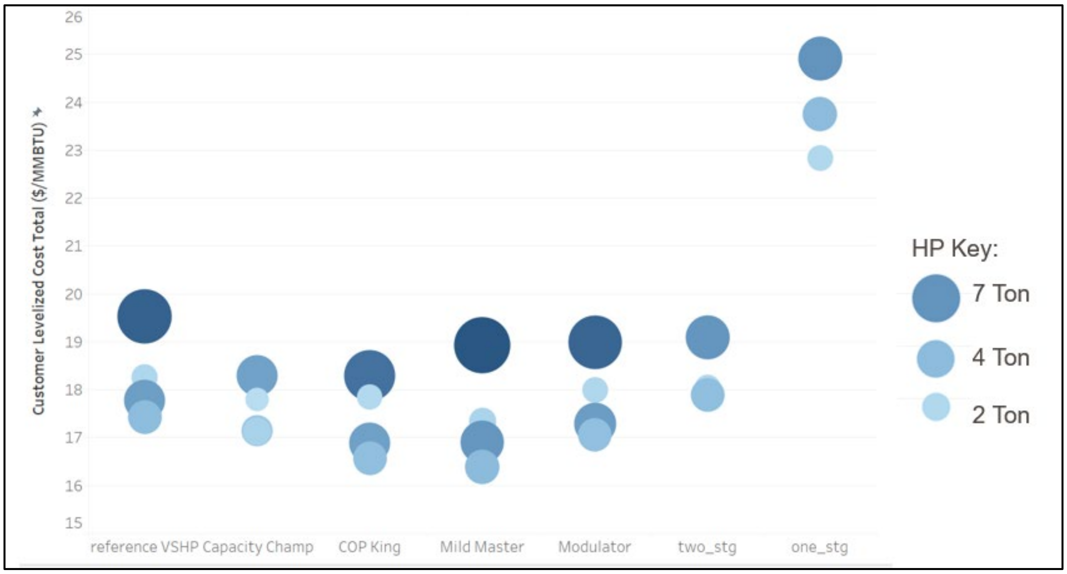


The red bars show the energy use from the HP during normal operation. The orange bar is electric resistance (ER) backup energy use. The One-stage was modeled with backup ER heat being used below 35°F; this resulted in a large amount of electric resistance backup heat energy use in Bozeman. The Capacity Champ archetype used the least amount of ER backup, but the COP King and Mild Master still had the lowest total energy use. This reflects the COP performance metrics for each archetype. Defrost energy use, represented by the green and teal bars, was similar among all systems, and cooling constituted a relatively minor load in Bozeman, as shown by the dark blue section.

Levelized Cost

This analysis defines levelized cost as the present value of the lifetime costs, which include install cost, maintenance, and operation (energy use) divided by the energy delivered over the system's lifetime. The figure below shows the levelized cost for each HP archetype and every HP size included in the analysis. The size of the HP is reflected by the size of the dot and the darkness of the color. The key provides a reference for the relative size and color of a specific HP tonnage. The darkest blue dots in the Reference, Mild Master, and Modulator heat pumps indicate 10+ ton sized heat pumps. The sizing section below provides further details on how each archetype was sized.

Figure 7. Levelized Costs by HP Size—Bozeman, MT

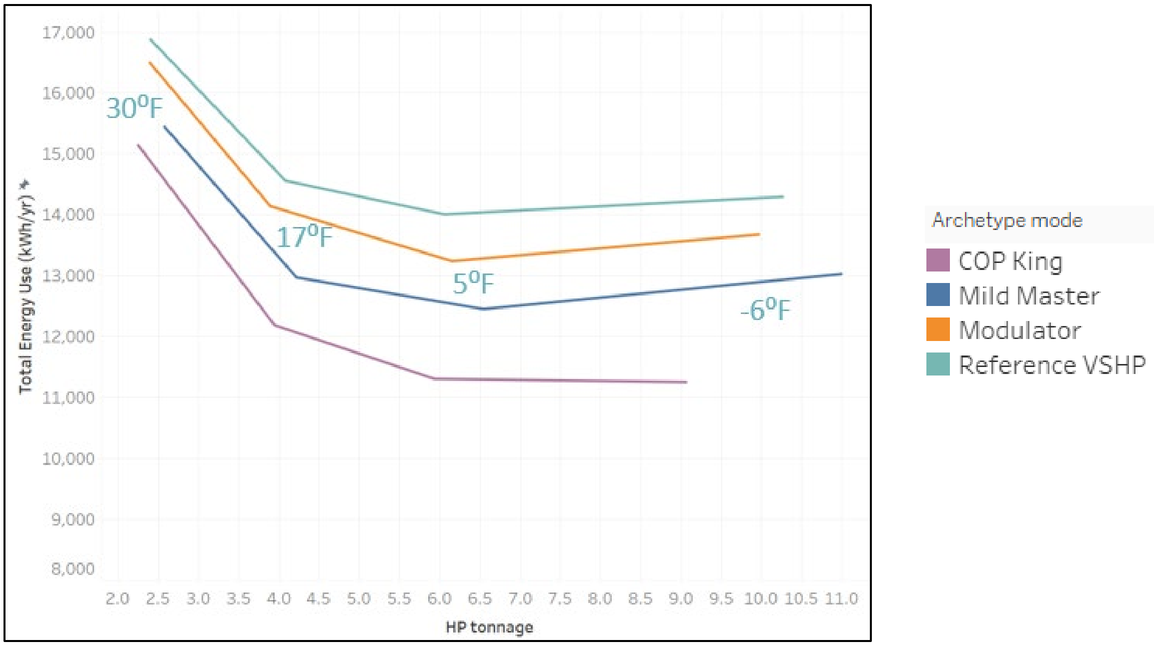


The Mild Master had the lowest levelized cost at $16.40 per lifetime MMBtu delivered. COP King ranked second with a cost of $16.60 per MMBtu. The COP King had almost the lowest levelized cost even though it had the highest sales price, as shown above in Table 4; its lower annual energy use drove this. The Mild Master showed a good mix of low energy use and a lower price point. Notably, sizing systems to meet the home's heating load at 17°F resulted in the lowest levelized cost for all archetypes (Capacity Champ was the same for both 17°F and 5°F). This shows that the additional cost for a larger HP was not justified by the additional energy savings a larger system delivers; more detail is provided in the following section on sizing.

Sizing

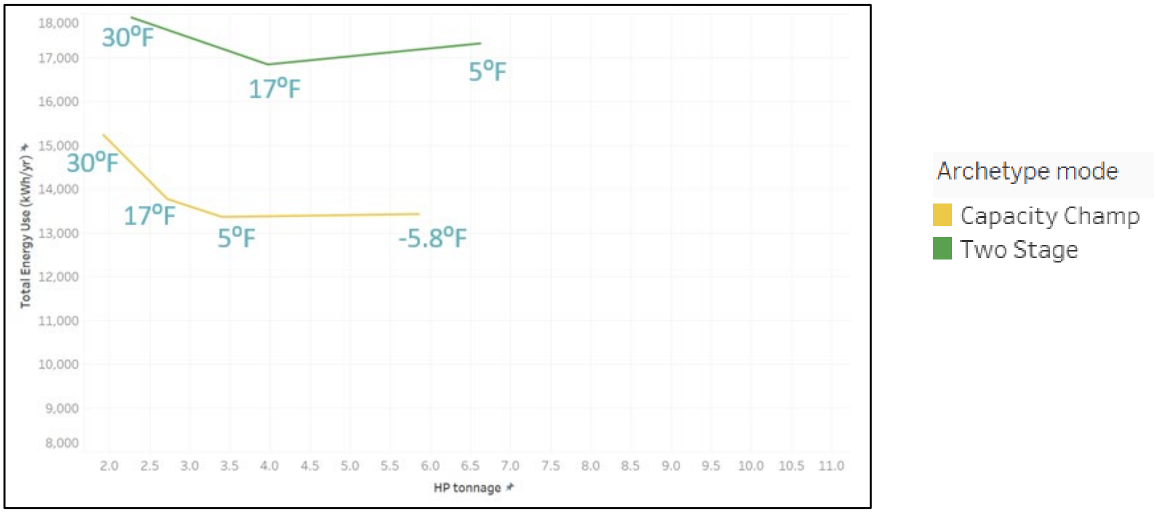
As mentioned earlier, each archetype was sized to meet the heating load at four temperatures: -6°F, 5°F,17°F, and 30°F. Figure 8 shows the energy use versus the HP size for most HP archetypes. Each archetype followed the same general trend with smaller heat pumps resulting in more energy use; this was driven by ER backup energy use when the HP cannot meet the home's heating load. As the size of the HP increased, energy use decreased, but eventually, it plateaued and even went up. At this point, the HP was greatly oversized, which resulted in more energy use from the system cycling on and off. In general, the lowest annual energy use occurred when the system was sized to meet the heating load at 5°F.

Figure 8. Total Energy Use by HP Size—Bozeman, MT



Additionally, the Capacity Champ and Two-stage archetypes exhibited unique variations on a similar pattern. The Capacity Champ could meet the heating load at each design temperature with a much smaller system, and the Two-stage system's total energy use increased between the design temperatures of 17°F and 5°F, as shown in Figure 9.

Figure 9. Total Energy Use vs. HP Tonnage—Capacity Champ & Two-Stage—Bozeman, MT



Cold Climate Summary

Sizing a system to meet a home's heating load at 5°F yielded the lowest annual energy use; however, the lowest levelized cost was achieved when a system was sized to meet the load at 17°F. This is due to the increased equipment cost for a larger system, which the resultant lower annual energy costs do not outweigh.

The two archetypes with the best COP metrics resulted in the lowest annual energy use and the lowest levelized cost. These systems outperformed archetypes with better capacity, modulation, and equipment cost metrics. This held true when considering utility system peak as well as peak demand, which was the same for all archetypes. The **Peak Energy Use** section below covers this in greater detail.

Mild Climate—Portland, OR

Methodology

Similar to the cold climate modeling, the mild climate modeling runs compared each of the seven HP archetypes across a variety of sizes. Again, some tool inputs remained fixed, so energy use, peak demand, and levelized cost could be easily compared across HP archetypes.

For this analysis, the HP archetypes were sized to meet the home's heating load at 17°F, 31°F, and 40°F. The results of these modeling runs are broken out below into sections on energy use, levelized cost, and sizing, as well as a summary of findings.

Energy Use

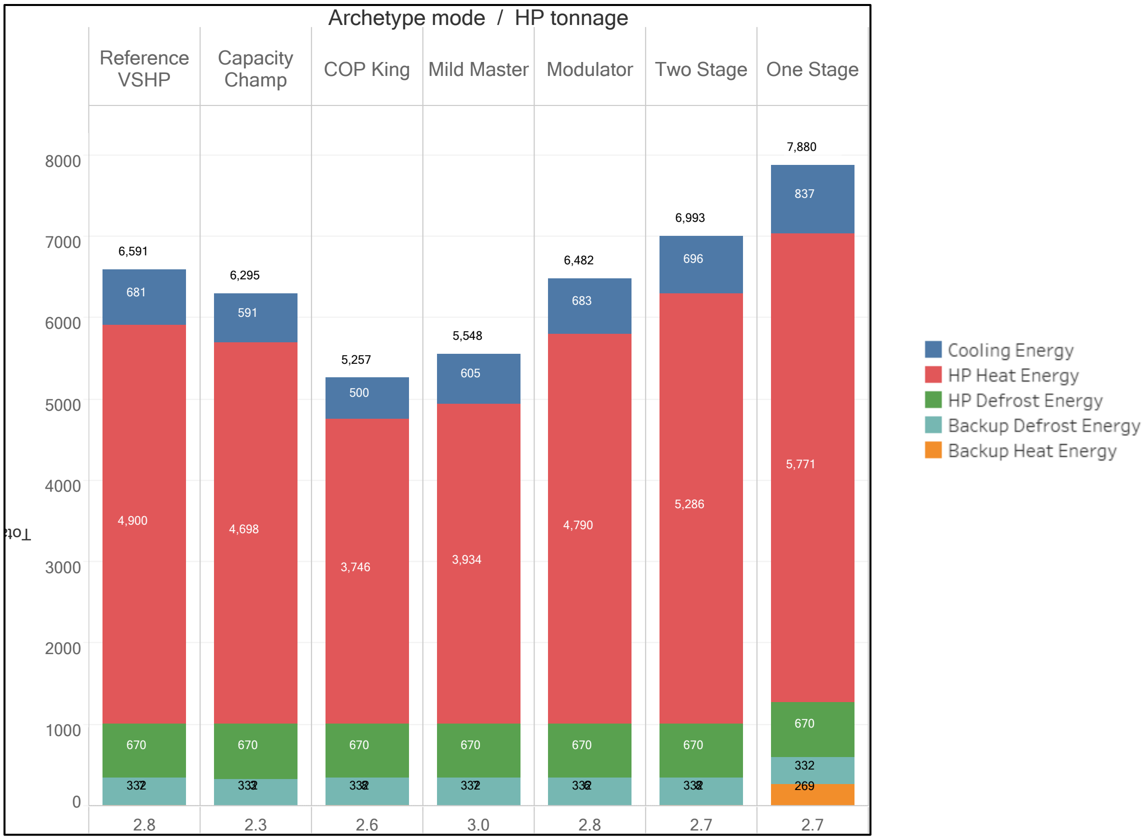
The table below summarizes a comparison of the total energy use for each HP archetype. These systems were designed to meet the heating load at 31°F, which resulted in the lowest levelized cost of ownership (discussed further in the Levelized Cost section that follows). Each archetype's energy use is compared to the Reference VCHP.

