slipstream

July 2024

Heat Pump Technical Analysis

Authors:

Karthik Panchabikesan, FSEC

Chuck Withers, FSEC

Dan Cautley, Slipstream

Brady Peeks, Northwest Energy Works

Contributors:

Michael Lubliner, Oak Ridge National Laboratory

Scott Pigg, Slipstream

Shannon Stendel, Slipstream

Acknowledgements

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.”

TABLE OF CONTENTS

EXECUTIVE SUMMARY

Manufactured homes are required to be shipped with heating systems – installing a heat pump's air handler with electric resistance heat in the factory satisfies this requirement. The outdoor unit of the heat pump can be connected after the manufactured home reaches the home site to become the primary heating and cooling system. Heat pumps in manufactured homes can reduce energy usage compared to conventional energy-intensive electric resistance heating and stand-alone cooling systems. To study the heat pump's ability to satisfy thermal comfort and energy requirements in both cool and hot climates, the research team funded by the U.S. Department of Energy's Advanced Building Construction Initiative installed the same 2-ton, variable-capacity Carrier 40MBAAQ24XA3/38MARBQ24AA3 ducted heat pump in an occupied manufactured home (MH) in Oregon and a lab home at the Florida Solar Energy Center (FSEC) in Cocoa, Florida. This heat pump model is a cold climate heat pump as defined by ENERGY STAR and was selected because it has an air handler that can function as a standalone electric furnace with a variable capacity compressor and air handler operation at a fairly affordable price point. This study investigates the performance of this MH suitable heat pump in different climates.

In Oregon, the team monitored the heat pump from September 24, 2022, to April 15, 2023. In Florida, the heat pump was monitored from June 30, 2022, to November 5, 2022, and from December 24, 2022, to March 31, 2023. We used a simple linear regression model to predict the energy consumption of the heat pump and auxiliary heating system through a full heating season at the Oregon site. Ultimately, we quantified the potential reduction in heating energy consumption due to the use of heat pumps compared to the electric resistance heating system.

The key lessons learned from the heat pump data technical analysis are:

- The Carrier heat pump installed in a new Clayton manufactured home in Oregon (cold climate) effectively managed the entire heating load throughout the winter, with minimal reliance on backup electric resistance heat. The backup heat was used on eight days, each time for less than 10 minutes.
- The heat pumps at both sites maintained thermostat setpoints in both heating and cooling under the full range of conditions encountered during the study.
- The heat pump showed over 60% heating energy savings (kWh) compared to electric resistance heat in the Oregon site.
- The heat pumps at both sites were, in general, able to maintain comfortable supply air conditions. At the Oregon site, the residents reported their home to be comfortable in the heating season. Summertime supply air temperature and relative humidity delivered by the Florida system were in the expected range for central cooling systems.
- This heat pump model showed significant power modulation in heating mode, as expected from variable capacity systems. There was very limited power modulation in cooling mode, with short cycles during low cooling load periods. Proper installation was confirmed, and the manufacturer could not determine a cause for the cooling performance observed in the two systems. Sometime after the study began, the air handler model tested in this study had been discontinued by the manufacturer and replaced by a new model with improved control.
- Running the heat pump in cooling while connected to attic ducts used 11.5% more daily cooling energy during a typical Florida summer day compared to when connected to the floor duct system. Both duct systems were reasonably airtight, but the floor ducts are within the primary thermal barrier of the house and attic ducts outside the thermal barrier in a very hot location.

HEAT PUMP MODEL AND SPECIFICATIONS

The same variable-capacity Carrier 40MBAAQ24XA3/38MARBQ24AA3 ducted heat pump was used in the two test sites, an occupied home in Oregon and a lab home at FSEC in Cocoa, Florida. It is a 2-ton, variable speed cold climate heat pump as defined by ENERGY STAR[1]. It has 22k Btu/hr capacity at 5 °F with a COP of 1.75 and a heating capacity ratio of 81% at 5 °F[2]. This heat pump model was selected for this study because it has an air handler that can function as a standalone electric furnace with a variable capacity compressor and air handler operation at an affordable price point. Manufactured homes are required to be shipped with heating systems – installing a heat pump's air handler with electric resistance heat in the factory satisfies this requirement and this heat pump seemed like a good fit.

DATA COLLECTION AND ANALYSIS – OREGON SITE

DESCRIPTION

We collected data at the Oregon site from September 24, 2022, to April 15, 2023. This period includes data from intentionally operating an auxiliary electric resistance heat system[3] between February 22, 2023 and March 14, 2023. Data from operating the auxiliary heat system allowed us to compare heat pump performance with that of the conventional electric resistance-based heating system. During the test period, however, there were some days (10/4/22, 10/5/22, 10/15/22, 10/19/22-10/21/22, 11/05/22-11/15/22) when no data was recorded due to power outages. These periods were excluded from the analysis.

The Oregon site was equipped with an ecobee 3 lite programmable thermostat programmed with a nighttime set back temperature. Parameters[4] related to heat pump power, thermostat set point temperature, room temperatures, supply air temperature etc., were measured with different sensors and at different resolutions as shown in Table 1. Figure 1 shows a picture of the manufactured home (left) and the heat pump installation at the Oregon site (right). Table 1 shows the source and resolution of various data collected at the Oregon site.

---

[1] ENERGY STAR Program Requirements Product Specification for Central Air Conditioner and Heat Pump Equipment, Eligibility Criteria Version 6.1. https://www.energystar.gov/sites/default/files/2024-08/ENERGY%20STAR%20Version%206.1%20Central%20Air%20Conditioner%20and%20Heat%20Pump%20Final%20Specification%20Rev.%20January%20%202022.pdf

[2] Carrier Product Information for 38MARB Outdoor Unit Single Zone Ductless System Sizes 09 to 36, 38MARB-01PD.fm

[3] The term 'auxiliary heating system', 'auxiliary heat', 'aux_heat', and 'electric resistance heating' all describe electric resistance-based heating.

[4] Apart from the parameters mentioned in Table 1, other parameters (such as crawl space temperature, relative humidities, the moisture content in each room, ecobee events) were measured using different sensors. The parameters used for the data analysis, however, are shown in Table 1.

Figure 1. Picture of the manufactured home (left) and heat pump installation (right)

Table 1. Parameters used in the study and their data resolution

Parameter	Data resolution	Sample value/Options
Egauge		
Epoch timestamp (seconds)	1 second	1555688409
PDT (for Pacific Daylight Time)[5]		2022-09-24 10:40:09
Heat pump power (p_comp) (W)		1385.683
Auxiliary heating system power (p_auxht) (W)		9560
Voltages (v) • Phase A (v_a) • Phase B (v_b)		118.7
Omni		
Temperature (ºF) • Supply and return air temperature • Outdoor air temperature • Room temperature – Living room/Kitchen, master bedroom (MBR) and three bedrooms (BR1, BR2 and BR3) • Dewpoint temperature – Outdoor and Indoors (including supply air, return air and rooms)	5 minutes	62.6
Relative humidity – RH (%) • Supply and return air RH • Outdoor air RH • Room (including crawl space) RH		59.4
ecobee 3 lite		
ecobee setting (ec_setting)	5 minutes	Heat/cool/auto/off
ecobee mode (ec_mode)		compressorHeatStage1On, compressorCookStage1On, etc.
ecobee program mode (ec_progmode)		Home/Away/Sleep
Heating and Cooling setpoint temperature (ºF)		68.0

---

[5] Pacific Daylight Time is used in plots and analysis throughout this report, including times when local clocks would be set to Pacific Standard Time.

