

Field Performance of Variable-Capacity Heat Pumps in Southeastern Homes, A DER Option?

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ABSTRACT

At homes co-located in Asheville, North Carolina, the study team evaluated potential customer and utility benefits of high-efficiency heat pump HVAC technologies (e.g., ground-source and air-source). Based on data collected from February 2019 through September 2021, the findings indicate that:

- These high-efficiency heat pumps coupled with other ENERGY STAR® certified new home features provide low monthly customer energy consumption, moderate customer comfort and beneficial utility coincident peak performance during high utility grid demands.
- The HVAC system average hourly power during the utility coincident peak trended below 5 kilowatts (kW) for the winter heating season (indoor temperatures of 61-81 F) and below 2.5 kW for the summer cooling season (indoor temperatures of 70-75 F).
- The HVAC systems' winter peak demand matched the same utility winter coincident peak demand hours of 7 a.m. and 8 a.m. less than 25 percent of the time.
- None of the HVAC systems' winter peaks occurred during the same outdoor temperature/month. The system peak hourly average in heating mode of all three study homes reached a maximum between 2.9 kW and 5.4 kW.
- The HVAC systems' summer peak demand matched the same utility summer coincident peak demand hours of 4 p.m., 5 p.m. and 6 p.m. less than 25 percent of the time.
- None of the HVAC systems' summer peaks occurred during the same outdoor temperature/month. The system peak hourly average in cooling mode of all three study homes reached a maximum between 2.9 kW and 5.4 kW.
- While the ASHRAE-recommended indoor comfort conditions (ASHRAE 2015) were not achieved during various times, occupants did not report indoor discomfort at any point in the study.

Introduction

The AHRI Directory of Certified Product Performance documents lab-based ratings of whole-home variable-capacity heat pump systems, but limited field research exists on the energy and non-energy features and benefits of these systems in occupied homes. Because these systems can modulate their heating and cooling output with the weather and indoor requirements (DOE 2017), manufacturers claim that, compared to standard-efficiency, single-speed equipment, they can better maintain comfort, lower energy demands at part-load conditions and provide more affordable heating during colder outdoor temperatures. The market interest in incorporating high-

efficiency heat pump equipment in both new home construction and existing home changeouts is rapidly growing in North Carolina’s mixed-humid climate.

The purposes of this project were to verify that these systems can be sized and installed to be more energy efficient overall than standard systems, to determine system performances without any heat strip usage during the heating season without compromising resident comfort and to verify the systems’ performance during humid outdoor conditions.

Methodology

To create a chronological dataset for each site a full dataset was cleaned and compiled. Interactive plots of unedited data for each site were used to flag potential quality control issues and periods of missing data for Advanced Energy’s review. Additional quality control actions were taken to remove duplicate records and to fill periods of missing data, such that the dataset for each site was as complete as possible.

From each site’s full chronological dataset, measured electrical usage variables from power meters (and associated energy readings) were used to calculate the variable-capacity HVAC equipment power demand. A summary dataset was created by calculating the hourly sum or average of variables of interest. Additional variables (not collected through on-site monitoring) were added to these hourly summaries and include:

- Hourly outside air temperature (dry bulb) from the Asheville Regional Airport.
- Utility seasonal (summer/winter) peak energy demand hours (Duke Energy 2016, 2018). “Summer” was defined as May through October, while “winter” was defined as November through April. Summer peak hours were defined as 4 p.m., 5 p.m. and 6 p.m., and winter peak hours were defined as 7 a.m. and 8 a.m. Peak-exempt was identified as all weekends and North American Electric Reliability Corporation (NERC) holidays (accessed from <https://www.energygps.com/HomeTools/PowerCalendar>). For example, 7 a.m. on a Saturday would not be identified as a peak energy demand hour at any time of the year.
- Identifiers for the shoulder season periods — “spring” (April through May) and “fall” (September through October) — were defined by Advanced Energy for insight purposes on occupant comfort.
- Hourly summary datasets for each site, comprised of 15-minute interval data, were then combined to provide an analysis dataset.

Locations and Climate Data

The study selected three homes co-located in Asheville, North Carolina. Weather details for this location compared to Raleigh and Charlotte are shown in **Table 1**.

Table 1. North Carolina Weather Data (NOAA and ASHRAE)

City	Climate Zone	Design Heating Dry-bulb Temp (F)	Heating Degree Days (Base 65 F)	Heating Season Indoor Temp (F)	Design Cooling Dry-bulb Temp (F)	Cooling Season Indoor Temp (F)	Cooling Degree Days (Base 74 F)
Asheville	4A	19	4,144	70	86	75	748
Charlotte	3A	25	3,065	70	92	75	1,513
Raleigh	4A	24	3,275	70	92	75	1,313

Home Characteristics of Study Homes

The study team collected home characteristics for general context (**Table 2**). The intent of this study was to assess the as-installed performance of the HVAC system in each study home.