Table 5. Portland Total Energy Use Results

Archetype	Total Energy Use (kWh)	Energy Use Comparison	Percent Difference	Sales Price
Reference VCHP	6,591			$10,300
Capacity Champ	6,295	(296)	-4%	$11,400
COP King	5,257	(1,334)	-20%	$11,700
Mild Master	5,548	(1,043)	-16%	$10,400
Modulator	6,482	(109)	-2%	$10,300
Two-stage	6,993	402	6%	$8,615
One-stage	7,880	1,289	20%	$7,300

Again, the COP King and Mild Master produced the lowest annual energy use, with the COP King using 20% less energy than the Reference VCHP. Additionally, the mild climate results for the Two-stage and One-stage archetypes were more comparable to the Reference VCHP. In Bozeman, the Two-stage and One-stage archetypes used 16% and 82% more energy, but in Portland, they only used 6% and 20% more energy, respectively. Figure 10 provides a further breakdown in energy use by archetype.

Figure 10. Total Energy Use by Source—Portland, OR

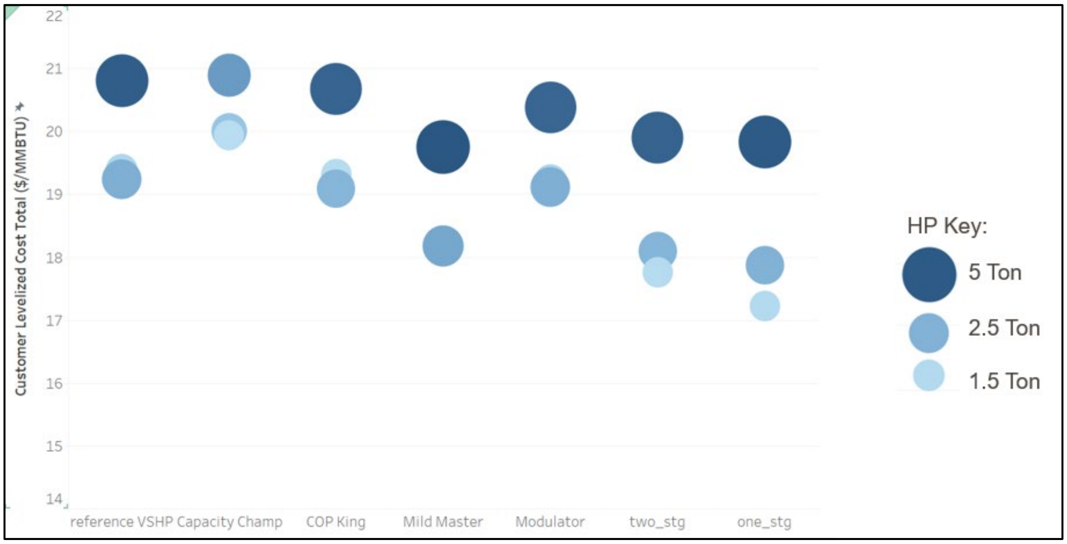


These systems were sized to meet the heating load at Portland's design temperature of 31°F (99th percentile), so little to no ER backup is needed. The One-stage archetype still used some ER backup (269 kWh) because it does not have frost protection, so the HP does not operate below freezing. Additionally, defrost energy use made up a larger portion of the overall energy use of the system compared to the Bozeman, MT analysis. This is due to Portland's humid climate and increased hours at moderate temperatures. Again, the COP King and Mild Master had the lowest annual energy use, driven by lower HP heating energy use (red bars), which shows the impact of good COP metrics.

Levelized Cost

The levelized cost results for every Portland modeling run are shown in Figure 11. The tonnage of each archetype was determined by the size needed to meet the home load at the design temperature, as discussed in the sizing section. These results differ from those for the cold-climate runs, as the One-stage, Two-stage, and Mild Master had the lowest levelized costs. Note the 1.5-ton systems were sized to meet the heating load at 40°F, which resulted in systems that were too small to meet the full cooling load. These systems should not be considered when evaluating levelized cost, as they save on annual operating cost by not delivering the necessary cooling load to keep the homeowner comfortable.

Figure 11. Levelized Costs by HP Size—Portland, OR

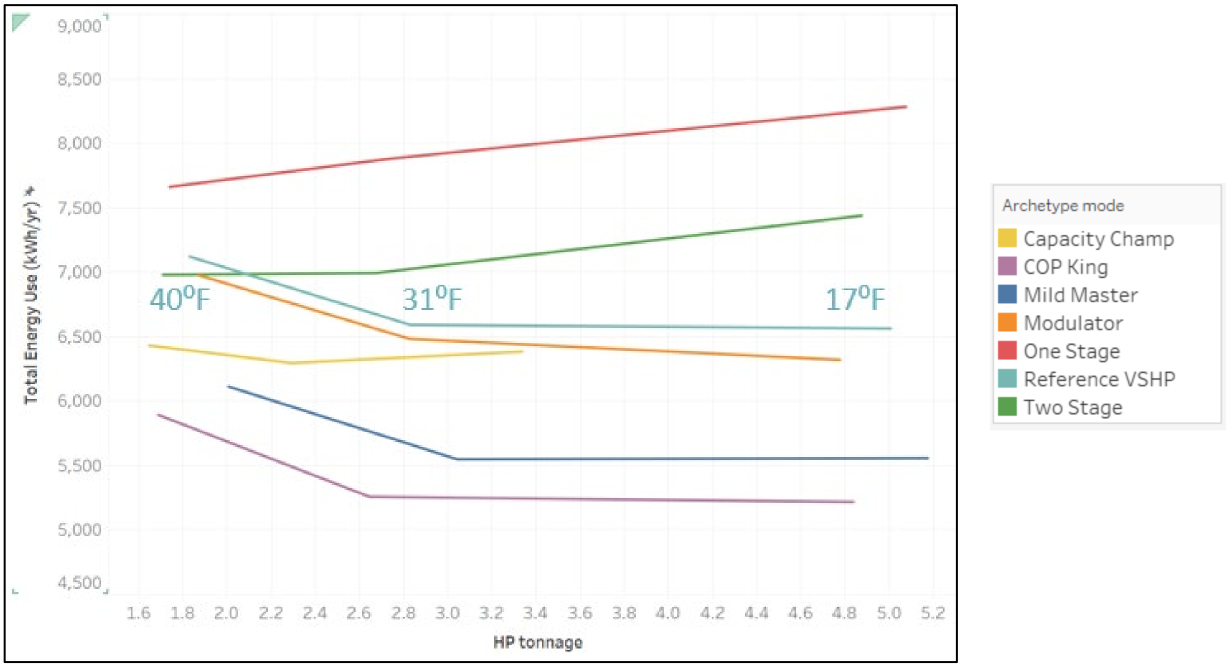


The One-stage archetype had the lowest levelized cost at $17.90 per lifetime MMBtu delivered. The Two-stage followed closely at $18.10 and the Mild Master at $18.20. These results were achieved when the archetypes were sized to meet the heating load at 31°F, which, interestingly, is 5°F warmer than the design temperature in Portland. The install cost drove these results, as the Mild Master used 30% less energy than the One-stage system and 20% less than the Two-stage system, but the One-stage system is $3,100 cheaper than the Mild Master. Given Portland's mild climate, upfront cost becomes a more significant factor in the levelized cost equation because every system's annual operating costs are lower. The Mild Master still has a levelized cost very similar to those for the One-stage and Two-stage systems and offers additional benefits as a VCHP. With a small change to the equipment cost, possibly through a rebate, the Mild Master would offer the lowest levelized cost.

Sizing

Each archetype was sized to meet the heating load at three temperatures: 17°F, 31°F, and 40°F. For most HP archetypes, the lowest annual energy use occurred when the HP was sized to meet the load at 31°F. The One-stage and Two-stage systems had the lowest energy use when sized at 40°F. This is partially because these systems were too small to meet the cooling load when sized in this manner. These systems also experienced less performance degradation from cycling on and off when sized at 40°F, which is closer to the majority of Portland's heating hours than is 31°F.

Figure 12. Total Energy Use by HP Size—Portland, OR



The Modulator had the lowest energy use when sized at 17°F. The system demonstrated the benefits of better modulation capabilities because this oversized system was still able to modulate to lower capacity outputs at mild temperatures due to reduced degradation in performance caused by cycling on and off during mild outdoor conditions. The remaining VCHP archetypes showed similar trends for sizing, with increased energy use for smaller systems that need ER backup and similar annual energy use when sized at either 31°F or 17°F.

Mild Climate Summary

The HP archetypes with the best COP metrics had the lowest annual energy use; however, even though the COP King has a higher COP, the increased equipment cost of the COP King resulted in a higher levelized cost than the Mild Master archetype. The Mild Master, therefore, proved to offer the best bang for the buck of any system archetype. The lower first cost single and two speed systems could be attractive to consumers, as they have lower upfront costs and lower levelized costs when compared to VCHPs, but will have higher levelized cost than the Mild Master.

Somewhat surprising is that sizing at 31°F produced the lowest levelized cost of ownership for every HP archetype that could meet the summer cooling load. This consistency could be used as design guidance on how to size systems in mild climates. The lowest levelized cost may occur at lower temperatures if the peak cost of power is added to the calculation. Sizing in any climate should always have some range of reserve capacity to ensure customer comfort when the house is cold and needs to be heated up or to ensure some buffer against diminished capacity as the system ages. Sizing for 110%–120% of design load would likely constitute more appropriate design guidance, assuming the sizing calculations are done without any exaggeration of heat loss rates.

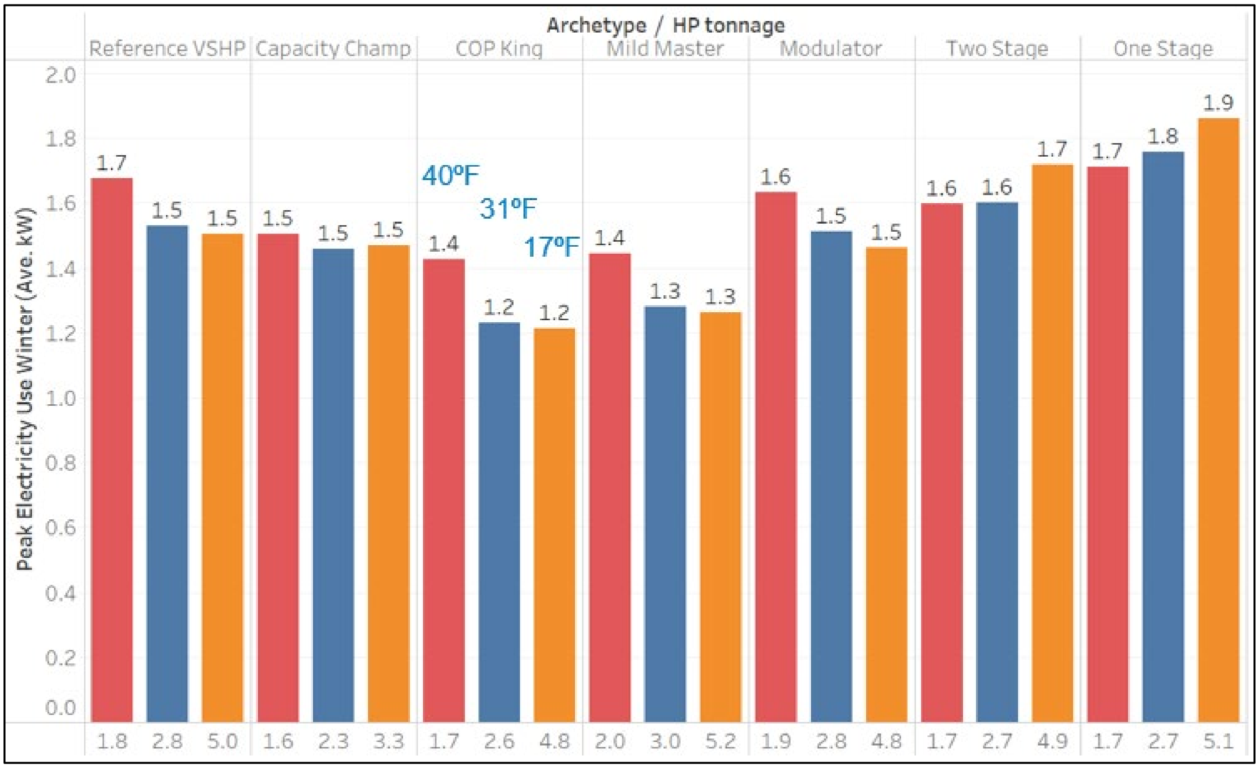
Peak Energy Use

In addition to annual energy use, peak energy use is a key consideration for utilities. The team evaluated peak energy use in two ways. The first is the utility system peak, meaning the time of day when homeowners typically consume the most energy. For this analysis, the team chose 6:00 p.m. and used January to evaluate the utility system's winter peak. The second evaluation method involved comparing the single hour with the highest energy use, defined as peak demand, across the modeling runs. Below are the results for Portland and Bozeman.