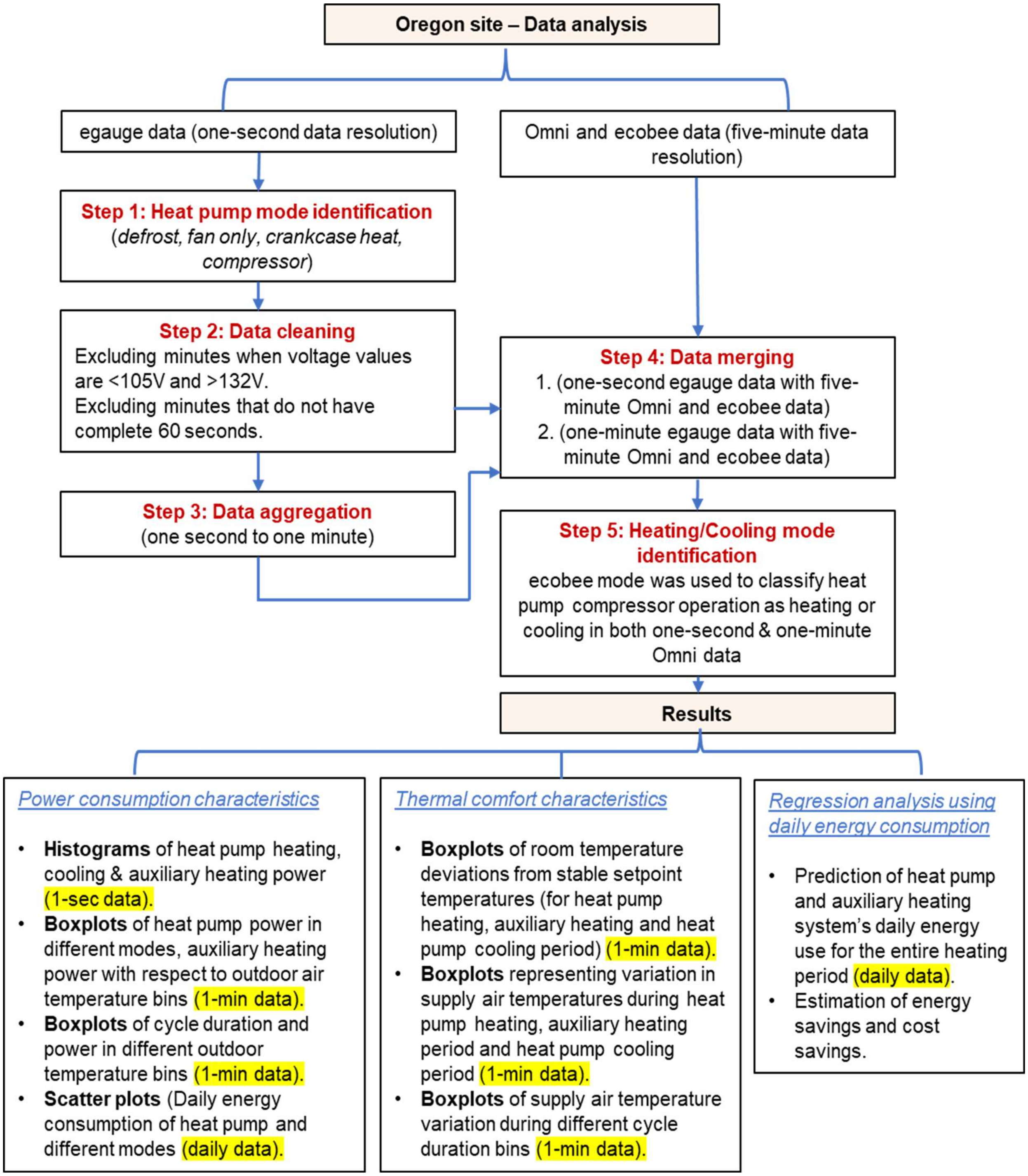
There were some discrepancies among the three sensors’ timestamping of data. These were likely due to the sensors different time labelling behavior, which was also affected by some power outages.

We primarily used the power values measured from egauge sensors to study the heat pump and auxiliary heat system power consumption and for the regression analysis. We used the voltage values measured from egauge sensors to identify the low voltage signals that indicated power loss (if any) during the data logging. Measured values from all three measurement systems (Omnisense, egauge and ecobee) were used for the comfort analysis.

APPROACH

Figure 2 shows the data analysis procedure followed to analyze the heat pump performance at the Oregon site. A similar data analysis was performed in the FSEC MH lab, however, the data sets used, and data resolution were different. We cover details on the FSEC MH lab data analysis later in the report and show the data analysis procedure in Figure 29.

Figure 2. Data analysis procedure for Oregon site



Step 1: Heat pump mode identification (*defrost, fan only, crankcase heat, compressor*)

Step 2: Data cleaning
Excluding minutes when voltage values are <105V and >132V.
Excluding minutes that do not have complete 60 seconds.

Step 3: Data aggregation (one second to one minute)

Step 4: Data merging
1. (one-second egauge data with five-minute Omni and ecobee data)
2. (one-minute egauge data with five-minute Omni and ecobee data)

Step 5: Heating/Cooling mode identification
ecobee mode was used to classify heat pump compressor operation as heating or cooling in both one-second & one-minute Omni data

Power consumption characteristics

- **Histograms** of heat pump heating, cooling & auxiliary heating power (1-sec data).
- **Boxplots** of heat pump power in different modes, auxiliary heating power with respect to outdoor air temperature bins (1-min data).
- **Boxplots** of cycle duration and power in different outdoor temperature bins (1-min data).
- **Scatter plots** (Daily energy consumption of heat pump and different modes (daily data).

Thermal comfort characteristics

- **Boxplots** of room temperature deviations from stable setpoint temperatures (for heat pump heating, auxiliary heating and heat pump cooling period) (1-min data).
- **Boxplots** representing variation in supply air temperatures during heat pump heating, auxiliary heating period and heat pump cooling period (1-min data).
- **Boxplots** of supply air temperature variation during different cycle duration bins (1-min data).

Regression analysis using daily energy consumption

- Prediction of heat pump and auxiliary heating system's daily energy use for the entire heating period (daily data).
- Estimation of energy savings and cost savings.

Table 2 shows the conditions applied to classify the heat pump operation, such as defrost, fan only, crankcase heat, and compressor mode. Unless otherwise stated, "fan" refers to the indoor air handler fan throughout this report.

Table 2. Thresholds used to identify different modes of heat pump operation

Conditions used for heat pump operating mode identification	Heat pump operating mode
Minimum heat pump power < 170 W, Mean heat pump power > 800 W, AND Cycle duration[6] >1.5 minutes and < 13 minutes	Defrost[7]
Heat pump power ≤ 6 W	OFF
Heat pump power > 6 W and ≤25 W	Controls
Heat pump power >25 W and ≤75 W	Crankcase heat[8]
Heat pump power >75 W and ≤200 W	Fan Only (may include additional crankcase heat)
Heat pump power >200 W	Compressor[9]

We didn’t identify a mode for auxiliary heat because it was powered through a separate circuit. In general, we use the term “heat pump” to indicate the power of the heat pump system (fan, compressor, crankcase heater, and controls).

HEAT PUMP SYSTEM BEHAVIOR

We generated time series plots of events, such as defrost cycles, heat pump operation during thermostat setback and recovery periods, power consumption of the auxiliary heating system, etc., to illustrate certain types of trends under specific conditions.

Figure 3 shows an example of the characteristic part load operation of the heat pump and cyclic operation of the fan while the compressor was not operating. The cyclic fan operation when compressor is off is identified on Figure 3 as “Fan cycles”. This is a characteristic that is also observed in ductless minisplits, when there are no heating or cooling cycles after a while, the indoor fan turns on to pull air past an on-board temperature sensor to get a measurement of indoor air. It is understandable that a minisplit without an independent wall thermostat would do this to sample the temperature but is not necessary for a system that has an independent thermostat unless the heat pump system is doing this to observe the rate of change in indoor temperature as part of its operational algorithm. This may be the reason for the automated fan-only cycles since this system was designed to operate with third party thermostats and did not require a proprietary digital communicating thermostat. The figure shows characteristic observed operation, with compressor power relatively constant for some periods, and frequent modulation at other times. It also shows the fan cycles drawing power between 100 to 150 W,

---

[6] The cycle duration threshold is applicable only for defrost mode.

[7] The thresholds mentioned in Table 2 for different mode identification were set after several attempts.

[8] During mode identification, there was an underestimation of crankcase heat power values. We did not isolate crankcase heat when it was running simultaneously with the fan-only operation. It is however a minor power impact.

[9] As seen in Figure 2, a variable from the ecobee dataset called “ec_setting” data was used to classify a compressor operation as either heating/cooling mode.

during the compressor off time. We found that whenever the compressor stayed off for more than 15 minutes, the typical on/off time for a fan cycle was 7.5 minutes (i.e., 7.5 minutes ON, 7.5 minutes OFF).