Table 2. Home Characteristics

City	Asheville, North Carolina		
Home “Name”	Copperhead	Heron	Marmot
Year Built	2010	2018	2018
Square Footage of Conditioned Space (ft ²)	3,200	2,710	2,015
# of Stories	3	3	2
# of Bedrooms, Bathrooms	3 bedroom, 2.5 bath (home office)	3 bedroom, 2.5 bath	3 bedroom, 2 bath
HVAC System Type & Efficiency	Ground-source Heat Pump 18 EER, 3.5 COP	Air Source Heat Pump 17 SEER, 10.5 HSPF	Air Source Heat Pump 16.5 SEER, 9.8 HSPF
HVAC System Configuration	Cooling: One centrally ducted air handler with two zones Heating: Multiple radiant floor zones	Multi-head mini-split system (three wall units, one ceiling cassette, one ducted air handler)	Two ducted mini-split air handlers
HVAC System Capacity and Fan Speeds	2-ton max output; variable-speed fan	3-ton max output; variable speeds	2 ½-ton max output; variable speeds
HVAC System Location	Conditioned basement office	Living space	Closed crawl space

Ductwork Insulation	One air handler with R-6 insulated ducts	One small air handler with R-8 insulated ducts	Two small air handlers with R-4.2 insulated ducts
Ductwork Tightness to Outdoors	Tight (0 CFM25)	Tight (0 CFM25)	Tight (22 CFM25)
House Tightness	Very Tight (0.82 ACH50)	Tight (1.53 ACH50)	Tight (1.59 ACH50)
HERS Rating (At Time of Construction)	16	53	56

EER = Energy Efficiency Ratio, COP = Coefficient of Performance, SEER = Seasonal Energy Efficiency Ratio, HSPF = Heating Seasonal Performance Factor.

Findings

This section provides observations from the data collected. The study team wanted to determine the average hourly electric demand for the HVAC units when the grid is at peak demand (known as coincident peak). For this study, the seasonal utility coincident peaks for 2019, 2020 and 2021 include 7 a.m. and 8 a.m. in the winter and 4 p.m., 5 p.m. and 6 p.m. in the summer.

Figure 1 shows scatterplots of the average power consumption in kW over the 7 a.m. and 8 a.m. hours, Monday through Friday, during the winter months versus the outdoor air temperature (OAT).