Portland, OR

Figure 13 shows the average kW usage for each archetype during the utility system winter peak, defined as the average kW usage at 6:00 p.m. in January for every archetype at each design temperature. These results mirror the lowest annual energy use results, with the COP King and Mild Master archetypes producing the lowest utility system peak energy use. The results also indicate little benefit from oversizing these systems.

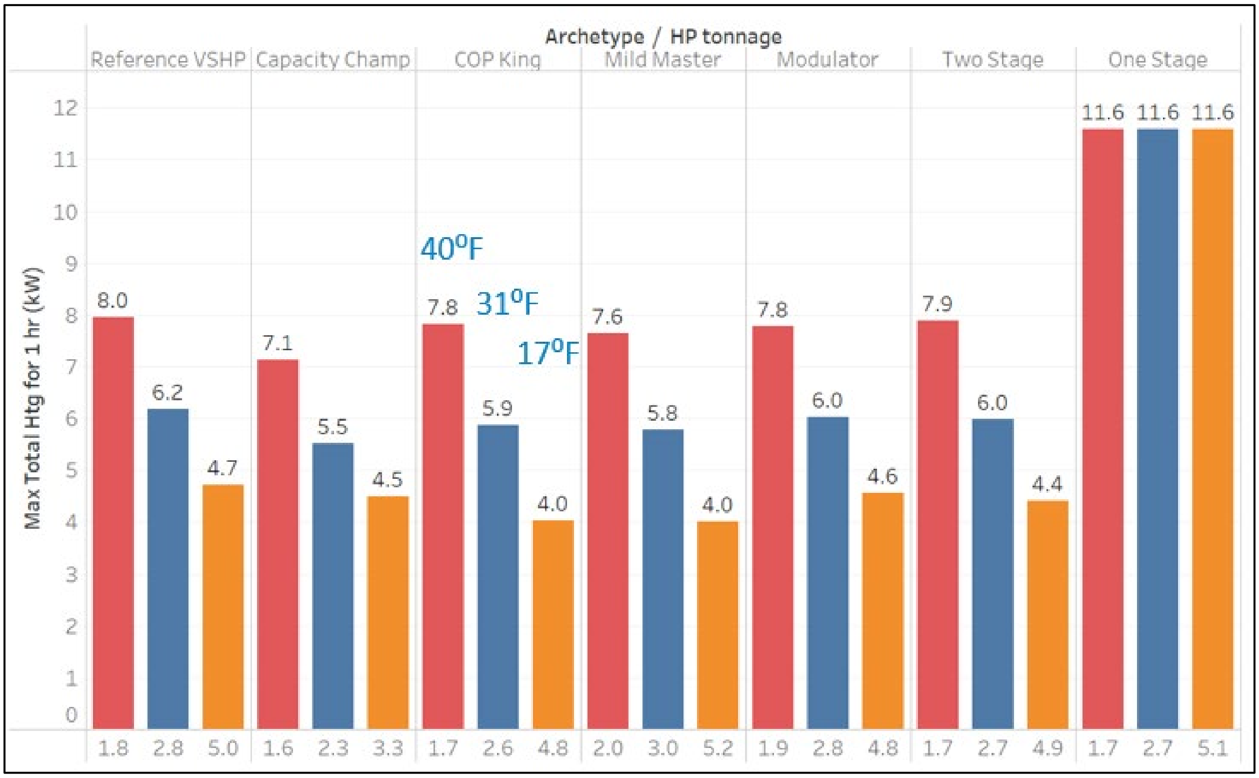
Figure 13. Average kW Usage during Utility System Winter Peak—Portland, OR



Size of heat pump in tons

The peak demand, which reflects the highest single hour of energy use, is shown in Figure 14. With the exception of the One-stage and Two-stage units, the lowest peak demand for each archetype occurred when the system was sized to meet the heating load at 17°F (orange columns). These larger HPs were able to meet the heating load of the home without ER backup, which greatly reduced peak demand. Note that the Capacity Champ delivered the lowest peak demand when comparing each archetype sized at 31°F (the design temperature with the lowest levelized cost). The Capacity Champ was able to maintain higher capacity at lower temperatures, which is reflected in the capacity performance metrics and resulted in lower peak demand.

Figure 14. Peak Demand Usage (kW)—Highest Single Hour—Portland, OR

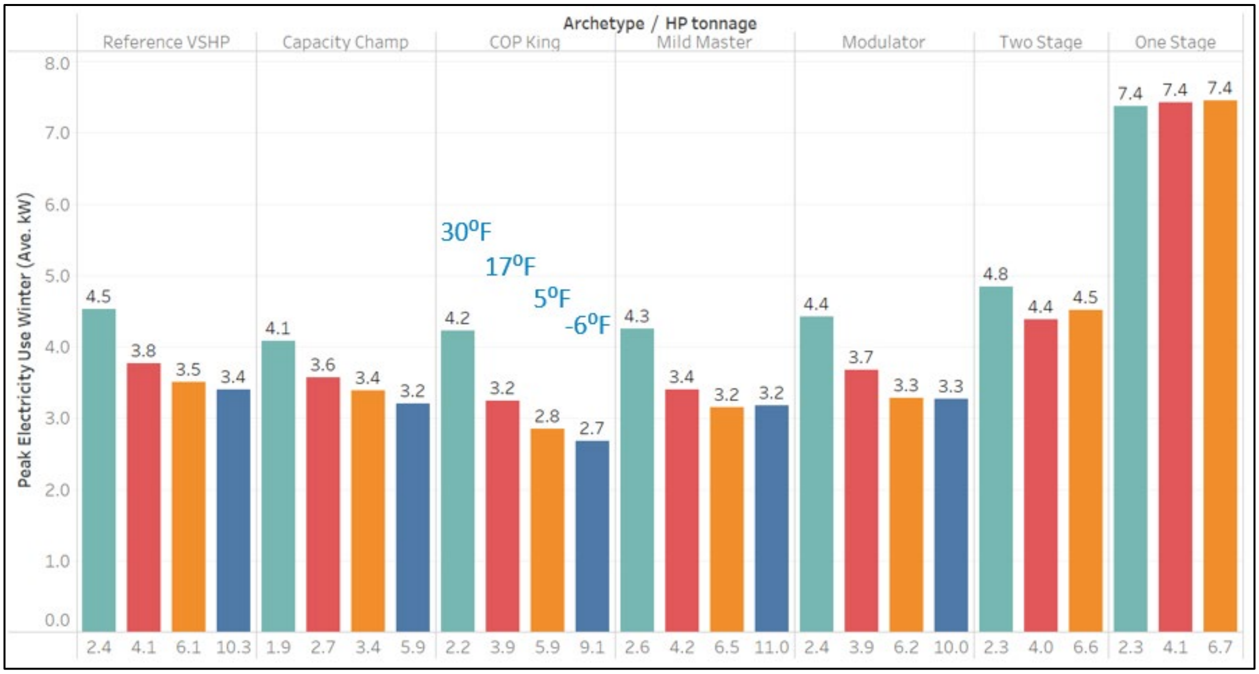


Size of heat pump in tons

Bozeman, MT

The Bozeman results are similar to Portland's for the utility system peak. As shown in Figure **15**, the COP King and Mild Master had the lowest average kW energy use during the utility system peak. Peak benefits also occurred by sizing the system to meet the home's load at 5°F. This differed from the levelized cost results, which suggested 17°F but mirrored the energy use results in Bozeman. Note that the One-stage and Two-stage units were not sized for -6°F.

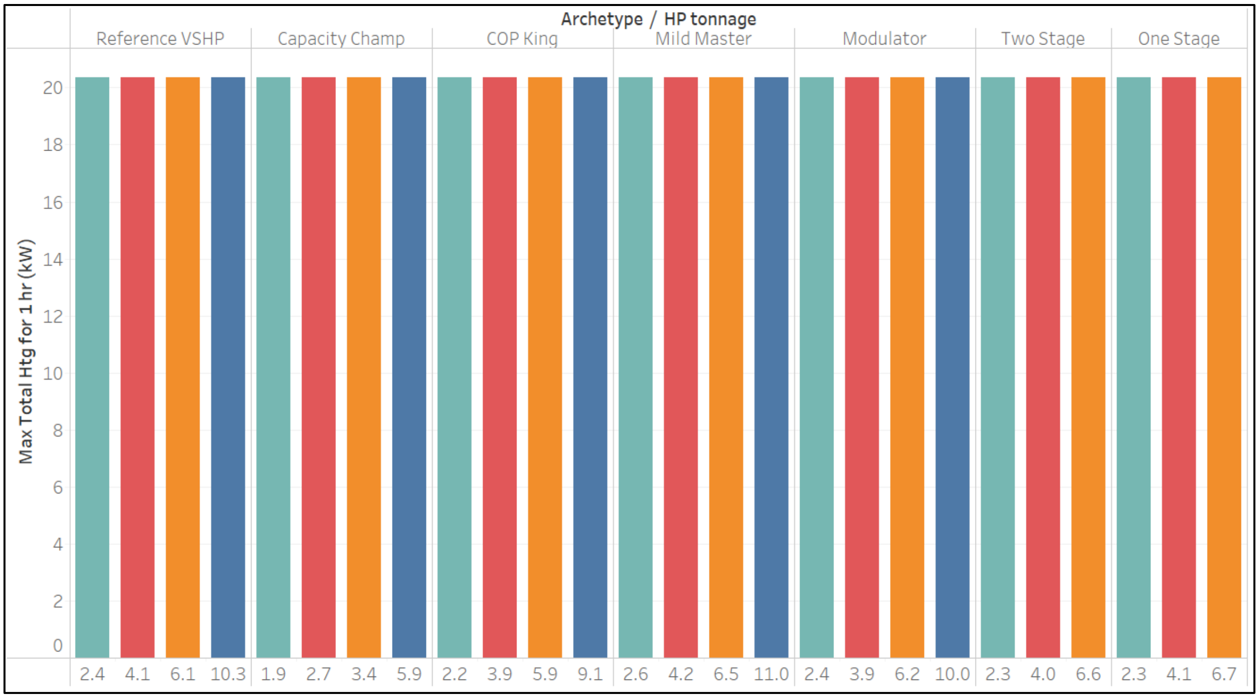
Figure 15. Average kW Usage during Utility System Winter Peak—Bozeman, MT



Size of heat pump in tons

Figure 16 shows peak demand energy use for Bozeman, MT. The peak demand was the same for every archetype at every size, which occurred when it was -28°F outside. This is not surprising because all systems rely on 100% ER backup below their minimum operating temperatures. While some HPs can operate down to -30°F, the capacity and COP are so low that it makes little difference in energy use. This means that in very cold climates such as Bozeman, the most effective way to reduce peak demand is to improve the building's envelope rather than focus on the capacity or COP of the heat pump.

Figure 16. Peak Demand Usage (kW)—Highest Single Hour—Bozeman, MT



Size of heat pump in tons

Additional HP Performance Factors

The additional performance factors outlined below operate independently of the metrics used to define the HP archetypes. Though these factors can significantly affect performance, in many cases, data on the controls and impacts of these factors are not well-documented. Since information on these factors and how they differ by manufacturer is limited, the user can adjust them independently within the modeling tool. Additional information on these factors is outlined below, including a sensitivity analysis to help quantify the potential impacts of each.

To complete this sensitivity analysis, the team specified a single HP archetype, location, and design temperature: Reference VCHP, Boise, ID, and 17°F. The team then independently adjusted each performance factor from low to high, so the overall impact on performance could be compared across these performance factors.

Cycling Degradation

Cycling degradation accounts for losses in efficiency from a system turning on and off. This occurs when the home's load is below the system's minimum capacity output, causing it to cycle on and off. The team calculated this degradation in performance using a coefficient of degradation, commonly referred to as Cd. An industry-accepted default for Cd is 0.25; for the sensitivity analysis, the team adjusted this value from a low of 0.05 to a high of 0.50.