Figure 3. Characteristic part load operations of the compressor and an example of cyclic fan operation during the compressor off-time

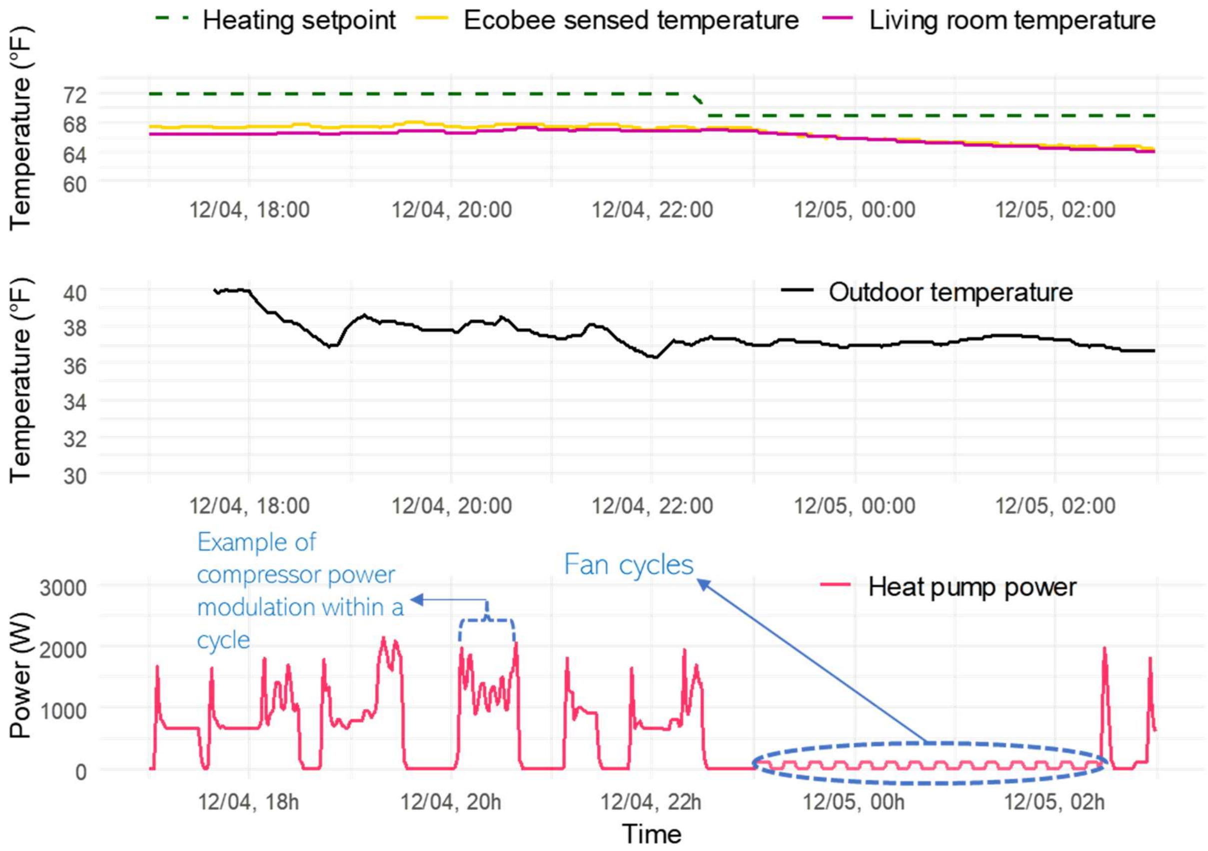


Figure 4 shows an example of four defrost cycles that occurred during winter weather. Auxiliary heating was not called into operation during defrost, and the living room temperature did not decrease more than 0.5ºF. The heat pump power reached a maximum of 4,134 W on 12/17/2022 at 8:00h, when the ecobee program changed from scheduled "sleep" to "home" which resulted in a setpoint increase from 65ºF to 68ºF.

Figure 4. Time series plot showing various instances of defrost cycles and the corresponding outdoor temperature and heat pump, auxiliary heating system power

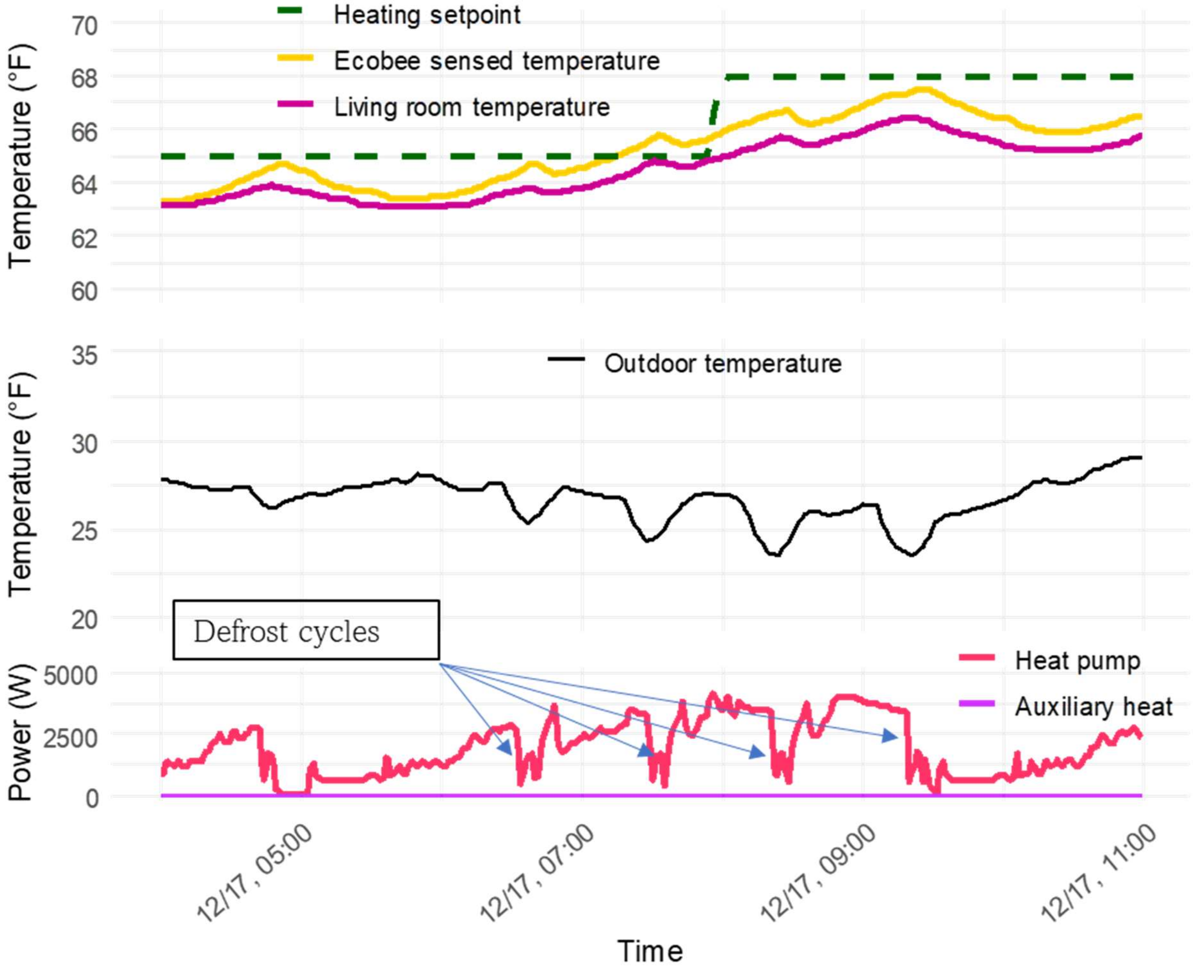
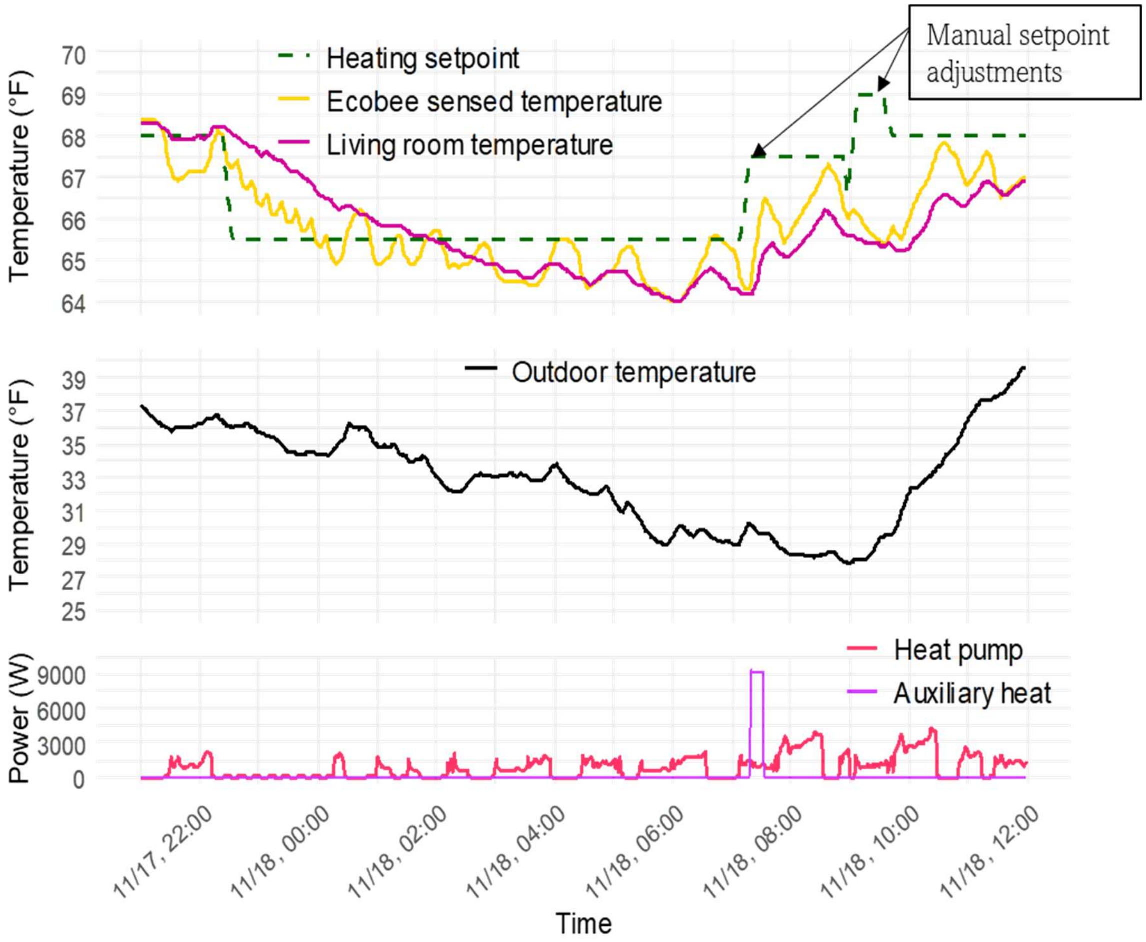