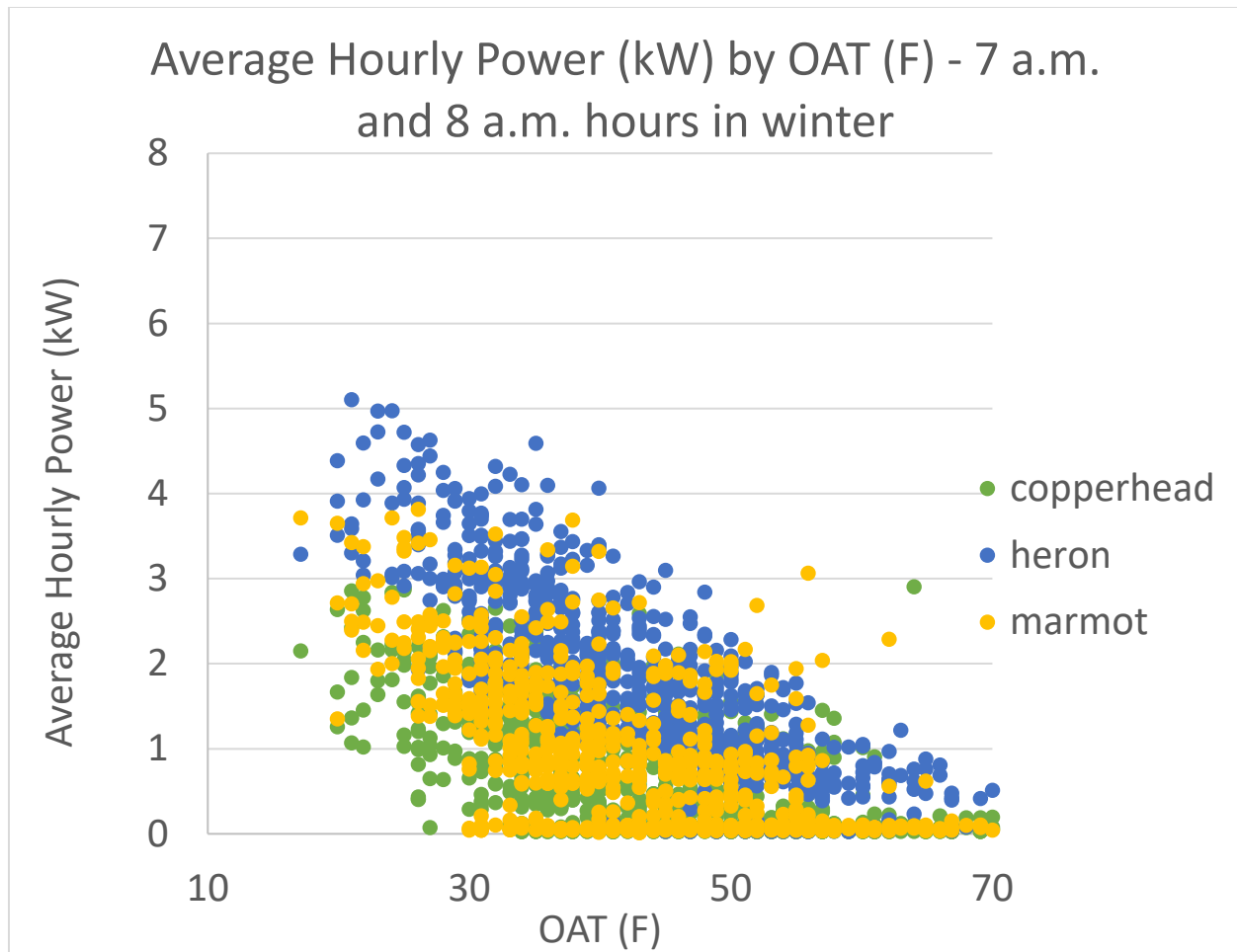


Figure 1. Average hourly power at 7 a.m. and 8 a.m. M-F during the winter months versus the OAT; Heron & Marmot — variable speed with multiple ductless indoor units; Copperhead — ground-source heat pump.

Figure 2 is a scatterplot of the average electric power in kW over the 4 p.m., 5 p.m. and 6 p.m. hours, Monday through Friday, during the summer months (May 1 to October 31) versus OAT.

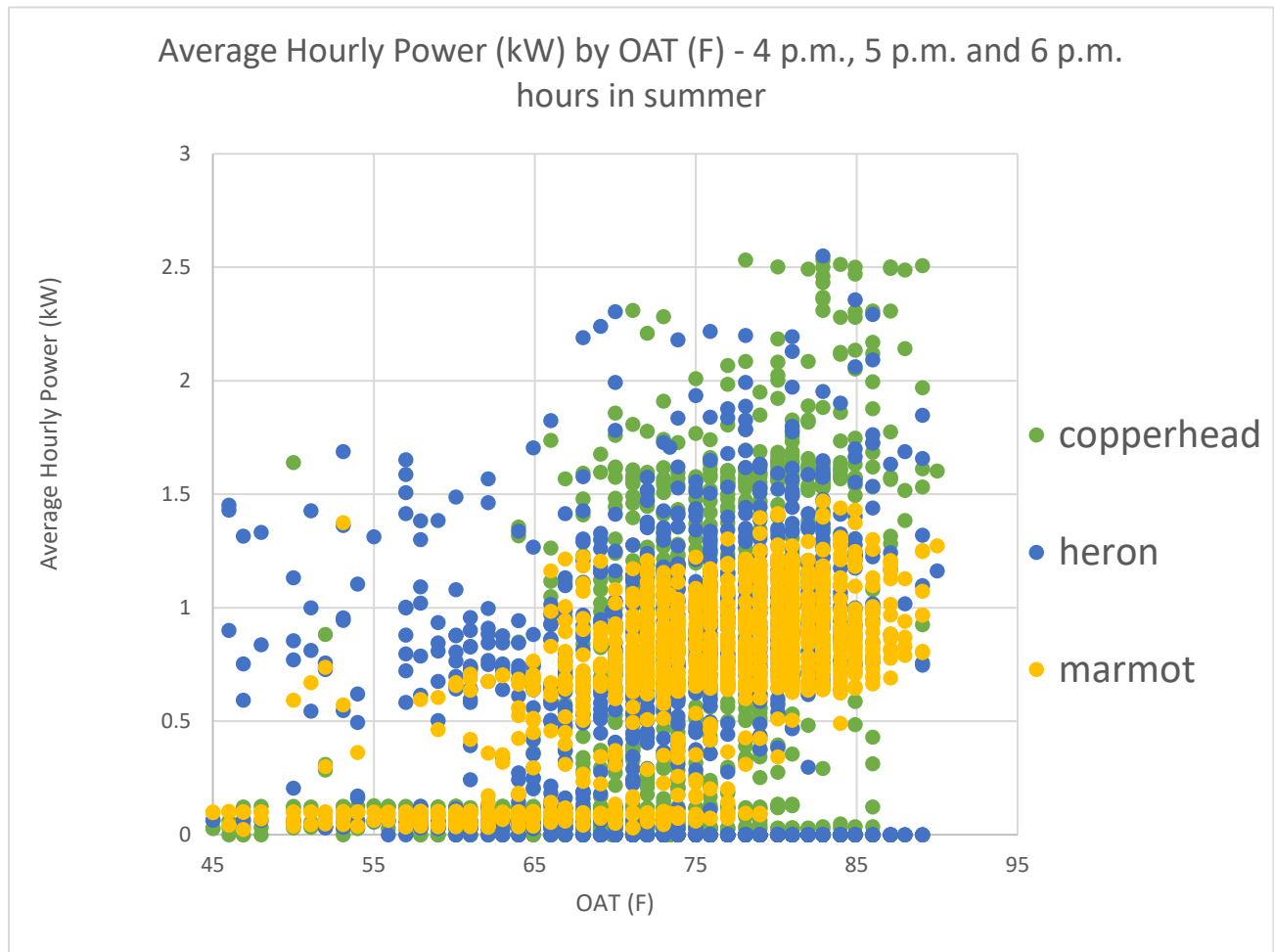


Figure 2. Average hourly power at 4 p.m., 5 p.m. and 6 p.m. M-F during the summer months versus the OAT; Heron & Marmot — variable speed with multiple ductless indoor units; Copperhead — ground-source heat pump.