Table 6. Cycling Degradation Results - Boise

Area	Input	Total Energy Use	Difference in Energy Use (kWh)	% Impact
Cycling Degradation	0.50	10,182	547	**6%**
	0.25	9,839		
	0.05	9,635		

Table 6 outlines the sensitivity analysis results. Adjusting the coefficient of degradation from low to high resulted in a difference of 547 kWhs in annual energy use or a 6% impact on overall system performance.

Defrost

Some research exists on the impacts of the defrost cycle on the overall performance of the HP; however, little information is available on the impacts of specific defrost control strategies on HP operation and ER backup use in the field. MN CEE field research on defrost cycles found the impact on heat pumps ranges from a 5%–15% reduction in overall COP. These data, along with information from field monitoring, were used to incorporate low, medium, and high defrost inputs into the modeling tool.

Table 7. Defrost Results - Boise

Area	Input	Total Energy use	Difference in Energy use (kWh)	% Impact
Defrost	High	10,523	1,282	**13%**
	Medium	9,839		
	Low	9,241		

Table 7 outlines the results of adjusting this input from low to high, with a difference of 1,282 kWhs in annual energy use. This equates to a 13% impact on overall performance[2].

Duct Loss

Duct loss is another factor that can significantly impact system performance. Though this is external to the equipment, it is important to consider in ducted VCHP applications. The impact of duct loss varies by region. In cold climates where homes have basements, the ductwork is typically inside the envelope, so duct loss has less of an 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 a range of duct loss inputs from 5% to 30%. These inputs represent the percentage increase in building load caused by duct loss.

Table 8. Duct Loss Results - Boise

Area	Input	Total Energy Use	Difference in Energy Use (kWh)	% Impact
Duct Loss	30%	10,578	1,846	**19%[3]**
	20%	9,839		
	10%	9,101		
	5%	8,732		

The results in Table 8 show the extent of the impact of duct loss across this range. The difference between 30% duct loss and 5% duct loss equates to 1,846 kWhs of annual savings. This results in an overall impact on performance of 19%.

ER Backup Integration

HP systems have different controls and strategies for using electric resistance backup heat. However, these vary greatly and are either not well-documented or not publicly available. To account for these differences in the modeling tool, the user can adjust how well the system

[2] Percent impact is calculated by calculating the difference between the high and low values and dividing by the medium value.

[3] Based on 30%-5% value divided by 20% value

integrates backup heat when needed. For example, if a user enters 10%, the ER backup will deliver 10% more heating load than what is needed. If 0% is entered, the ER backup meets the home's load perfectly. Notably, this applies only when ER backup heat is needed, and the HP cannot meet the home's heating load. Table 9 compares the results of a low input of 5% to a high input of 50%.

Table 9. ER Backup Integration Results - Boise

Area	Input	Total Energy Use	Difference in Energy Use (kWh)	% Impact
ER Rate	50%	9,983	162	**2%**
	10%	9,839		
	5%	9,821		

This factor had minimal impact on performance, with only 162 kWhs between the low input of 5% and the high input of 50%. This is in part due to the HP sizing to meet the heating load at 17°F, which is the heating design temperature in Boise, so backup heat is rarely needed.

However, the same sensitivity analysis completed for Bozeman still yielded a relatively small impact, as shown in Table 10. This sensitivity analysis was completed with a Reference VCHP sized to meet the heating load at 10°F (Bozeman's heating design temperature is -6°F). This scenario required more ER backup use but still resulted in a relatively small impact on energy use with an annual savings of only 532 kWhs between the low and high inputs.

Table 10. ER Backup Integration Results - Bozeman

Area	Input	Total Energy Use	Difference in Energy Use (kWh)	% Impact
ER Rate	50%	14,598	532	**4%**
	10%	14,125		
	5%	14,066		

Summary of Additional Performance Factors

Table 11 summarizes the results of the sensitivity analysis for all performance factors. The performance impacts from duct loss and defrost greatly outweighed the impacts of cycling degradation and ER backup integration. Understanding the duct losses and the impacts of the ductwork's location will significantly affect the sizing and performance of VCHP installations. Moreover, a better understanding of defrost cycles and their impacts on energy use and performance is needed.

Table 11. Additional Performance Factors Comparison

Area	Input	Total Energy Use	Difference in Energy Use (kWh)	% Impact
Cycling Degradation	0.50	10,182	547	**6%**
	0.25	9,839		
	0.05	9,635		
Defrost	High	10,523	1,282	**13%**
	Medium	9,839		
	Low	9,241		
Duct Loss	30%	10,578	1,846	**19%**
	20%	9,839		
	10%	9,101		
	5%	8,732		
ER Rate	50%	9,983	162	**2%**
	10%	9,839		
	5%	9,821		
ER Rate, Bozeman	50%	14,598	532	**4%**
	10%	14,125		
	5%	14,066		

Conclusions and Next Steps

Conclusions

The conclusions and results from this study assume the HP is operating as designed and reported by the manufacturer. This requires proper installation, refrigerant charge, etc., which are key factors to proper HP performance. The team explored some factors such as sizing, ER backup integration, cycling degradation, and duct loss, but this report mostly assumes optimal operation. This allows for an apples-to-apples comparison of HP archetypes and their defining metrics, and the results indicate the relative performance of one unit compared to another.

COP is the most important HP performance metric.

The HP archetypes compare HP performance metrics for modulation, capacity, and COP. These archetypes were modeled across a variety of sizes and climates, and COP clearly produced the best overall energy performance in all cases. The archetypes with the best COP metrics, COP King and Mild Master, had the lowest annual energy use and lowest levelized costs in all scenarios compared to other VCHP archetypes. These archetypes saved between 11% and 20% annually compared to the Reference VCHP archetype in mild and cold climates. They also saved more energy at every design temperature for which the archetypes were sized, showing better performance than any other archetype in all scenarios.

Defining COP metrics for the HP archetypes relied on two key metrics: low-load COP, defined as minimum capacity COP at 47°F, and high-load COP, defined as max capacity COP at 17°F. Centrally ducted systems with a low-load COP above 5 and high-load COP above 2.6 represent systems in the top 25% of NEEP's QPL. HPs that can achieve these metrics will deliver lower annual energy use than all other VCHPs.

Extended capacity and modulation have less impact on performance than expected.

A HP archetype with excellent extended capacity metrics (Capacity Champ) or excellent modulation metrics (Modulator) reduced annual energy use by only 2% to 5% compared to the Reference VCHP archetype in mild and cold climates. These results were surprising given the inherent value of modulation and extended capacity. Still, the modeling results show modest savings from great modulation or extended capacity, whereas HP archetypes with great COP metrics clearly indicated substantial energy savings.

Slightly undersized is has lower levelized cost of ownership

In both climates, the homeowner saves more money by opting for a slightly undersized system, with reference to the sizing recommendation below, compared to slightly oversizing[4]. A smaller HP has a lower upfront cost, while a larger HP has diminishing returns because it is more expensive, and this cost difference is not made up through energy savings. When sizing equipment, following the guidance below, a contractor should round down if they are between HP tonnages. This will produce the lowest levelized cost of ownership for the homeowner.

Mild-climate sizing—meet the load at the 99th percentile design temperature

In mild climates with 99% design temperatures above 17°F, such as Portland, OR, HPs should be sized to the 99% design temperature. Oversizing the system past the 99% design temperature (31°F in Portland) may reduce ER backup and peak energy use during the very coldest days of the year, but these energy savings are minimal for the customer, and the costs to put in a larger system are significant, which leads to a higher levelized cost of ownership. A homeowner will experience a lower levelized cost of ownership if the system is slightly undersized, allowing for a smaller, less expensive system.

Cold-climate sizing—meet the heating load between 5°F and 17°F

In cold climates with 99% design temperatures below 0°F, the system should not be sized to meet the load at the design temperature. For example, in Bozeman, MT, with a 99% design temperature of -6°F, a system sized to meet the heating load at 17°F had a lower levelized cost of ownership than sizing a system at 5°F. Again, this is due to the greater equipment cost for a larger system and the minimal heating hours below 5°F. A contractor should select a system that meets the load between 5°F and 17°F and opt for a smaller system with a lower installation cost.

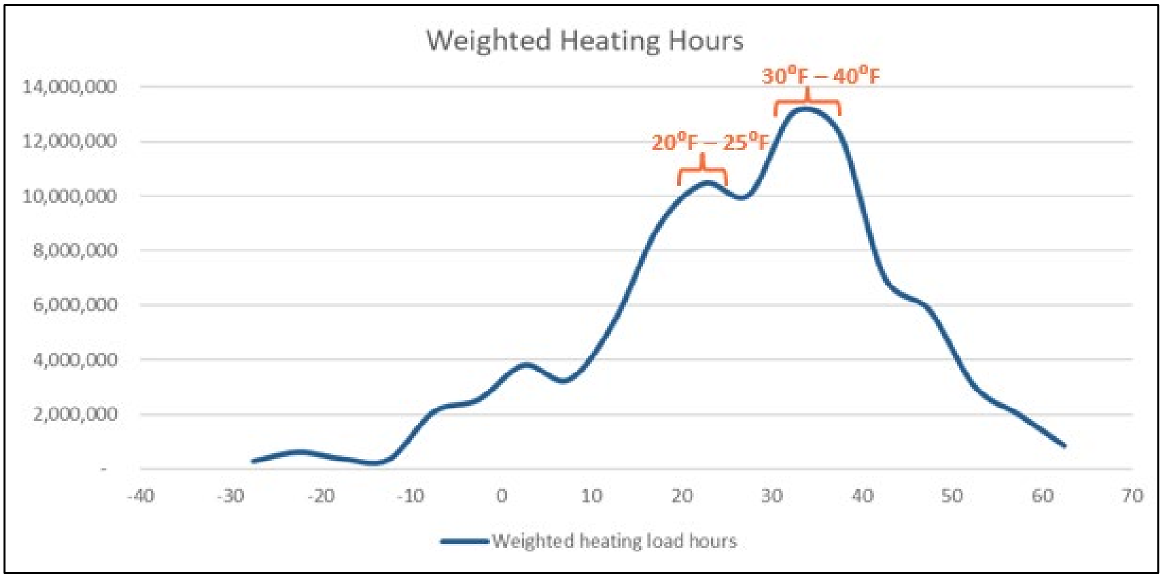
---

[4] Assumes a flat rate for electricity. If cost of energy were higher during peak hours, sizing could be increased to reduce peak power costs.

HP performance between 35°F and 50°F is the most important in almost all climates.

This subsection summarizes the outcome of the analysis described in this report. Even in cold climates, the vast majority of weighted heating hours occur above 15°F. Therefore, HP performance above 15°F is the key driver to lower annual energy use. Figure 17 shows the weighted heating hours (house load in Btu times hours in temperature bin) for Bozeman, MT. This accounts for the higher heating loads at lower temperatures, but the hours that have the greatest impact on annual performance are still between 20°F and 40°F. In fact, 80% of the weighted heating hours occur above 15°F. Thus, system archetypes such as the Mild Master, which have very good COP metrics at 17°F and 47°F but a capacity ratio of 50%, outperform the Capacity Champ, which maintains 100% capacity down to 5°F. This is also why sizing the HP archetypes at 17°F, as opposed to 5°F, led to a lower levelized cost of ownership in Bozeman. As the levelized cost of ownership results show, the benefits of better COP metrics at these temperatures outweigh the benefits of extended capacity, even in cold climates.

Figure 17. Weighted Heating Hours – Bozeman, MT



These results are not unique to Bozeman, MT. Table 12 shows the peak weighted heating hours for every city in the VCHP model; these are the temperature ranges with the greatest impact on annual energy use for each city, and thus the temperature ranges for which HP performance is the most important. This occurs between 30°F and 40°F in most climates, signifying the importance of COP (typically at lower than max output) in this temperature range. In the coldest climate in the tool—Minneapolis, MN—the most important bin is 15°F–20°F, but the 30°F–35°F temperature bin is the 2nd highest peak and outweighs any temperature bin below 15°F–20°F. For more details on the Minneapolis findings, as well as those for each city, Appendix D provides weighted heating hour graphs for every city in the tool.

Table 12. Peak Weighted Heating Hours

Location	Peak Weighted Heating Hours (highest to lowest)
Sacramento, CA	45°F–50°F
Portland, OR	35°F–50°F
Boise, ID	35°F–40°F
New York, NY	35°F–40°F
Denver, CO	30°F–40°F
Bozeman, MT	30°F–40°F
Albany, NY	15°F–35°F
Minneapolis, MN	15°F–20°F

Equipment cost is a key driver of lowest levelized cost of ownership.

The cost of equipment has a large impact on the levelized cost of ownership, especially in mild climates. Because of this, the One-stage and Two-stage archetypes had the lowest levelized costs of ownership in Portland, even though they used 20% and 6% more energy, respectively, than the Reference VCHP. This is best exemplified when comparing the COP King to the One-stage archetype. The COP King used 33% (or 2,623 kWhs) less energy than the One-stage archetype; however, the One-stage still had a lower levelized cost of ownership over the 15-year lifetime because install cost for the COP King was $11,700 compared to $7,300 for the One-stage archetype. The $4,400 difference in upfront cost is not recouped through energy savings in a mild climate such as Portland, OR.