Figure 5 is an example of overnight heating behavior during heat pump operation when there were manual changes in the setpoint temperature. Manual setpoint changes were common in both heating and cooling operations in this home. Figure 5 shows that the night-time setback temperature (i.e., ecobee program changing from “home” to “sleep” occurred at 22:30h on 11/17/2022, and accordingly, the heating setpoint temperature was reduced from 68ºF to 65.5ºF. The setback temperature continued until 7:13h on 11/18/2022, at which time the setpoint was manually increased from 65.5ºF to 67.5ºF. Auxiliary heating was called for during a short period while the temperature was set at 67.5ºF, as shown in the bottom-line plot of Figure 5. Auxiliary heating in this instance was expected since the setpoint was set about 3.5ºF higher than the thermostat sensed the room temperature. Around 9:00h, the ecobee program changed from “sleep” to “home.” From 21:00h on 11/17/2022 to 11:59h on 11/18/2022, the minimum, average, and maximum outdoor temperatures were 27.8ºF, 32.9ºF, and 39.6ºF, respectively.

Figure 5. Time series plot showing the operation of the auxiliary heating system during a manual setpoint change



The ecobee thermostat uses a Smart Recovery function to ensure that the temperature is already at the setpoint by the time it is programmed to take effect. The Smart Recovery function operated regularly at this site with the thermostat in heating, cooling, and auto modes. It anticipated programmed thermostat changes by 15 to 90 minutes. Figure 6 demonstrates the Smart Recovery feature in action. Although the overnight temperature doesn't drop to the 65ºF setpoint, heating starts at 7:01 AM, anticipating the programmed temperature increase to 68ºF taking effect at 8:00 AM. The compressor operated for about 51 minutes, then turned off when the thermostat sensed room temperature within 1ºF of the 68ºF setpoint.

Figure 6. Time series plot showing the ecobee's smart recovery function

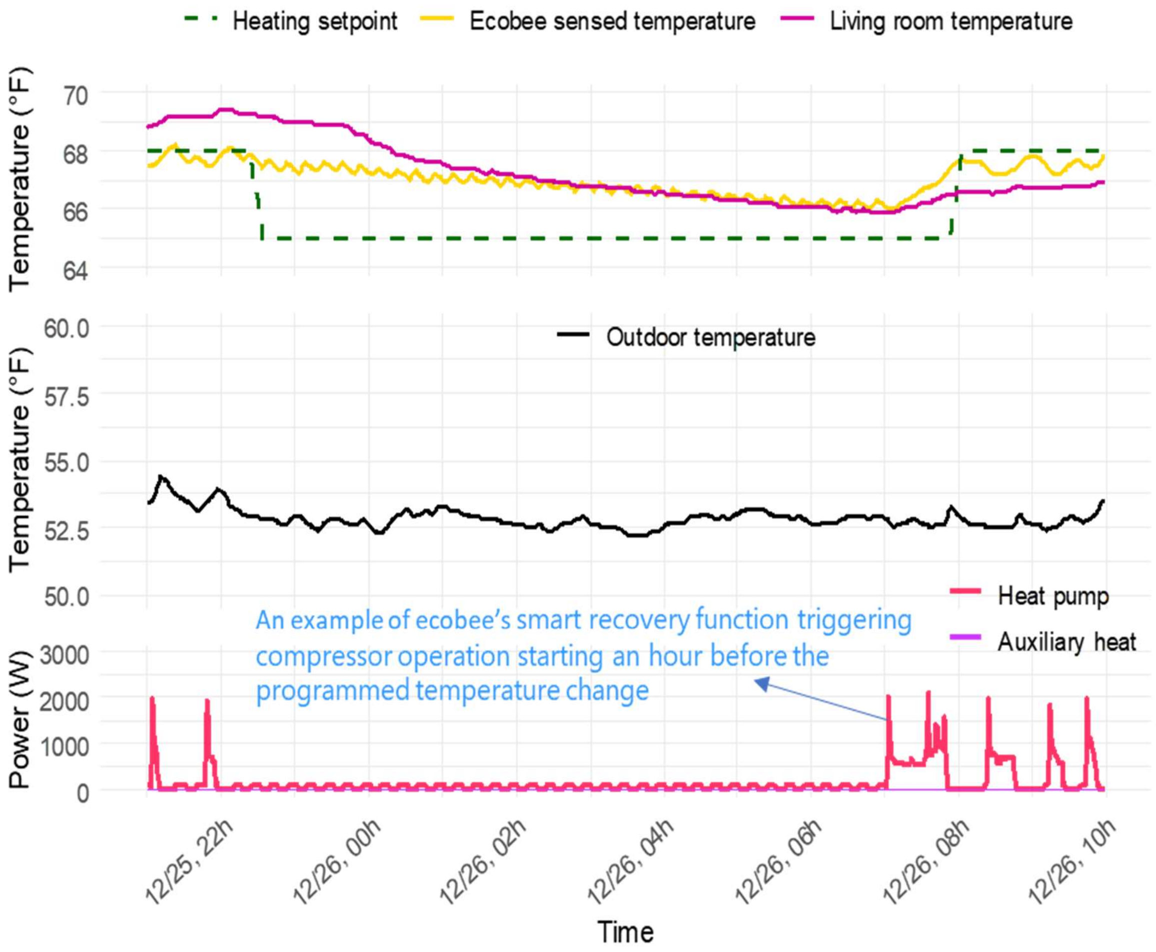


Figure 7 shows an example of the auxiliary heating system operational pattern (including the thermostat recovery period) during the period of intentional auxiliary heating. During this period, the outdoor temperature varied between ~36ºF and 43ºF. Auxiliary heating power generally (but not always) cycled at full power during the study. We observed prolonged operation of the auxiliary heat system (as highlighted in yellow in Figure 7) when there was a significant change/rise in the ecobee sensed temperature and the setpoint temperature. The ecobee Smart Recovery function was active during the first highlighted period, between 07h and 09h on 02/26 and the auxiliary heat system operated in anticipation of the programmed temperature increase. Later, around 12:00h, the household manually adjusted the setpoint temperature from 68ºF to 70ºF accounting for the second period of auxiliary heating.