In **Figure 3**, the peak power averaged over an hour in kW per month is charted. Winter heating energy performance across all homes ranged from a peak HVAC system demand of 2.9 kW to 5.4 kW averaged over an hour. When reviewing these data, it is important to note that the Heron and Marmot homes' overall peak demands were the same as the utility grid winter peak demands that occurred at the 7-9 a.m. hours. For the Copperhead home, the overall HVAC system peak demand was higher than the HVAC system demand during the utility grid winter peak demands.

All three study homes had similar demands in the two heating seasons. The largest peak demand for Copperhead was observed in January 2020 and 2021, the largest peak demand for Heron was observed in February 2021, and the largest peak demand for Marmot was observed in December 2019.

During the cooling seasons, the largest peak demand for Copperhead was observed in March 2019 at 2.9 kW. Copperhead had a much flatter profile than the other two homes; month

to month, its peak demand only ranged from 1.6 kW to 2.9 kW over an hour, with the exception of the mild October 2020 at 0.04 kW. The largest peak demand for Heron was observed in October 2019 at 5.3 kW, the same month the homeowners moved into the home. Month to month, its peak demand was lower and ranged from 2.0 kW to 2.8 kW over an hour, with the exception of October 2019. The largest peak demand for Marmot was observed in May 2020 at 2.7 kW; month to month, its peak demand only ranged from 1.1 kW to 2.7 kW over an hour.

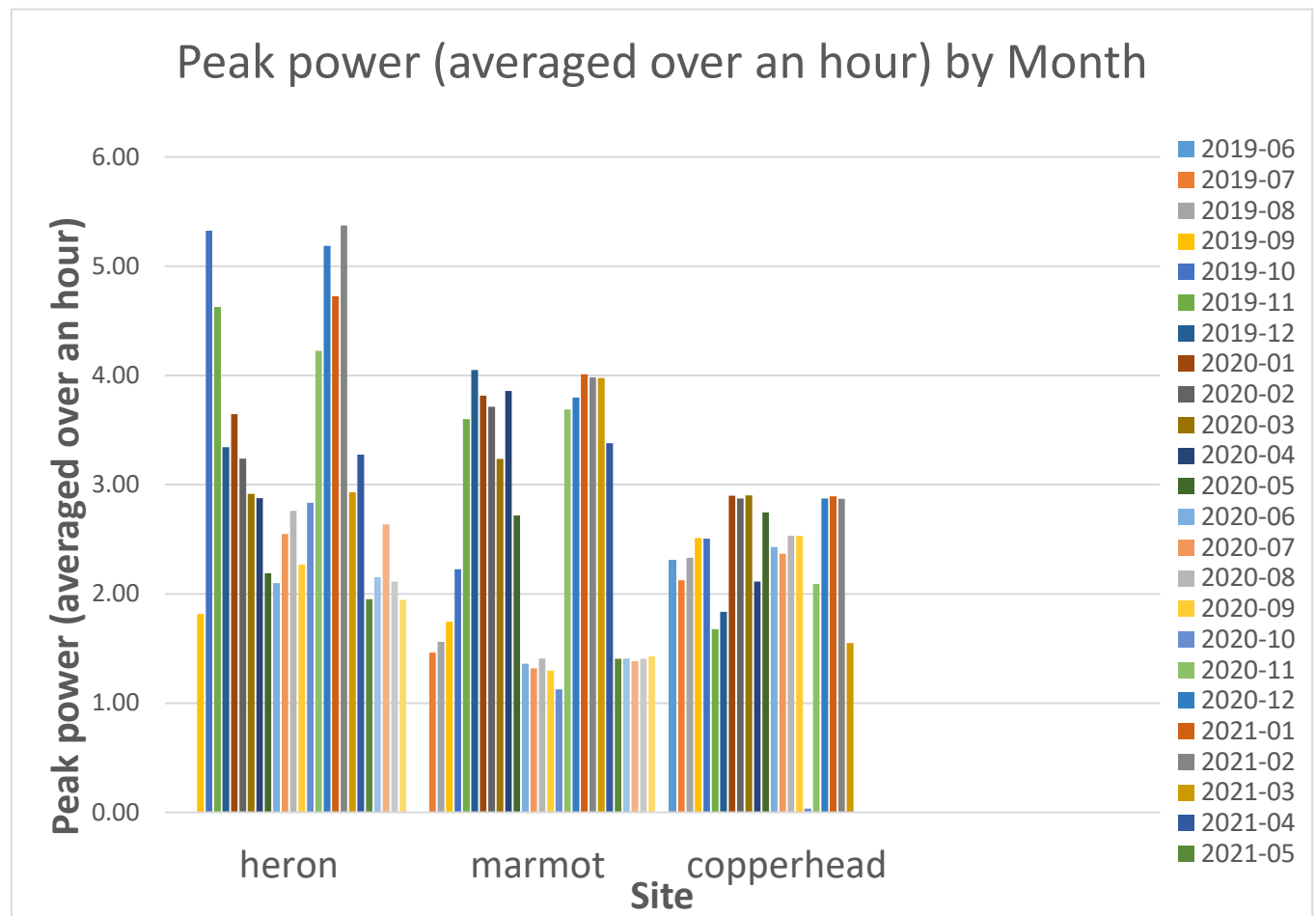


Figure 3. Peak power by month;
Heron & Marmot — variable speed with multiple ductless indoor units; Copperhead — ground-source heat pump.