Equipment cost is less of a factor in cold climates like Bozeman, MT where the VCHP archetypes saved more energy and had a lower levelized cost of ownership than the One-stage and Two-stage archetypes. However, equipment cost is still an important factor in sizing and equipment selection. As discussed in the sizing section, systems sized at 5°F saved more energy annually, but the upfront cost of the larger system necessary to meet the heating load at 5°F was not justified by the difference in energy savings. A homeowner can pay less upfront and have a lower levelized cost of ownership if they purchase a smaller HP that meets the load at 17°F.

Peak demand reduction is best addressed through building envelope upgrades and duct sealing.

In cold climates such as Bozeman, MT with heating design temperatures below 0°F, peak demand is best addressed with building envelope upgrades. The same applies for all climates, but is especially true for very cold climates that regularly experience temperatures below -15°F. Every heat pump has a low COP and limited capacity at these temperatures. In Bozeman, the highest peak demand occurred when the temperature was -28°F, and every archetype relied entirely on electric resistance backup, leading to a peak demand of 21 kWs. Some of this demand could be reduced through future advancements in HP technology, but there are just limited Btu in the air below -15°F that impact efficiency. A future system could offer more capacity below -15°F, but this would likely result in a lower COP; conversely, a system could have a better COP at -15°F, but this would likely limit the capacity output. However, the technologies to upgrade the building envelope and seal ductwork are already available. In this Bozeman modeling scenario, these upgrades can reduce peak demand by 35% to 40%, or 8 kWs. These upgrades would also save the homeowner money on equipment costs because they can purchase a smaller system once the upgrades are completed.

In mild climates such as Portland, OR, an HP can be oversized to meet the heating load during peak demand. The archetypes sized to meet the heating load at 17°F did just that and reduced peak demand by 1 kW to 2 kWs depending on the archetype (see Figure 14). However, the increased equipment cost for a larger HP leads to a higher levelized cost of ownership for the homeowner (see Figure 11). Alternatively, the homeowner could invest in envelope and duct sealing improvements, which would save them $1,000 to $2,000 on equipment costs and reduce peak demand by a minimum of 2 kWs. These results show the importance of coupling HP installations with building envelope and duct sealing upgrades.

Duct sealing is needed to achieve HP savings potential.

Of the additional HP performance factors modeled, duct loss had the largest impact on HP performance, with a nearly 20% difference in annual energy use between leaky and sealed ductwork. These results show the importance of sealing leaky ductwork outside of the building envelope. Emphasizing this with contractors and through utility programs will be key so the savings potential for HP installations is realized and comfort issues are avoided. This is a straightforward efficiency upgrade that can be easily incentivized through utility programs.

Better defrost controls are needed to improve HP performance.

Defrost is another factor with a large impact on HP performance. When modeled, a system with a low impact from defrost compared to one with high impact yielded a 13% difference in annual energy use. Currently, most HPs use rudimentary defrost controls, with a temperature sensor on the outdoor coil and a delay timer to determine when a defrost cycle is needed. This often results in unnecessary defrost cycles, significantly affecting annual energy use.

This could be improved through better controls that would greatly reduce the number of defrost cycles. For example, a pressure sensor could be added across the outdoor coil; if the pressure drop across the coil increases, signifying frost buildup, a defrost cycle would be triggered. This ensures that the HP runs in defrost mode only when it is needed, which has the potential to decrease the number of defrost cycles substantially. This control strategy would significantly reduce the energy use from defrost cycles, improve home comfort, and reduce the amount of ER backup used. This key finding from this study should be shared with manufacturers so they understand the impacts of defrost cycles on performance.

Next Steps

Widely sharing the results from this project constitutes a key next step. These results can help inform key stakeholders trying to accelerate heat pump adoption. The HP performance metrics and the accompanying results can guide this planning process and show the impacts of equipment selection and sizing. These results can also be used to inform utility programs and rebate offerings, as well as contractor resources.

Supply Chain Engagement

These results can be used to engage manufacturers and provide data that highlight the benefits of good COP metrics and HP performance between 15°F and 50°F. This information could inform future product development by highlighting the importance of certain controls such as defrost.

The modeling tool can also be used by key stakeholders who want to explore the results further or complete additional analysis.

Utility Engagement

These results show the substantial impacts of upfront costs on the lowest levelized cost of ownership—and the upfront cost is already a key consideration for homeowners. Utilities can play a key role in shifting the market to more energy efficient VCHPs by reducing the upfront cost with incentives. VCHPs save more energy annually and reduce peak demand compared to cheaper two-stage or one-stage heat pumps. Incentives can also be targeted at heat pumps with good COP metrics, which reduce annual peak energy use compared to other VCHPs.

This analysis also shows how building envelope and duct sealing upgrades can reduce peak demand and annual energy use. Utilities can create programs that encourage these projects during heat pump installations. This could be accomplished by offering bundled rebates with bonus incentives for multiple projects and through contractor training and education on the importance of these upgrades.

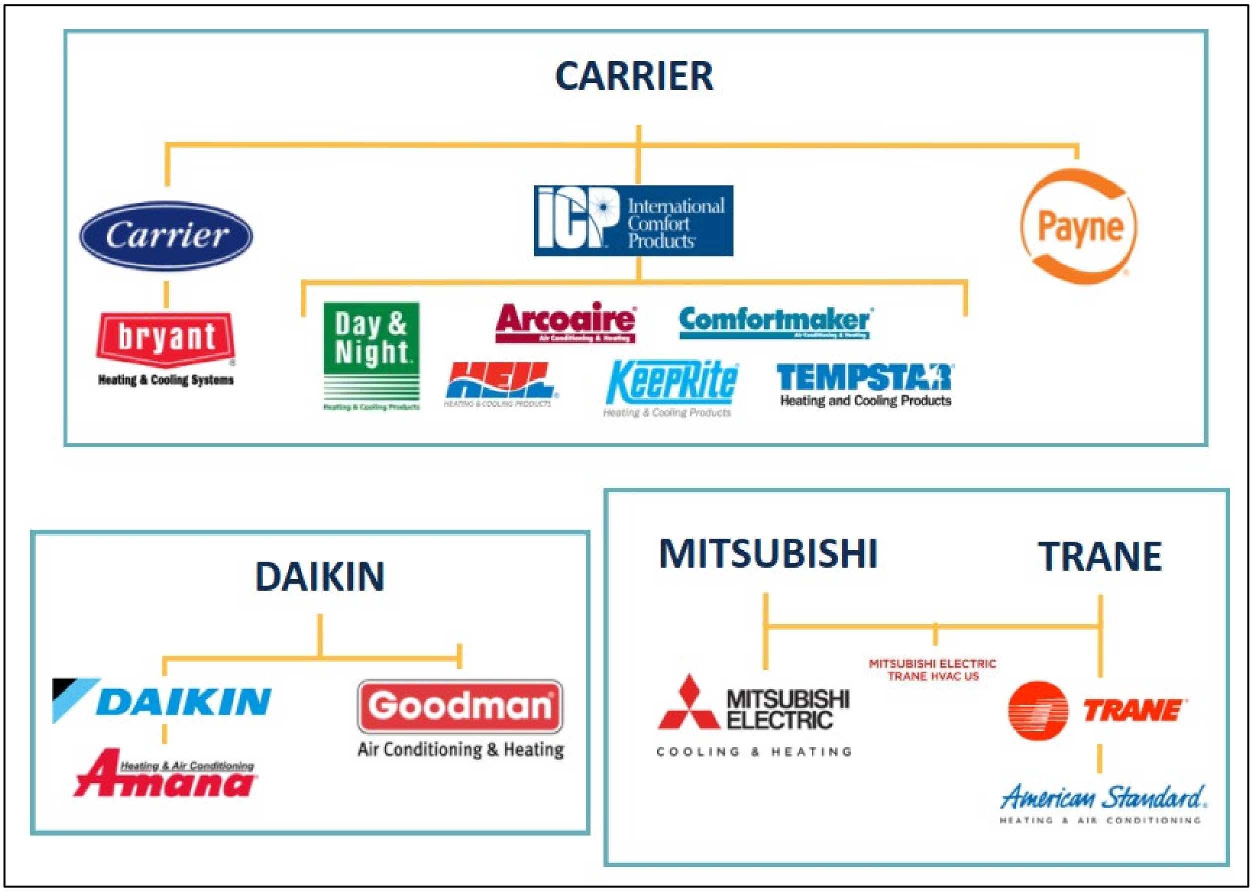
Utilities are also encouraged to use the VCHP modeling tool to further analyze these results and different scenarios specific to their territory and customers. The tool can incorporate specific utility costs, including 8,760 utility cost models, and different customer rate structures such as time of use. The modeling tool can help evaluate the impacts of HP performance specifications, sizing, and envelope upgrades on energy use and peak demand, which can aid in utility planning efforts and program development.