Figure 7. Example of auxiliary heating system operation (during intentional resistance heating system test period) and its response to the change in the setpoint temperature

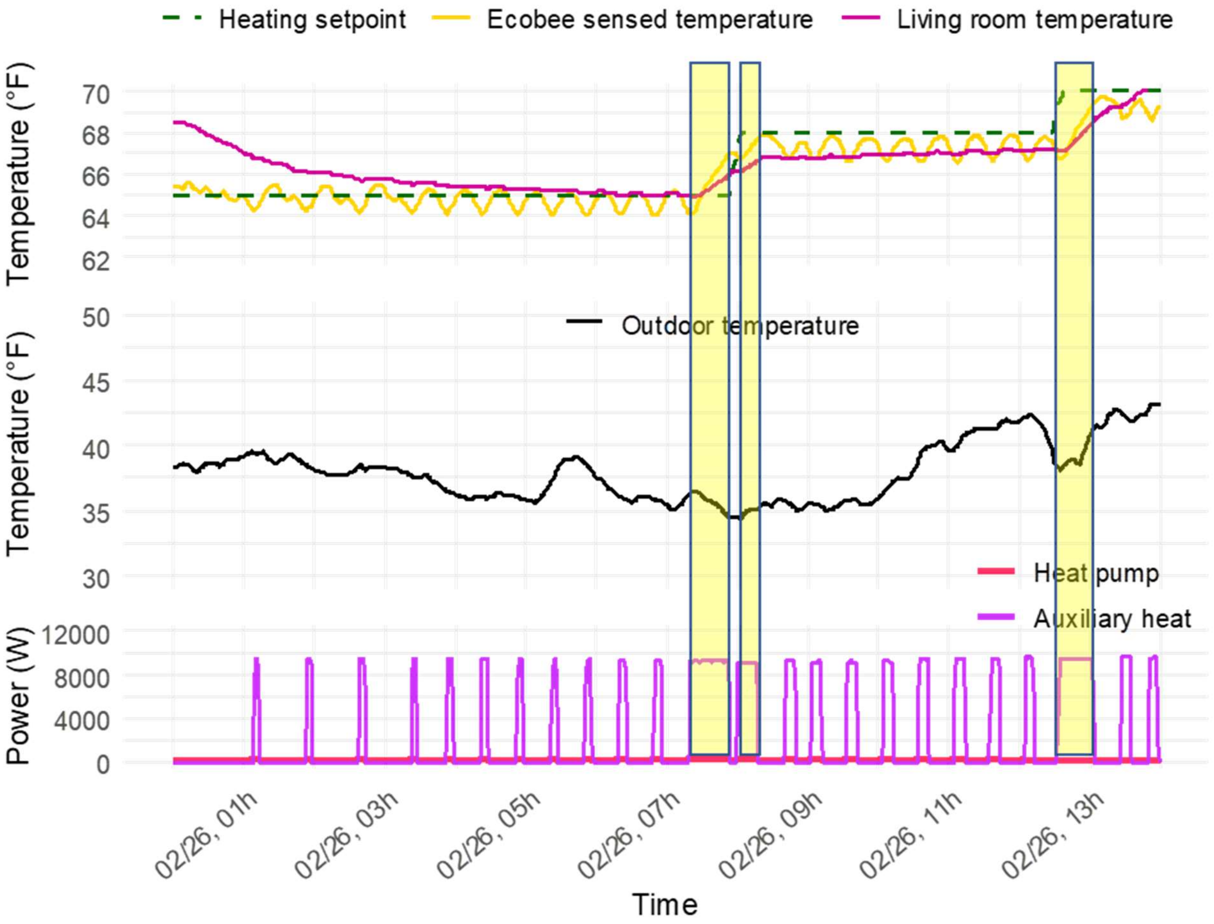
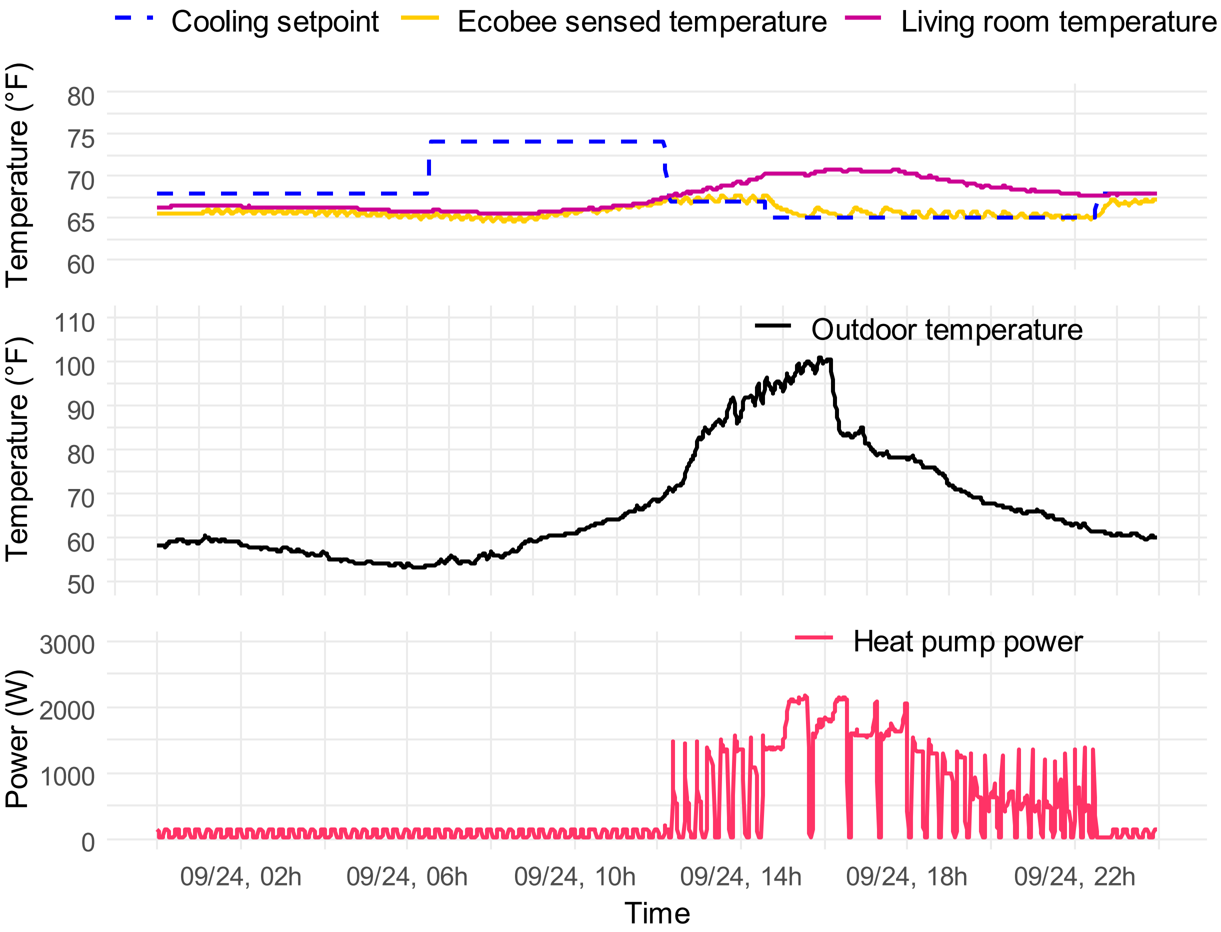


Figure 8 shows the heat pump operation, setpoint temperature, and the variation in outdoor temperature while cooling. The figure shows the cooling operation between 02h and 22h on 09/24. While compressor power does display limited modulation in cooling, it frequently operates in short cycles. This cycling contrasts with longer continuous cycles in heating operation. The power in cooling mode never exceeded ~2,500 W, compared to ~ 4,500 W while heating.   Outdoor temperature measured on site may include some bias due to solar heating near the sensor. However, the outdoor temperature and RH sensor on site was compared to the nearest available weather data and found to be suitable for general weather observations.

Figure 8. Example of heat pump operation in cooling mode



HEAT PUMP AND AUXILIARY HEAT POWER CONSUMPTION

The heating and cooling performance of the heat pump power and operational cycling was evaluated. Since this heat pump was a very high efficiency variable capacity system, we looked for expected trends of relatively long runtime cycles and generally lower power during lighter heating and cooling loads with maximum power output only at the highest loads. Data from the Oregon site found that heating power and cycling were as expected, however cooling data showed more evidence of short cycles during low load and less power modulation than heating. Figure 9 displays the heat pump power distribution (in 50 W power bins) during heating (excluding observations of less than 201 W, per Table 2). As described in Figure 2 ecobee data was used to identify whether the compressor was operating in heating or cooling mode. The variation in power draw is consistent with compressor modulation, with some concentration of power use around 700 W and in a broad band around 1,500 W. The maximum power measured during the heating operation was 4,680 W.