Figure 4 shows the 98th percentile for the power demand in kW to eliminate outlying values. The demand at the 98th percentile is lower for each of the three homes.

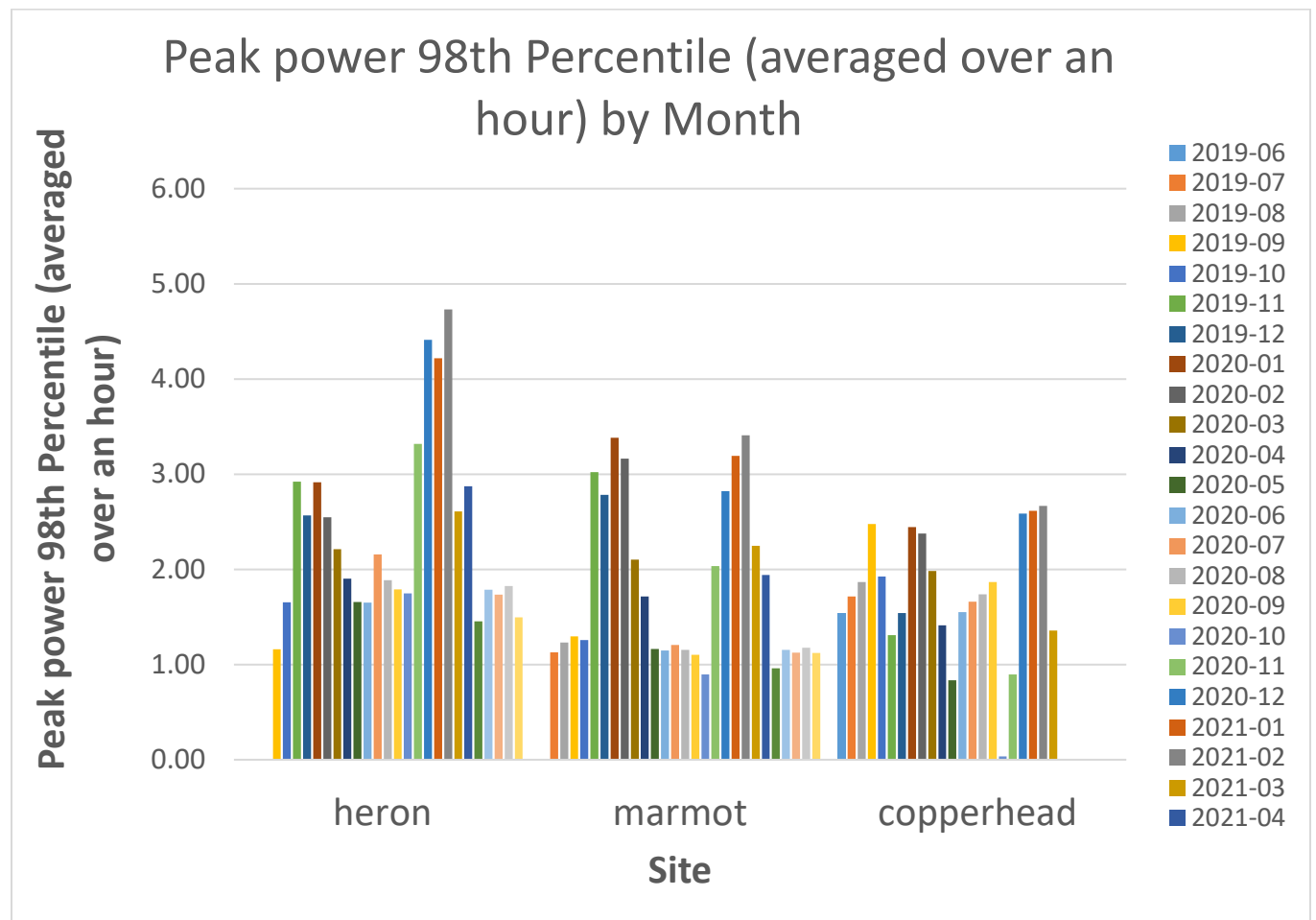


Figure 4. Peak power (98th percentile) by month;
Heron & Marmot — variable speed with multiple ductless indoor units; Copperhead — ground-source heat pump.

Figure 5 plots the time of the hourly average kW peak demand for each month. The yellow dashed boxes indicate summer months, and the solid red boxes highlight the hours mentioned above. This study found that most months had at least one home with a peak demand occurring at a similar time as the grid's coincident peak.