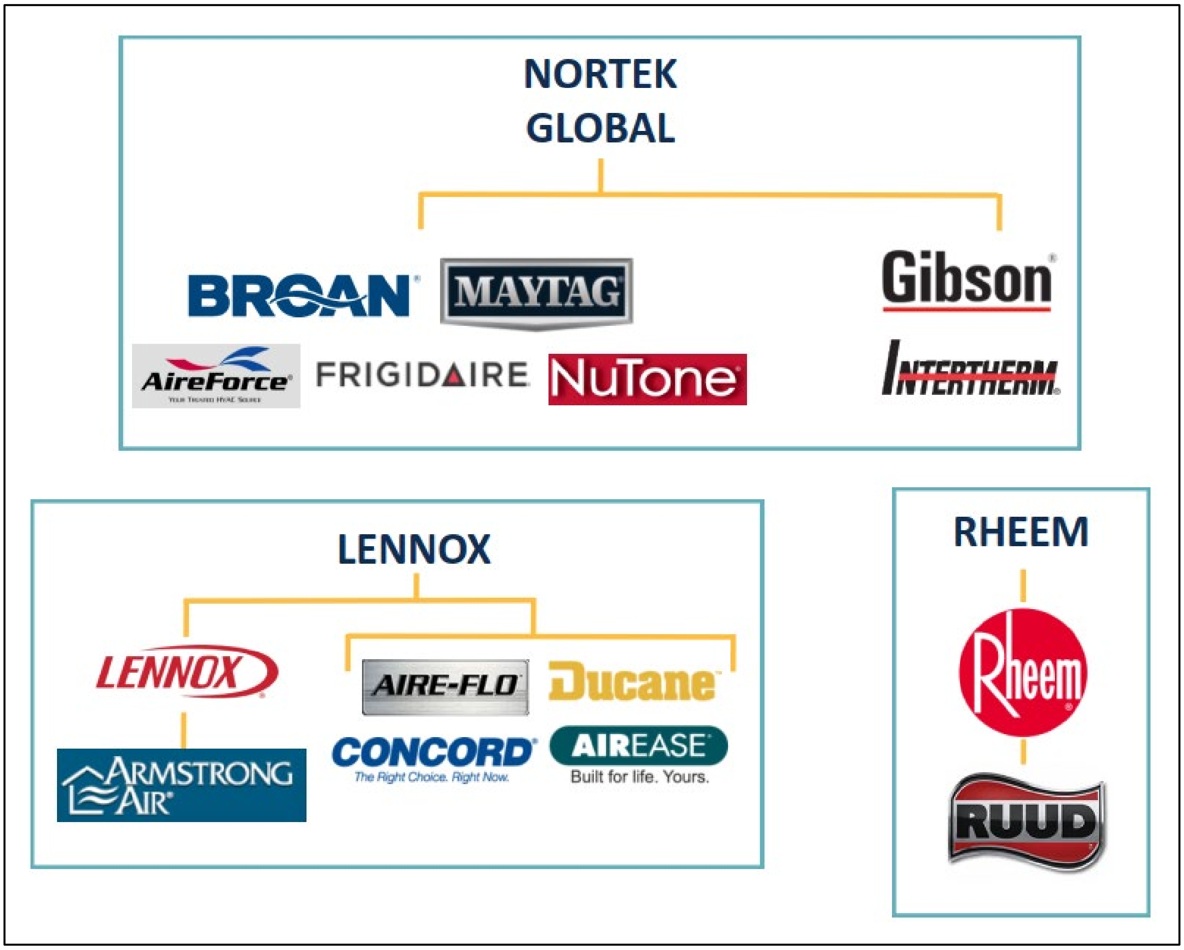
Further Analysis

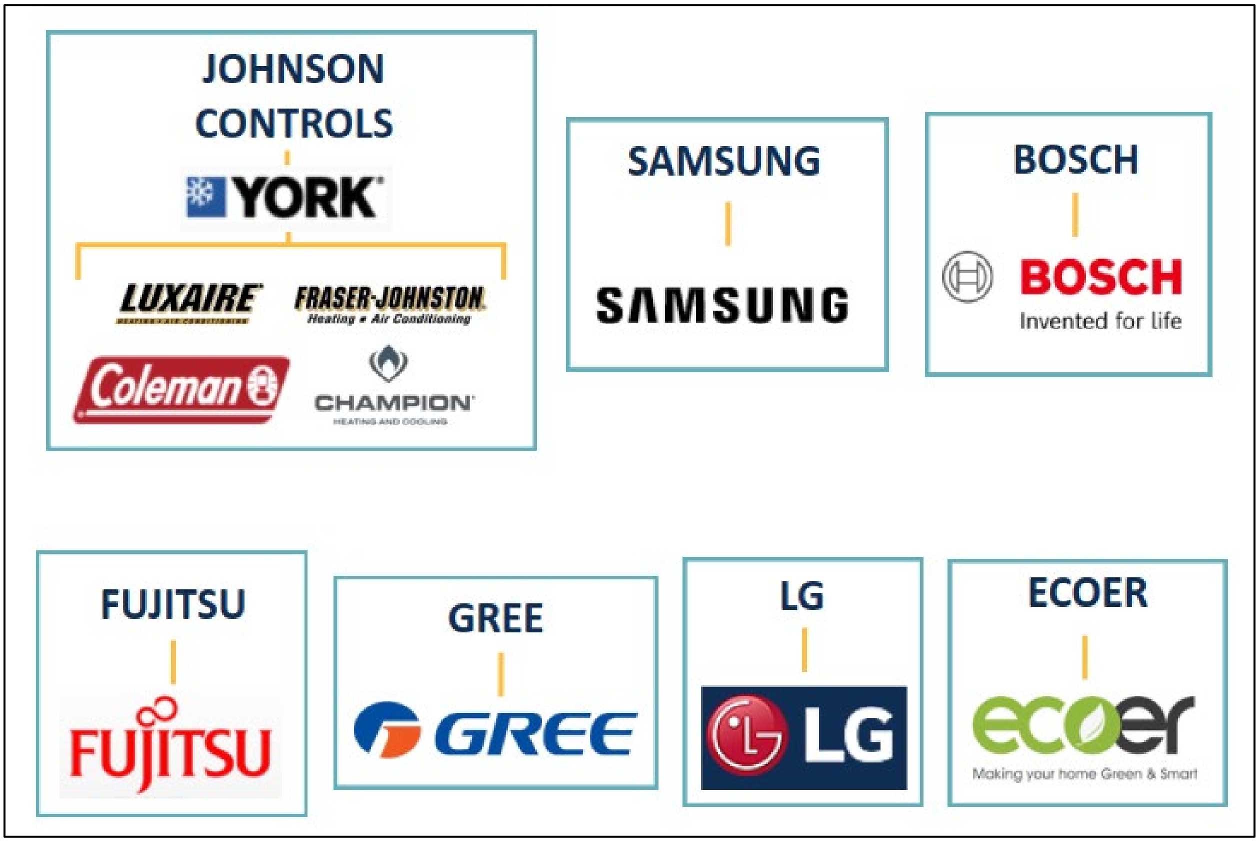
The modeling tool provides ample opportunity for further analysis. It is designed to test the impacts of different utility rates (customer and utility) as well as additional house types (low load, high glazing, etc.) and climates. Each modeling run outputs energy use and efficiency for every hour of the year to facilitate further exploration of peak usage and correlation with a utility's system peak. Dual-fuel applications with natural gas or propane backup heat can also be modeled and explored further. The tool is designed for the user to select different switchover temperatures, which they can use to test the impacts of these choices on customer cost and energy use.

The VCHP tool can also be used to explore additional heat pump performance factors and controls in more detail, such as the impact of different ER backup controls (such as temperature lockouts and ER backup use from thermostat setbacks) and cycling degradation that may occur within the modulation range of the heat pump. The VCHP tool can be used to complete additional analysis of results found in lab tests or field evaluations of heat pumps. The tool can be used to continually analyze heat pump performance, as it creates an easy way to compare hundreds of scenarios and measure the impact of detailed outputs related to heat pump performance.

Appendix A: Manufacturer Family Tree




NORTEK GLOBAL
BROAN
MAYTAG
AireForce
FRIGIDAIRE
NuTone
Gibson
INTERTHERM
LENNOX
LENNOX
ARMSTRONG AIR
AIRE-FLO
Ducane
CONCORD
The Right Choice. Right Now.
AIREASE
Built for life. Yours.
RHEEM
Rheem
RUUD


JOHNSON CONTROLS
YORK
LUXAIRE
FRASER-JOHNSTON
Heating • Air Conditioning
Coleman
CHAMPION
HEATING AND COOLING
SAMSUNG
SAMSUNG
BOSCH
BOSCH
Invented for life
FUJITSU
FUJITSU
GREE
GREE
LG
LG
ECOER
ecoer
Making your home Green & Smart

Appendix B: Product Database

See associated spreadsheet with the inventory of resources.

Appendix C: VCHP Tool Calibration

The VCHP Modeling Tool, developed by the Center for Energy and Environment (CEE) in Minneapolis, MN, models VCHP performance based on heat pump COP and capacity versus outdoor temperature profiles for central forced air heat pumps. The tool aims to compare different heat pump performance and system design characteristics and to evaluate which combination yields the lowest levelized lifecycle cost.

The tool is not a home energy simulator. It employs a steady state heat loss and gain calculation driven by envelope heat transfer coefficient (UA value), infiltration, and insolation. The tool can use TMY3 data or any equivalent ambient condition profile to calculate the imposed load on any home for a given outdoor temperature. A simple hourly energy balance is then employed to determine the energy load that the heat pump, backup, or both must deliver. This is calculated for every hour of the year, creating an 8,760 model for heating and cooling. This allows for hourly outputs of energy use, backup load, COP, and other metrics.

Once completed, CEE used available field data (site) to evaluate both modeled results and assumptions used to address known design and installation impacts on system performance. This appendix presents five calibration or evaluation exercises to confirm that the results represent heat pumps' field performance.

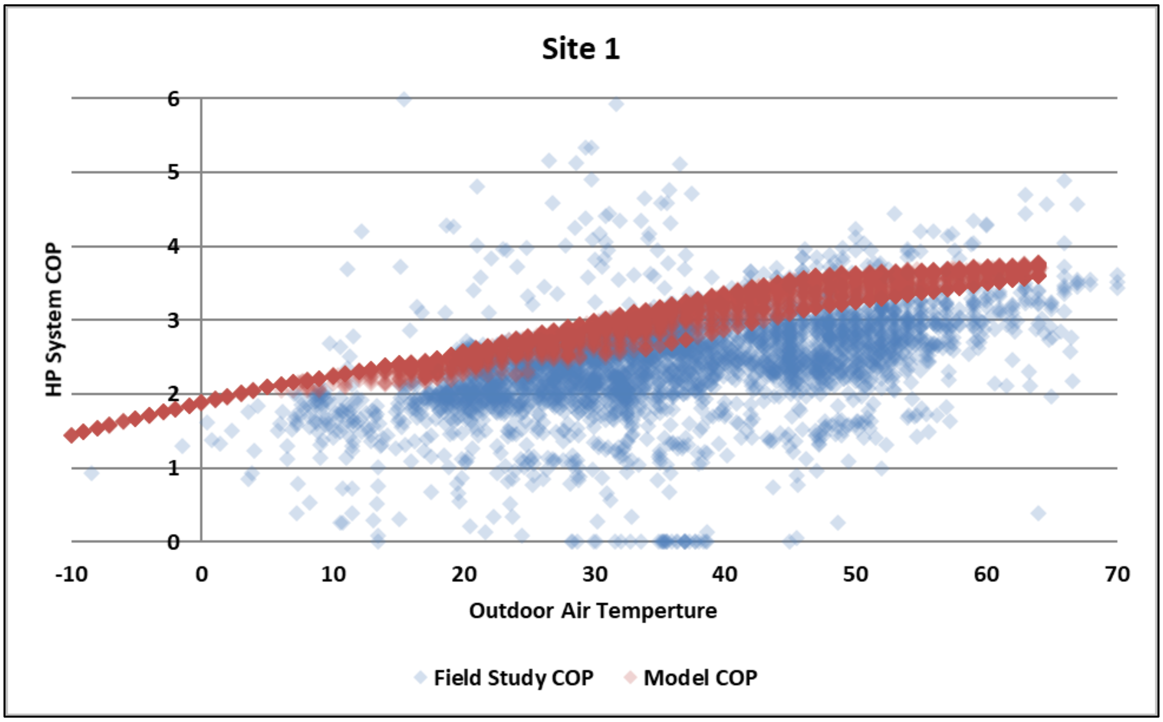
- System Performance—Field Data Comparison
- Defrost Cycle
- Cycling Degradation
- Backup Heating Energy Use (backup integration)
- Duct Losses

System Performance—Field Data Comparison

The tool is designed to model and compare the relative performance of VCHPs in the market today. The team compared modeling tool outputs to data collected during CEE's field research to verify that the tool properly reflects heat pump performance. The equipment that CEE monitored in the field was entered into the tool using the NEEP AHRI Index feature. This feature builds comprehensive COP and capacity curves based on manufacturers' COPs and capacity values reported to NEEP. CEE's field research indicates that these manufacturer-reported values reflect the relative performance of heat pumps in the field.[5] Additionally, the field-site characteristics were entered into the tool, so the design temperature heating load and annual heating demand aligned.

Figure 18 through Figure 20 compare the models' outputs to three CEE field sites. Each graph has the outdoor air temperature (OAT) on the X-axis and the heat pump COP on the Y-axis. The blue dots show the heat pump COP from field monitoring, and the red dots show the heat pump COP outputs from the modeling tool.

Figure 18. System Performance Comparison—Site 1



[5] CEE's field research indicated that a heat pump's steady-state performance in the field was consistent with the manufacturer reported values. It is important to note that most heat pump operation is not in steady state, which is why the other key variables are incorporated into the modeling tool.