Figure 9. Frequency distribution of heat pump power in heating mode (using one-second data) in 50 W power bins

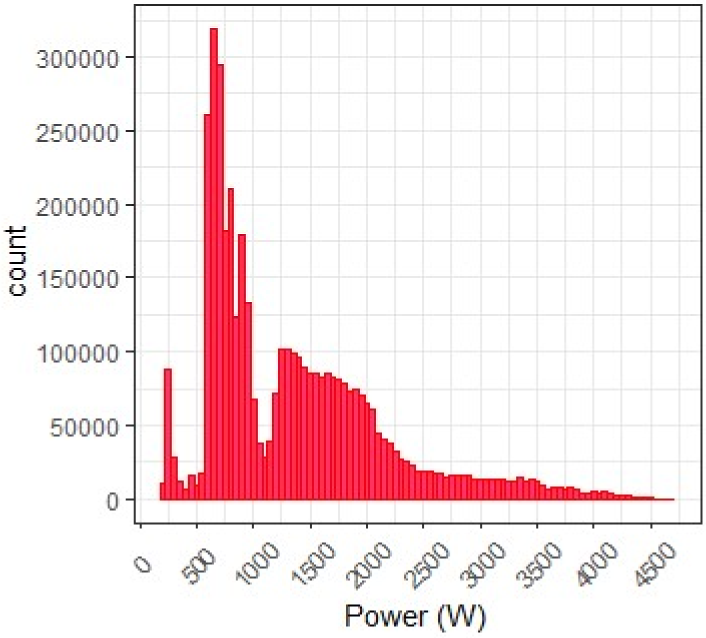


Figure 10 shows the power distribution of the heat pump compressor operation in cooling mode. Less cooling data was recorded at the Oregon site because there was less need for cooling. The maximum cooling power recorded was 2,793 W. Forty-one percent of the data count falls in the power range of 1,001W-1,500 W.

Figure 10. Frequency distribution of heat pump power in cooling mode (using one-second data) in 50 W power bins

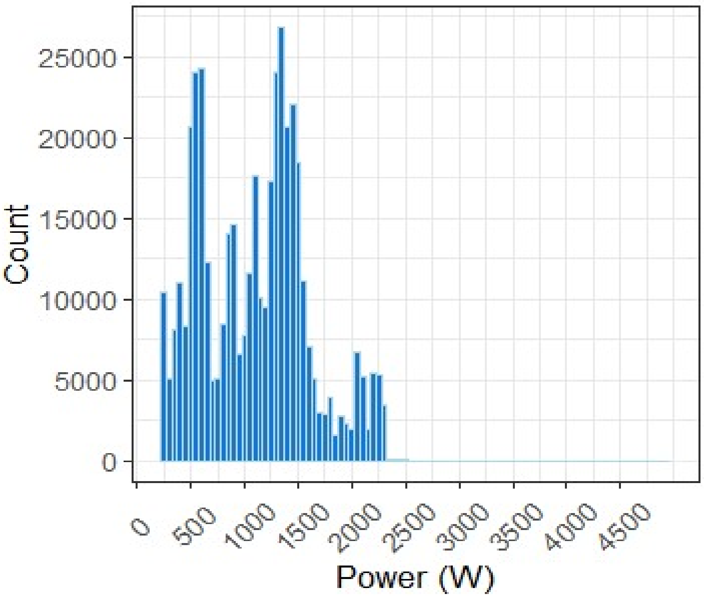
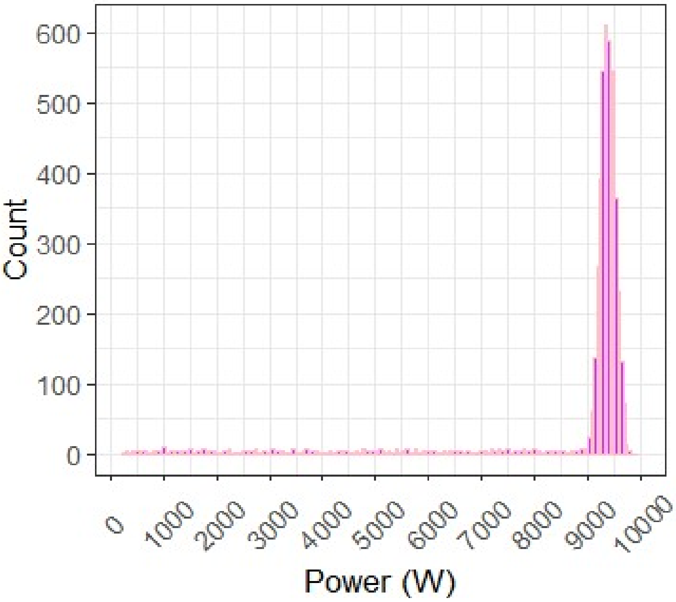


Figure 11 depicts the power distribution of the auxiliary heating system. We intentionally operated the auxiliary heating system between February 22, 2023, and March 14, 2023 to compare its performance to the heat pump. As seen in Figure 11, the auxiliary heating system does not show significant variations in the power consumption, which ranged between 9,000 W to 10,000 W, unlike heat pump operation in compressor mode.

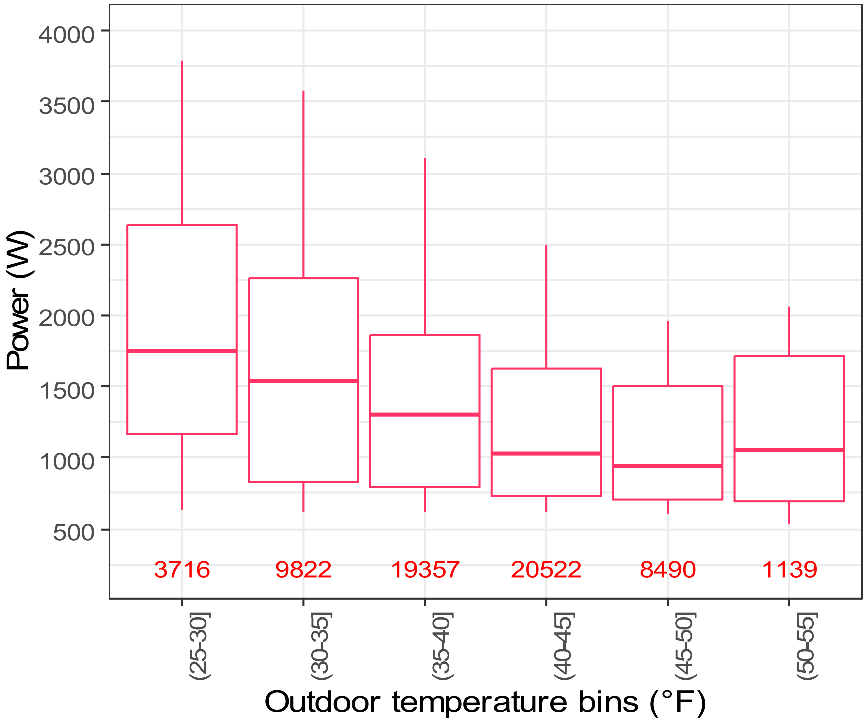
Figure 11. Frequency distribution of auxiliary heating system (using one-second data) in 50 W power bins



The boxplot in Figure 12 shows the operating watts of the heat pump compressor during heating operation in 5ºF outdoor temperature bins. We measured the outdoor temperature using sensors that recorded every five minutes, while heat pump power was averaged over every minute. We used hourly average values for the outdoor temperature instead of the five-minute data to avoid potential quick variations from events like cloudbursts (rainfall) being grouped in 5ºF bins. The stored energy and mass of building materials prevents quick variations from influencing the heating or cooling load.

As seen in Figure 12, we excluded the power values from the first and last minute of each heating cycle since they do not represent the power values of typical complete compressor operation. As expected, the heat pump typically operated at higher power levels during periods of colder outdoor temperatures compared to higher outdoor temperatures based on median values. There was not enough heating data to use for a boxplot with outdoor temperatures between 55ºF to 60ºF. Figure 6

Figure 12. Hourly average heat pump (heating mode) power grouped in 5ºF hourly average outdoor-temperature bins. Groups of fewer than 100 points are excluded.



Notes on the boxplot[10]:

- Unless specified, the numbers inside the boxplot represent the data points in each outdoor temperature bin.
- The boxplots minimum and maximum represent the 5th and 95th percentile.
- The middle horizontal line in the boxplot represents the median value.
- The lower and upper horizontal lines in the boxplot represent the 25th and 75th percentile.
- The hourly average outdoor temperature was used with one-minute power data.

---

[10] The information presented as ‘notes’ below Figure 12 is applicable to all the boxplots presented in the report.

- The outdoor temperature bins are represented by the "(and]" parentheses. For example, (25-30]. In this case of (25-30], the interval includes values greater than 25 and less than or equal to 30. So, a value of 25 would not be included, but a value of 30 would be included in that bin.

Figure 13 shows the heat pump operating watts grouped in 10ºF outdoor temperature bins during the cooling mode. Again, we binned the outdoor temperature using the hourly average value instead of five-minutes value. Also, we had less cooling data so binned the outdoor temperature in 10ºF intervals rather than 5ºF bin intervals. During cooling, the heat pump generally operated at higher power levels during periods of higher loads, i.e., warmer outdoor temperatures. Just as we did for heating, we did not use the first and last minute of the cooling cycle.