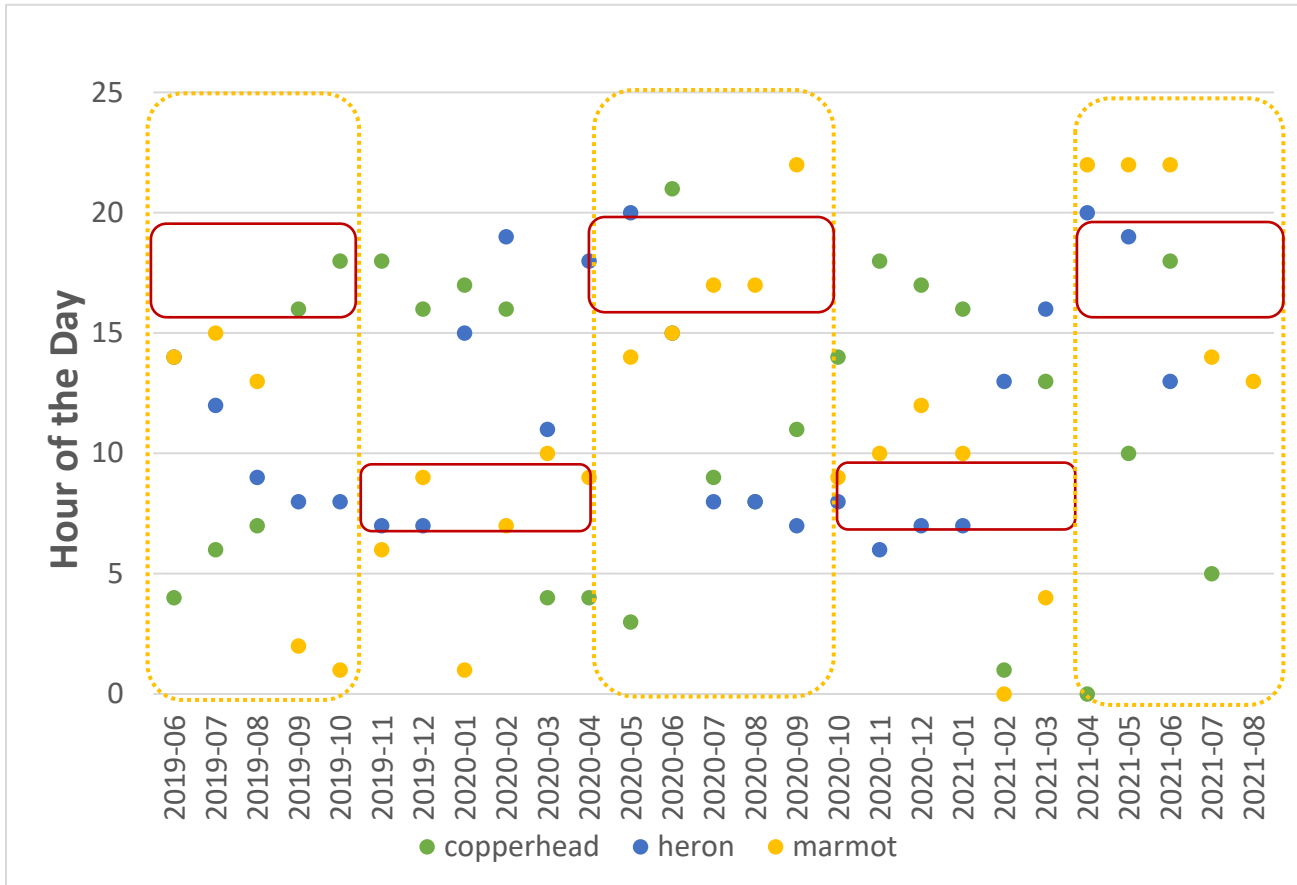


Figure 5. Time of the hourly peak kW demand (overlayed with summer and winter utility grid peak) by month; Heron & Marmot — variable speed with multiple ductless indoor units; Copperhead — ground-source heat pump.

In **Figure 6**, the average hourly electric power versus the OAT is shown. All three homes have similar demand profiles for OATs above 70 F; however, below that temperature, Heron uses more energy, peaking its energy usage at 5.0 kW when the OAT is 12 F; the high usage from this 5-indoor head system may be due to limited homeowner knowledge of system functionalities.