Figure 19. System Performance Comparison—Site 3

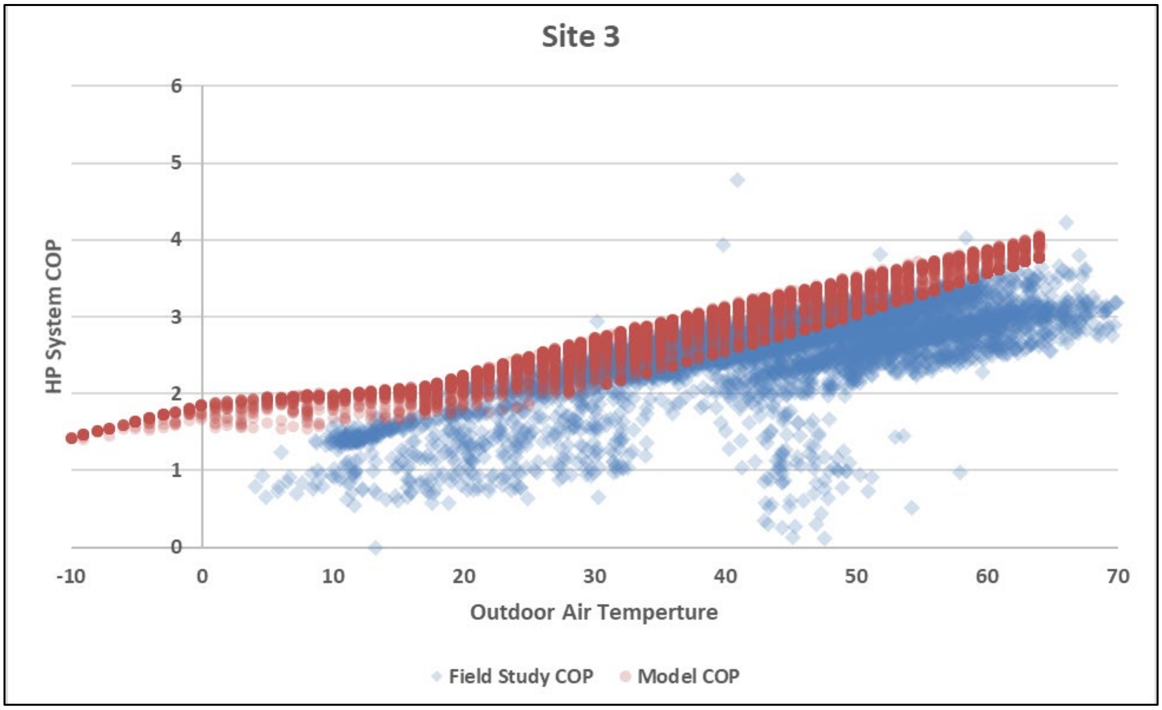


Figure 20. System Performance Comparison—Site 4

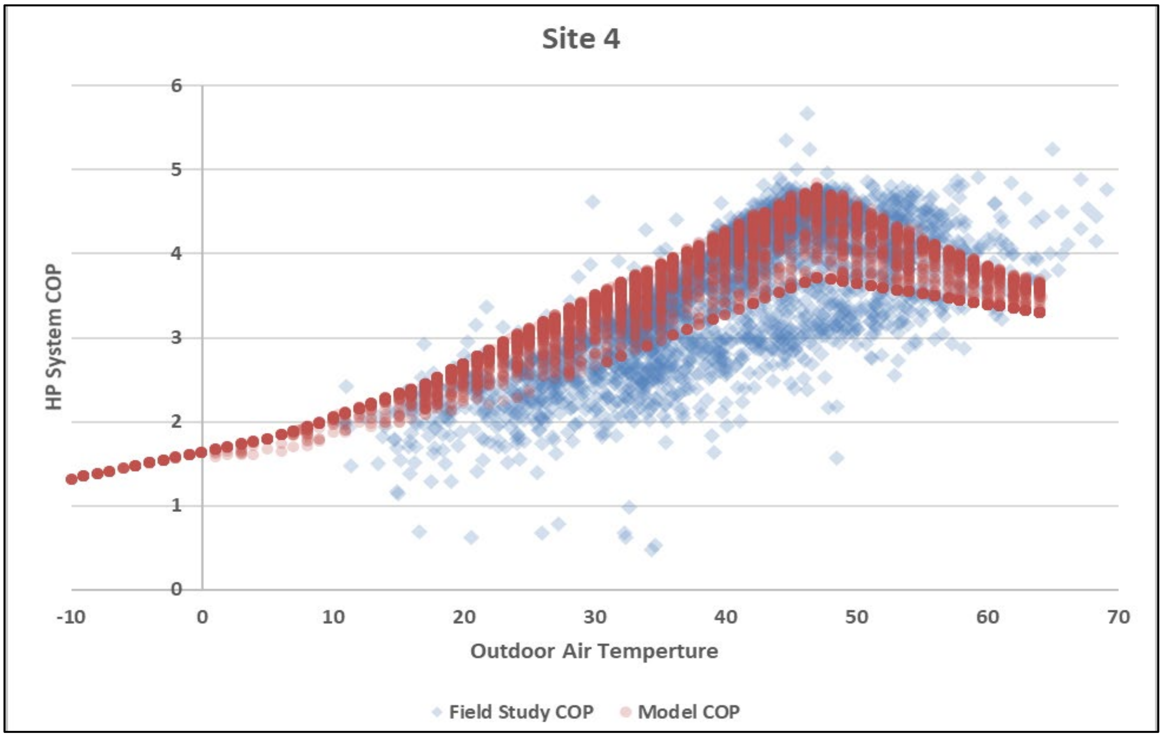


Figure 18 through Figure 20 compare the scatter plots of COP versus OAT for CEE's field sites and the outputs from the modeling tool. The field data in blue show how equipment varies in performance by site and installation, with Site 1 and Site 3 showing similar performance from similar HPs[6] and Site 4 showing different performance from a HP with higher COPs at moderate temperatures. The modeling tool reflects these differences in performance quite impressively. As seen in the figures above, the modeling tool COPs follow the same general trend or curve of the COP vs. OAT plot from the field data. It is also important that the modeling tool reflects key differences in HP performance. For example, the COPs from Site 4 are distinctly different between 30°F and 50°F, with COPs between 3 and 5. The modeling tool reflects this difference in performance, which indicates that the tool is correctly modeling HP performance and showing the key differences in performance between equipment.

Given the tool's ability to replicate field results and the key differences in performance between HPs, the team determined that further calibration was not needed. The model provides more consistent results and less variety than field data, which is expected when modeling performance. Field data often include unexpected events such as people coming and going, changing thermostat setpoints, doors or windows being left open, and more variables that cannot be incorporated into a model. The goal is to create a model that compares the relative performance of HPs, which is clearly accomplished given the tool's ability to mirror field performance from a variety of HPs as shown in Figure 18 through Figure 20.

The project team identified additional factors that influence heat pump performance. These factors—defrost cycle, cycling degradation, backup integration, and duct loss—can vary greatly depending on control strategies, equipment, and installation and are not well represented in the manufacturer-reported COP and capacity curves. Therefore, these variables were incorporated independently in the modeling tool and can be adjusted by the user to reflect system performance properly. The modeled results in Figure 18 through Figure 20 do not include all these variables because they were not represented in the field data. Each section indicates whether that variable is included in Figure 18 through Figure 20 above.

Defrost Cycle

The energy used during heat pump defrost cycles can vary widely. Documentation is lacking regarding how the control strategies, location of sensors, and differences in manufacturer components affect defrost performance in the field. The most common control strategy

[6] Sites 1 and 3 are both Carrier Greenspeed HPs, but vary in tonnage.

implemented by manufacturers utilizes a temperature sensor at the outdoor coil and a control that varies the time between each defrost cycle. The time between each defrost cycle can be set at 30-, 60-, 90-, or 120-minute intervals. The defrost runs until the exit coil temperature reaches a set point, typically 75°F. If this setpoint is not reached, the defrost cycle stops at a maximum of 10 minutes. A user can also select an auto setting, which determines the time between each defrost cycle by reading the temperature at the coil and the length of the previous defrost cycle. For example, Carrier's auto setting initiates defrost every 120 minutes if the previous defrost cycle was less than three minutes and initiates defrost every 30 minutes if the last defrost cycle was more than seven minutes. This set of controls is the most common defrost strategy on the market.

Controls for ER backup use during defrost cycles are likewise poorly-documented and can vary widely. Some manufacturers use ER backup during the majority of defrost cycles, while others use it only when a call for heat is initiated.

Based on an initial sensitivity analysis completed with the modeling tool, these two factors (defrost cycles and ER backup) could contribute as much as 50% of the annual heating energy use in humid climates such as Portland. These initial results indicate a need to delve deeper into how defrost and backup control strategies are implemented and their impacts on annual energy use and COP.

CEE's field research indicated a 9% reduction in COP during defrost cycles with a larger impact at colder temperatures (11% reduction in COP between 10°F and 20°F). A review of existing research indicated a range of impacts from 5% to 15%[7] on overall heat pump performance. These additional research findings showed results similar to CEE's, with longer defrost cycles and more energy use at colder temperatures.

The team incorporated three defrost archetypes in the modeling tool to account for the range of impacts from defrost and ER backup energy use. These archetypes represent the range of impacts from low (5% reduction in COP) to high (15% reduction in COP) and include controls that result in more energy use and longer run times at lower temperatures.

The impact of defrost is not included in the model or field data in Figure 18 to Figure 20.

[7] Defrost studies from NRC, Purdue, CEE, and NREL

Cycling Degradation

Heat pumps have optimal performance during long uninterrupted events of heating or cooling. Frequent starting, stopping, and modulation among different capacity operations degrades performance. The amount of performance degradation also increases based on the extent to which the system is oversized. Essentially, oversized systems turn on and off more often and have shorter run times, which leads to worse performance. To properly account for this in the modeling tool, CEE relied on research from the National Renewable Energy Laboratory (NREL)[8] that outlined a common method to account for this degradation in performance. This method uses a degradation coefficient (Cd) and a part load factor to properly reflect this performance degradation. Figure 21 has additional details on how this was incorporated.

Figure 21. NREL Cycling Degradation Modeling Methodology

In simulation programs such as DOE-2 and EnergyPlus (DOE 2013), air conditioner cycling is modeled using average performance degradation effects of cycling over a given time step rather than modeling individual on-off cycles. A detailed derivation of the following model, and references, are given in Henderson (2000).The modeling begins with a part load ratio, *PLR*, sometimes called a cooling load factor, *CLF*

$$PLR = \frac{sensible\ cooling\ load}{steady - state\ sensible\ cooling\ capacity}$$

PLR is used to calculate the part load fraction, *PLF*, sometimes referred to as the part load factor or part load function

$$PLF = \frac{part\ load\ efficiency}{steady - state\ efficiency}$$

A simple and common method for relating *PLF* to *PLR* is through a concept called the degradation coefficient, C_D. The value of C_D is typically between 0.05 (lower cycling loss) and 0.25 (higher cycling loss); the values used in this study for the particular air conditioner units simulated are between 0.07 and 0.2. Modern, single-stage air conditioners tend to have C_D values around 0.07.

$$PLF = 1 - C_D(1 - PLR)$$

EnergyPlus defines the runtime fraction, *RTF* as follows

$$RTF \equiv \frac{PLR}{PLF} = \frac{PLR}{1 - C_D(1 - PLR)}$$

[8] NREL study outlining modeling techniques for cycling degradation

The coefficient of degradation is also an input that the user can adjust. The default value is 0.25, which represents the average degradation in performance for ASHPs as decided by the project team and advisory group. This value is used to calculate the PLF outlined in Figure 21. The PLF is then multiplied by the minimum capacity COP to reflect the system's degradation in performance from cycling properly.

A Cd sensitivity analysis indicated a relatively small impact on overall energy use. Changing Cd from 0.05 to 0.50 in the modeling tool leads to a 5.6% increase in energy use.

The impact of cycling degradation is included in both the modeled results and field data in Figure 18 to Figure 20. The modeled results use a Cd of 0.25.

Electric Resistance Backup Integration

The model assumes the heat pump is the primary mode of heating and cooling. When the heat pump cannot meet the total heating load of the home, the electric resistance (ER) plenum booster heater provides the necessary supplemental heat. The integration of this ER backup heat source represents the system's ability to deliver the correct amount of ER backup. For example, if the home needs 20,000 Btu of heat at 25°F, but the heat pump's max capacity is 18,000 Btu at 25°F, 2,000 Btu of heat should be delivered by the ER backup heat. In practice, the system must estimate the amount of backup heat required, and then the resistance heaters need to modulate (if they can) down to the necessary amount. This estimate and modulation are not precise and can vary greatly depending on proper installation and controls.

The modeling tool incorporates this variability by having a user input for ER backup integration. This input multiplies the amount of backup energy needed by the percentage entered by the user. For example, 2,000 Btu of backup energy was needed in the example above. If the user enters 20%, the ER backup would use and deliver 2,400 Btu of energy.

The default value for this variable in the tool is 10%. A sensitivity analysis of this variable determined a smaller impact on overall performance than expected. If this variable is adjusted from 5% to 50% in a climate such as Bozeman, MT, that needs significant ER backup energy, the overall energy use increases by only 3.8%. In more moderate climates such as Boise, ID, and Portland, OR, this adjustment affects the overall energy use by less than 1.7%. Since this variable has a relatively small impact on overall performance, the research team did not explore or calibrate it further.

Electric resistance backup heat was not included in the modeled results because the data were not included in the field data.

Duct Loss

Duct losses significantly affect energy use, heat pump sizing, and homeowner comfort. The amount of duct loss can vary widely and change regionally. For example, many cold climates with basements have ductwork located inside the building envelope, while milder climates often have ductwork in crawl spaces or attics that are outside the building envelope. To account for this variability, the user can select the percentage of duct loss with recommendations based on duct location.

Duct losses are incorporated in the tool as a percentage of the additional load that the heat pump needs to deliver. For example, if the home needs 20,000 Btu at 25°F and the home's duct loss percentage is set to 10%, the heat pump will need to deliver 22,000 Btu of energy. The available percentages for user input range from 0% to 30% in increments of 5%. The upper range is based on studies of distribution efficiency from the Northwest, which indicate a duct efficiency ratio of 0.691, as illustrated in Table 13. 0% is available as a hypothetical baseline, and 5% is used when ducts are located inside the envelope.

Table 13. Duct Efficiency Ratio[9]

Duct Delivery Efficiency by Vintage

Vintage	Duct Efficiency Ratio		N
	Mean	Std.Dev.	
Pre-76	.701	.170	26
76-80	.686	.156	20
80-86	.675	.170	15
86-92	.599	.125	18
92-2000	.721	.153	24
2000+	.790	.189	10
Total	.691	.163	113

Note: From Table 23 in source document

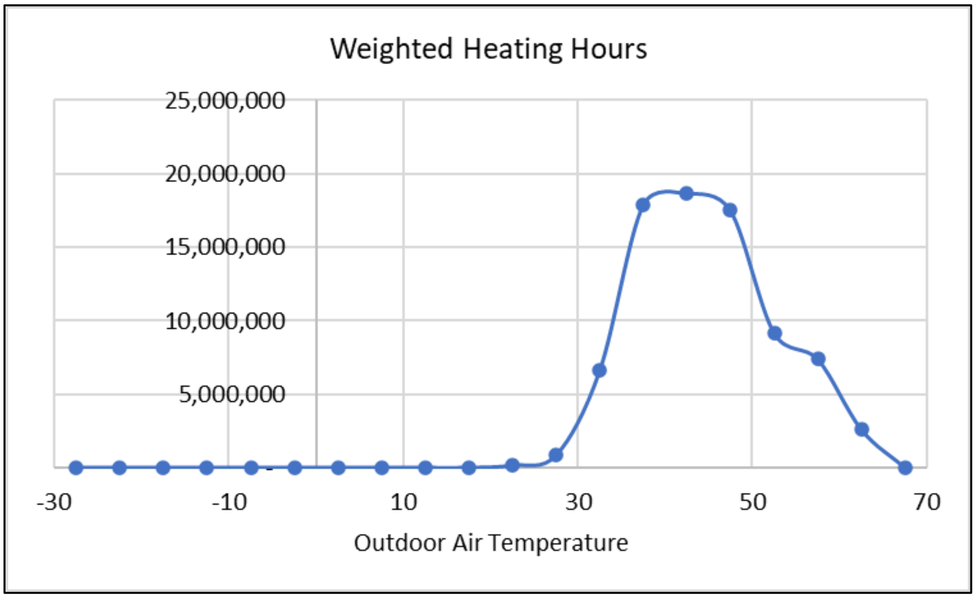
The sensitivity analysis completed with the modeling tool indicated that duct loss can have a significant impact on energy use. Adjusting this variable from 5% to 30% can increase overall energy use by 19%.