Figure 13. Heat pump (cooling mode) power in 10ºF hourly average outdoor-temperature ranges (using one-minute data)

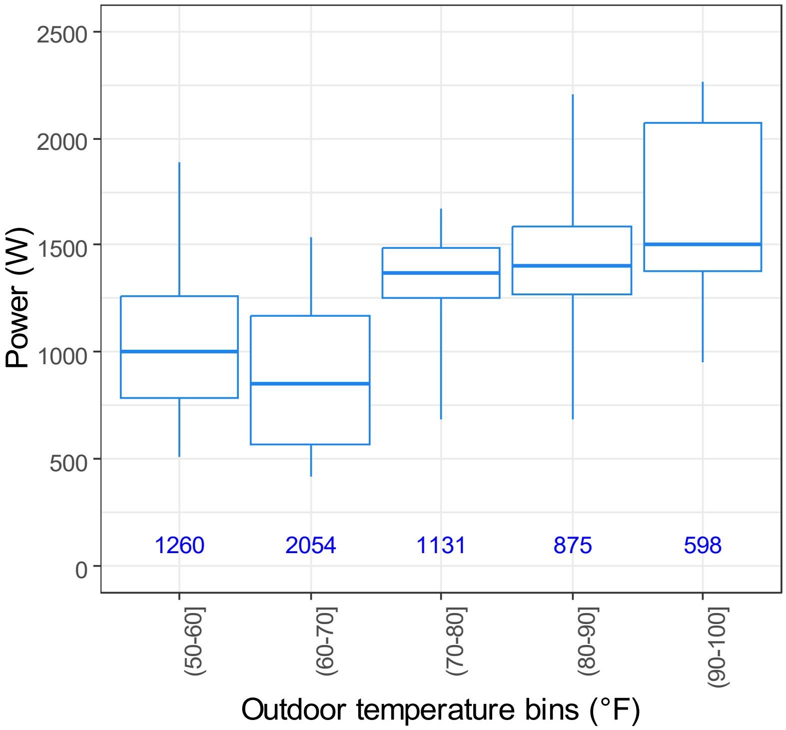
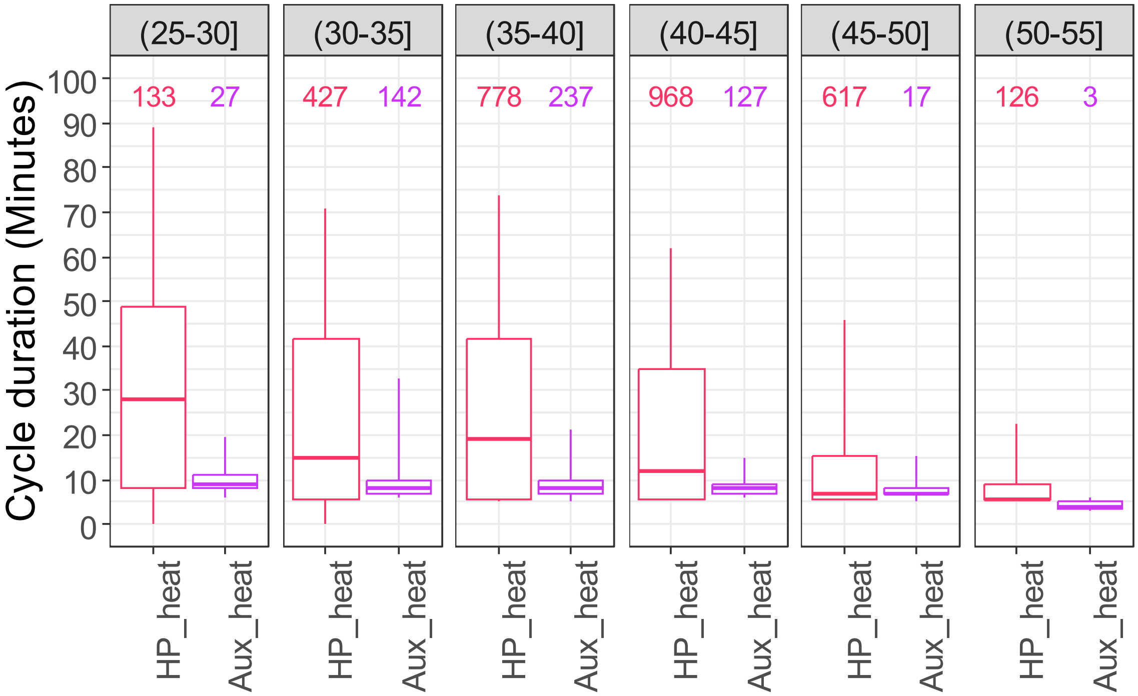


Figure 14 shows heating cycle duration (in minutes) during heat pump heating and during the period of intentional auxiliary heating. The numbers within each subplot denote the number of cycles and not the number of one-minute data points. Unlike Figure 12, we included the entire cycle duration without omitting the first and last minute of the cycle for both the heat pump and auxiliary heating.

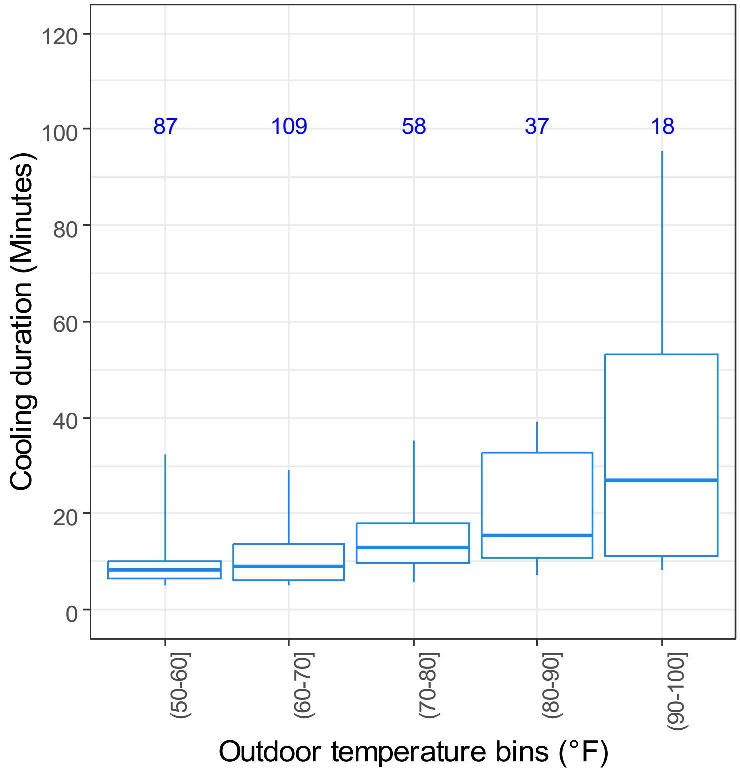
We had negligible data points from the auxiliary heating system for the outdoor temperature bins of (45ºF to 50ºF] and (50ºF to 55ºF], thus making those statistics inconsequential. Additionally, we excluded the heat pump heating cycles data when the ecobee setting was on auto mode. Figure 14 indicates that the heat pump compressor operated in long cycle periods during the colder outdoor temperatures since, by design, it had variable heating output. We did not observe many variations in the cycle duration of the auxiliary system, with respect to the outdoor temperature, however. For the auxiliary heating system, 82% of the cycles had a cycle duration between 5 and 10 minutes.

Figure 14. Heat pump heating and auxiliary heat cycle duration 5ºF hourly average outdoor-temperature ranges (using one-minute data). The numerical values within each box represent the number of heating cycles



Similar to Figure 14, Figure 15 shows the duration of the heat pump compressor cycle during cooling. The numbers inside the boxplot represent the number of cooling cycles in each outdoor temperature bin. We used the entire cycle duration without omitting the first and last minutes of the heat pump compressor cycle for our calculation. As expected, the cycle duration was longer for the higher outdoor temperature bins.

Figure 15. Heat pump cooling cycle duration 10ºF hourly average outdoor temperature ranges (using one-minute data). The numerical values above each box represent the number of cooling cycles



HEAT PUMP AND AUXILIARY HEAT SYSTEM ENERGY CONSUMPTION

Figure 16 shows the daily total heating energy used during two different modes of operation: when the system was set to typical heat pump operation and when it was intentionally set to auxiliary heating only. The monitoring period occurred from late September through mid-April. Compressor heating and any of its associated operations were not operated when the system was set to auxiliary heating. The last part of the plot shows the return to heat pump operation.

The purpose of this analysis was to compare the energy use of the electric resistance heat equipment to the heat pump. The auxiliary heat test period started on 2/22/2023 at 19:08 PDT and ended on 3/14/2023 at 13:30 PDT. We calculated daily total heating energy shown in Figure 16 and for the space heating analysis using the following considerations:

During the normal heat pump operation period with no auxiliary heating operation, we calculated the daily total heating energy kWh (for the heat pump) as the total energy consumed by the heat pump (i.e., power consumed in the compressor, defrost, fan-only, crankcase heat, and controls-only operating modes) for each day in our analysis period. We excluded days during which the thermostat was set to cooling control mode.