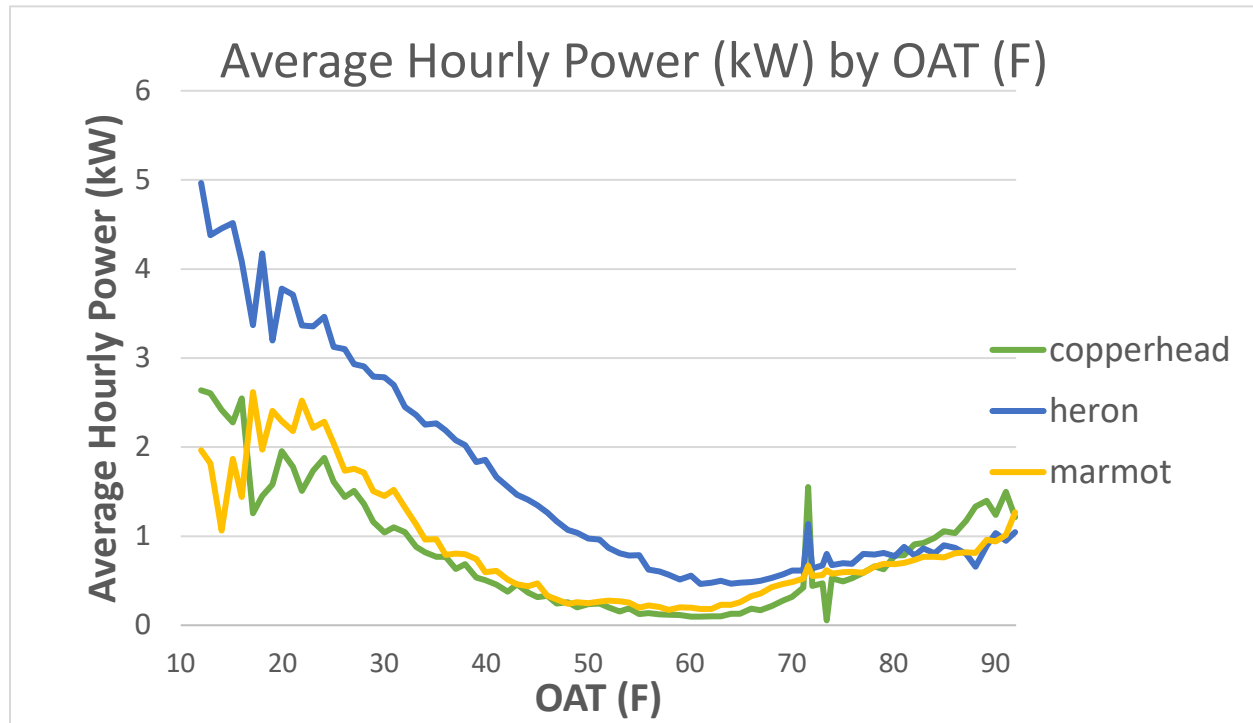


Figure 6. Average hourly power versus OAT;
Heron & Marmot — variable speed with multiple ductless indoor units; Copperhead — ground-source heat pump.

In **Figure 7**, the average hourly return temperature versus the OAT is shown. Each of the three homes has different preferences, but each preference is predictable across the outdoor temperatures. As noted in Table 2 Home Characteristics, the indoor design temperatures for HVAC sizing was 70 F for winter and 75 F for summer. These design conditions most align with the field measurements at the copperhead study home.

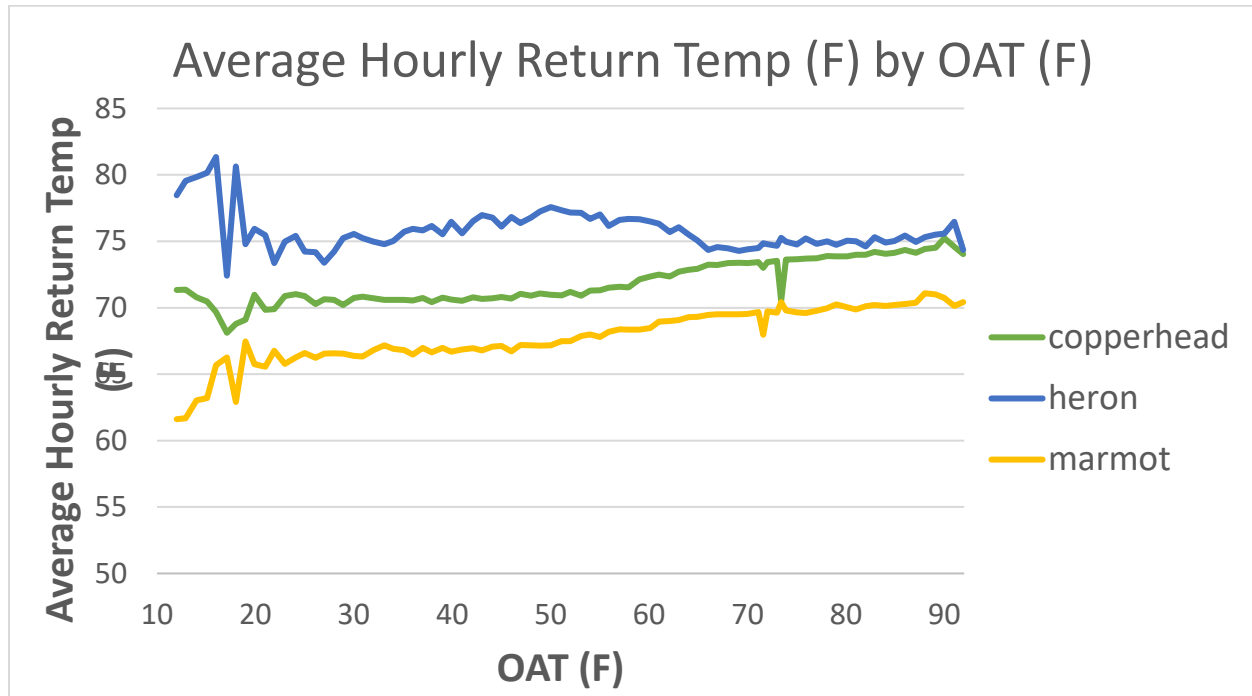


Figure 7. Average hourly return temperatures versus OAT;
Heron & Marmot — variable speed with multiple ductless indoor units; Copperhead — ground-source heat pump

The average hourly return RH versus the OAT is shown in **Figure 8**. RH above 60 percent can encourage mold growth, while RH below 30 percent can encourage the spread of viruses, like the flu. For thermal comfort of occupants during cooling, the 2015 ASHRAE Handbook (Chapter 62) recommends 75 F and a 55 F dew point (which equates to approximately 50 percent RH) (ASHRAE 2015). When the OATs were observed to be above mid-60s F, the RH in all three homes started to exceed 60 percent.