Duct loss was set to 5% in the modeled results, but this isn't perfectly reflected in the results because the annual heating demand was calibrated to the field sites.

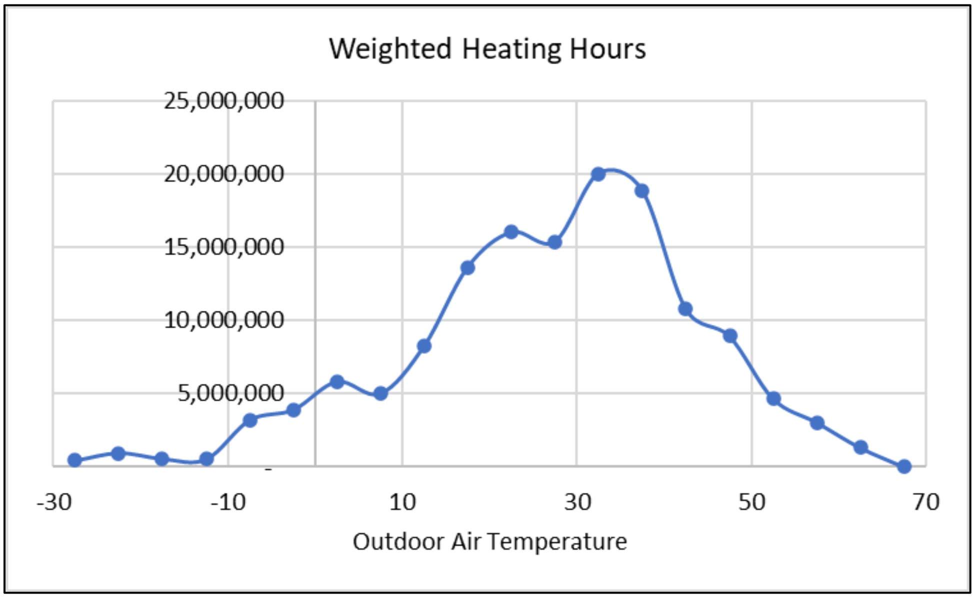
[9] Analysis of Heat Pump Installation and Performance. December 2005

Appendix D: Weighted Heating Hours

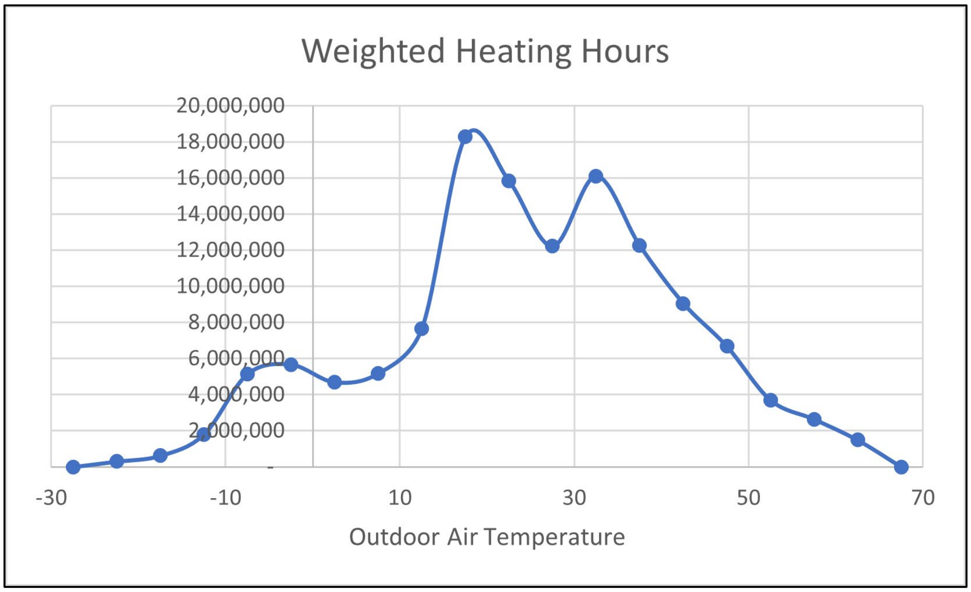
Portland, OR



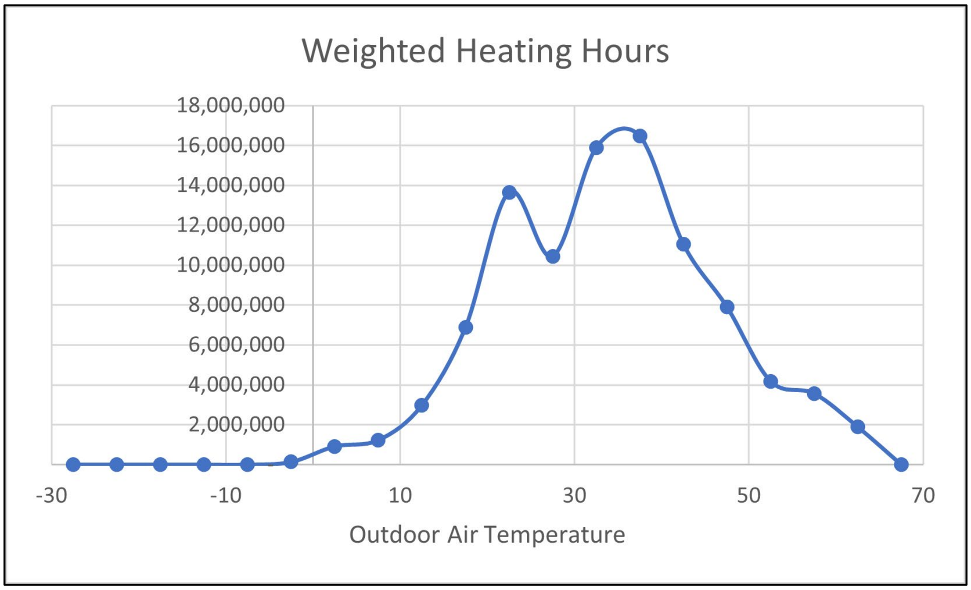
Bozeman, MT



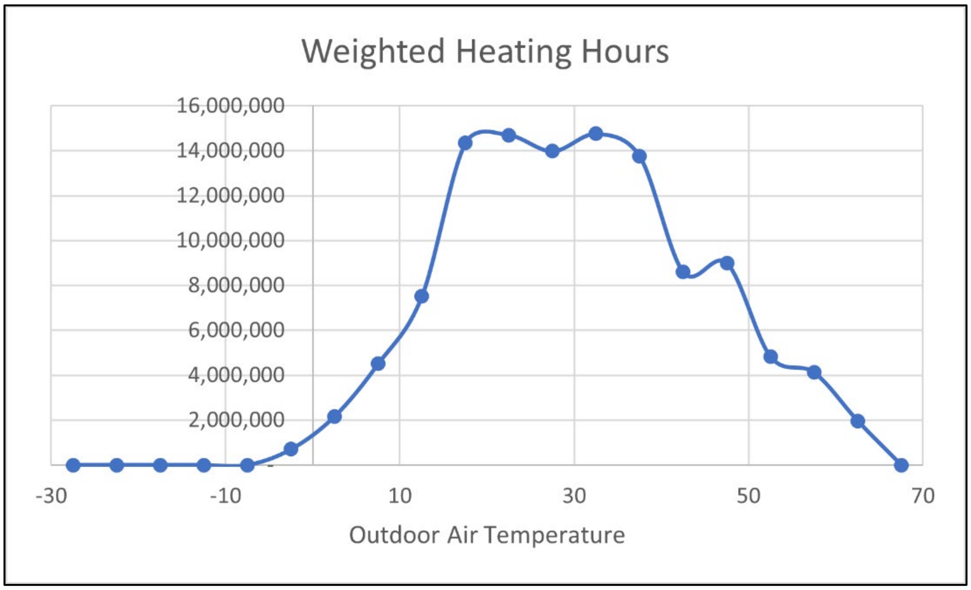
Minneapolis, MN



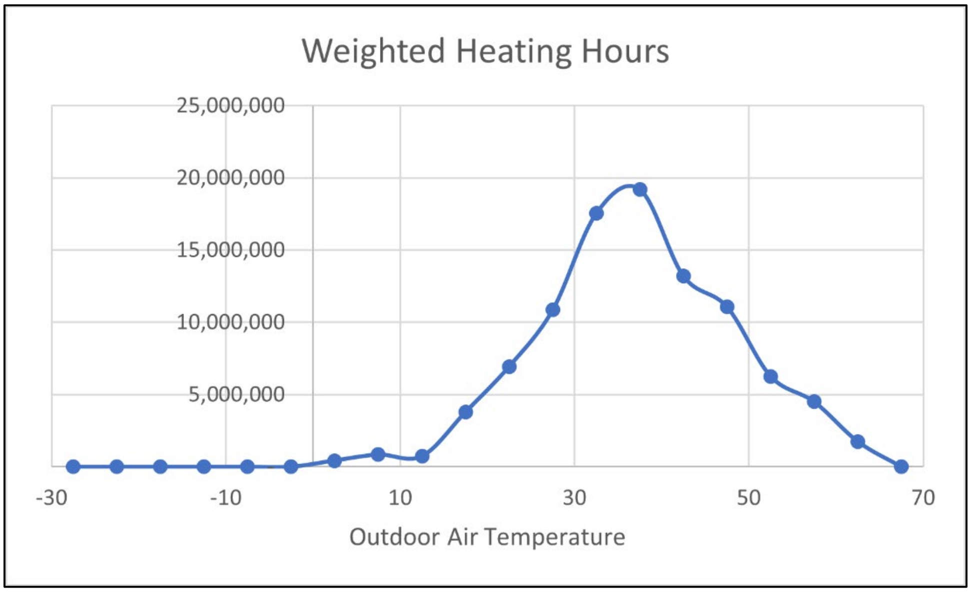
Denver, CO



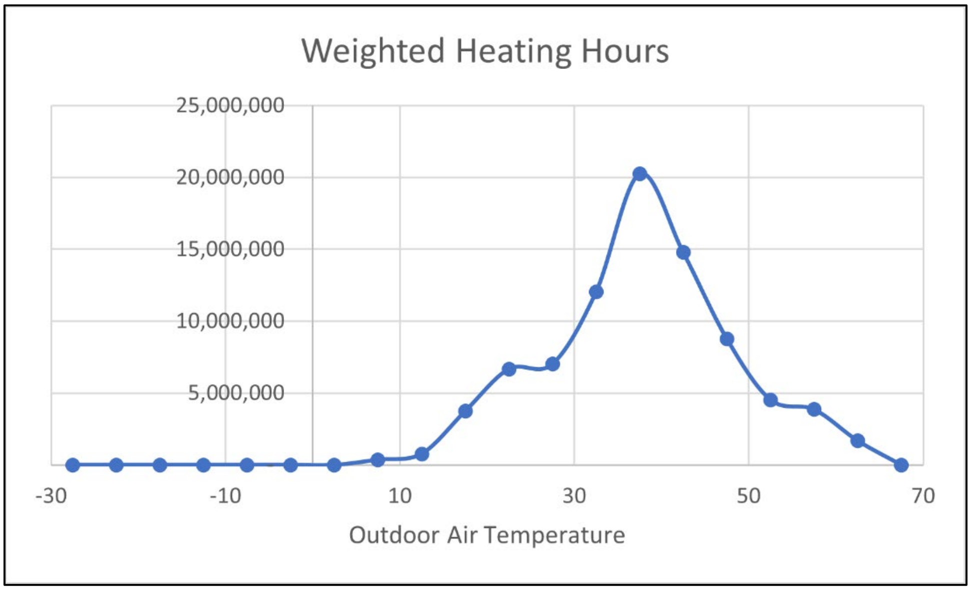
Albany, NY



Boise, ID



New York City, NY



Sacramento, CA