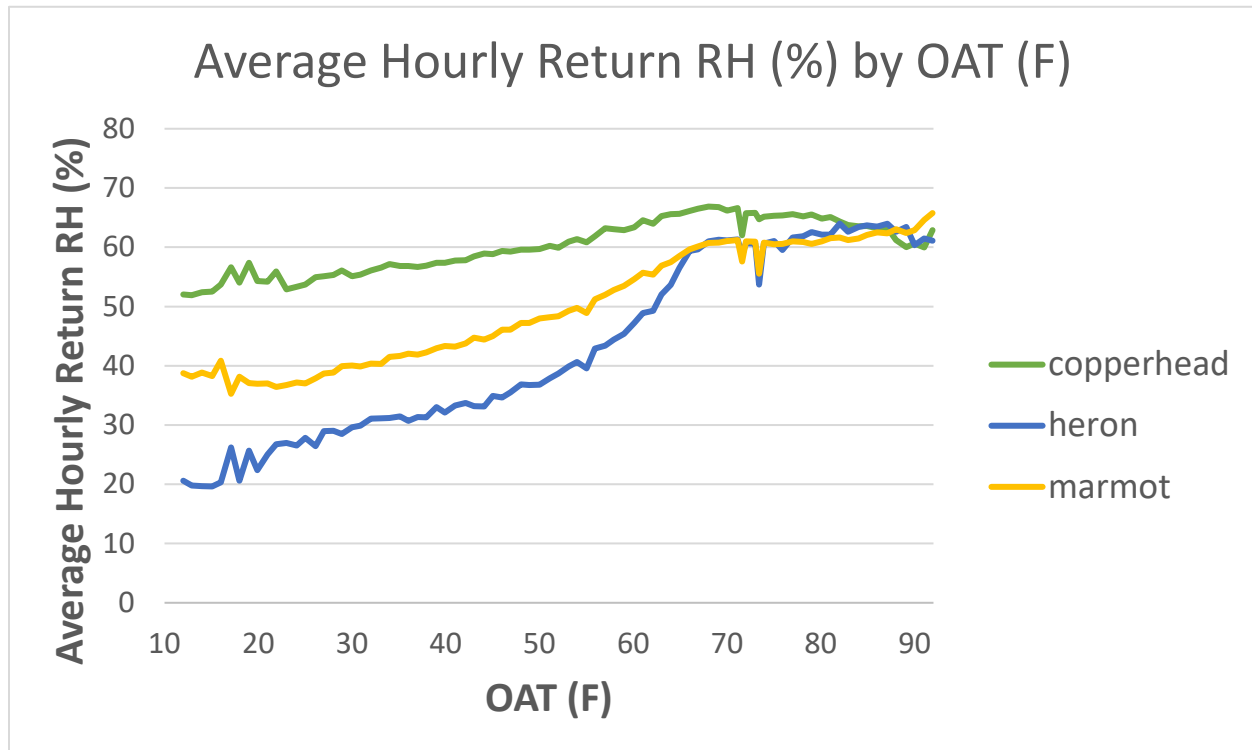


Figure 8. Average hourly return RH versus the OAT;
Heron & Marmot — variable speed with multiple ductless indoor units; Copperhead — ground-source heat pump.

Summary & Conclusions

- These high-efficiency heat pumps coupled with other ENERGY STAR® certified new home features provide low monthly customer energy consumption, moderate customer comfort and beneficial utility coincident peak performance during high utility grid demands.
- The HVAC system average hourly power during the utility coincident peak trended below 5 kilowatts (kW) for the winter heating season (indoor temperatures of 61-81 F) and below 2.5 kW for the summer cooling season (indoor temperatures of 70-75 F).
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- None of the HVAC systems' summer peaks occurred during the same outdoor temperature/month. The system peak hourly average in cooling mode of all three study homes reached a maximum between 2.9 kW and 5.4 kW.
- While the ASHRAE-recommended indoor comfort conditions (ASHRAE 2015) were not achieved during various times, occupants did not report indoor discomfort at any point in the study.
- In future studies, include existing homes and/or code-compliant new construction homes with standard construction details in study sample to better compare with these ENERGY STAR® certified study homes. For example, adding a new heat pump air handler to an existing leaky duct system may not achieve the full benefits of the heat pump equipment (ORNL 2012). Duct system leakage testing could be performed to capture baseline readings before sealing the ductwork to a reference standard. This systems approach could ensure that the field-installed efficiency of each heat pump is as close to matching its nominal performance as possible throughout its useful life. These follow-up details may also help provide insights into the features and benefits of combining multiple retrofit measures in customer homes and the coincident utility peak load impacts.
- In the future, documentation and increased knowledge of the thermostat settings/program selections may help the study better comprehend any HVAC system ramp-ups that may impact utility peak power demands.
- For future studies, performing an HVAC system load calculation on existing system changeouts and incorporating lifestyle preferences into the load calculation and system selection may especially help the occupant comfort impacts of a new variable-capacity heat pump system (FSEC Energy Research Center 2019).

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