During the normal heat pump operation period with incidental auxiliary heating system operation, we took into account the total heat pump kWh and the energy consumed by the auxiliary heating system.

During the intentional auxiliary heat test period, we calculated daily total heating energy as the sum of energy consumed by the auxiliary electric resistance heat element plus the heat pump fan and controls.

Figure 16. Total daily energy consumption (kWh) during heat pump operation and auxiliary heating test period

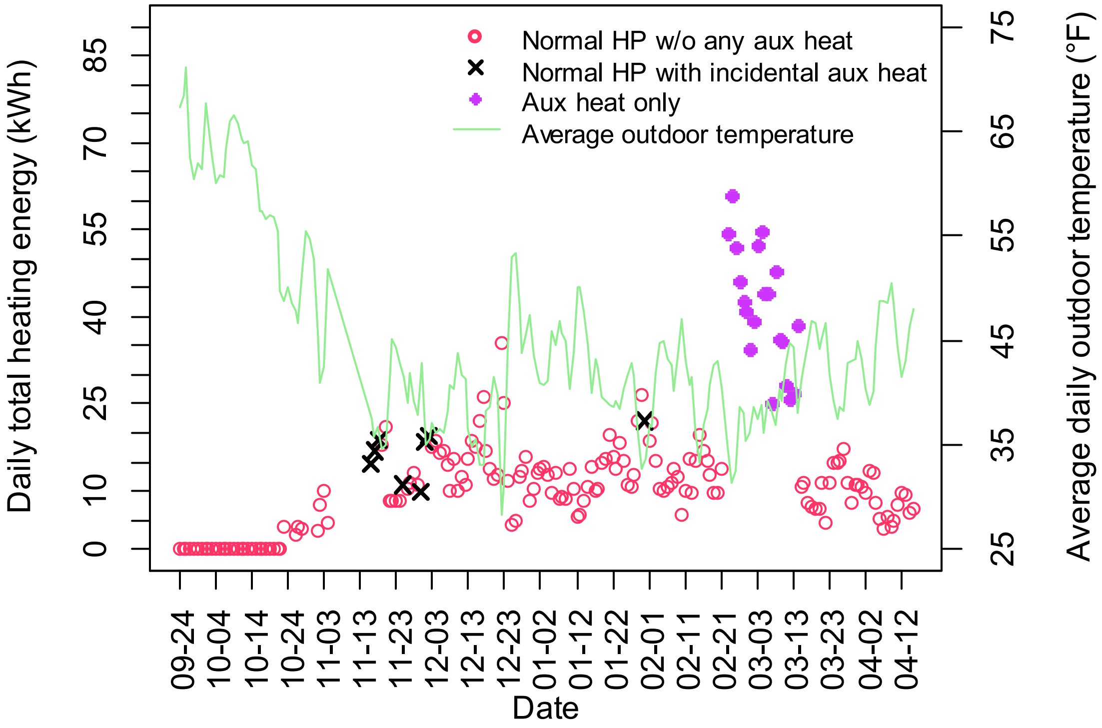


Figure 16 shows the higher energy consumption pattern of the auxiliary heating system compared to the heat pump. The heat pump heating operation period started approximately October 24, 2022. Before this period, the heat pump was predominantly operated in cooling mode. We also note that the heat pump was able to heat the space without calling on the auxiliary heating system. During normal heat pump operation (and excluding irregular behavior during recovery from a power outage), auxiliary heating was active for 10 brief periods on eight separate days, as shown in Table 3. There is just one case in which auxiliary heat appears to have been triggered during normal programmed thermostat recovery from night setback. In that instance, the outdoor temperature was about 24ºF. In all other cases of auxiliary heating, the thermostat had been placed in a manual hold. In most of these cases, someone had manually increased the temperature setting shortly before auxiliary heat was called. This data suggests that if there had been no manual thermostat changes, there would have been almost no use of auxiliary heat. In any case, auxiliary heat accounts for only a tiny fraction of the total heating energy for this system. More details on the average energy consumption during various heat pump modes (compressor, fan-only, crankcase heat, and defrost) are shown later in Table 4.

Table 3. Details on the episodes of auxiliary heating system operation during normal heat pump heating operation

Date time	Ecobee setting	Manual Ecobee setpoint change (Yes/no)?	Ecobee event & setpoint change	Ecobee temp at start of aux heat (ºF)	Ecobee t_out (ºF)
2022-11-16 09:22h	heat	Yes (66ºF -> 68ºF)	hold	64.7	27.2
2022-11-17 10:12h	heat	No (68ºF, no recent change)	hold	64.7	31.6
2022-11-18 07:19h	heat	Yes (65.5ºF -> 67.5ºF)	hold	64.3	27.5
2022-11-25 07:07h	heat	No (70.5ºF, no recent change)	hold	66.4	35.0
2022-11-30 08:39h	auxHeatOnly	Yes (67.5ºF -> 68.5ºF)	hold	66.0	46.1
2022-12-01 08:41h	heat	Yes (68.5ºF -> 69.5ºF)	hold	63.9	33.9
2022-12-02 09:20h	heat	Yes (68.0ºF -> 70.0ºF)	hold	66.4	33.9
2023-01-31 08:14h	heat	No – Looks like programmed change (66.0ºF -> 68.0ºF)	Not in hold	64.9	23.8
2023-02-22 19:08h to 2023-03-14h	auxHeatOnly				

We plotted the daily total heating energy against the daily average outdoor temperature for the two different heating modes of operation (heat pump in normal operations and the intentional use of the auxiliary heating system). Figure 17 shows the results. The black ‘x’ symbols in Figure 17 indicate total energy use during normal heat pump operation on days with some amount of auxiliary heating energy.

Figure 17. Daily total heating energy (while normal heat pump operation and auxiliary heating test period) vs daily average outdoor temperature

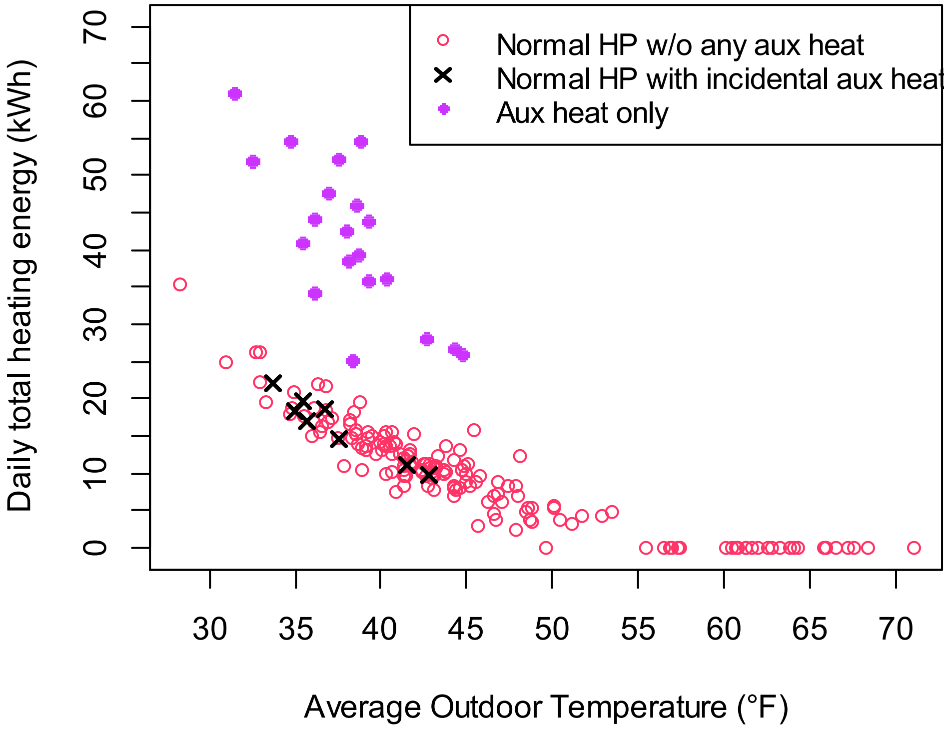


Figure 18 shows the heat pump's daily total energy consumption in heating, cooling, and auto mode (ecobee setting) against the daily average outdoor temperature. "Auto mode" here indicates the thermostat setting that allows automatic changeover between heating and cooling, so both may occur within a day. Note that heating and cooling energy converges around the outdoor temperature range between 50ºF to 55ºF. Table 4 summarizes the average daily energy consumption (during the normal heat pump operation in the entire data collection period) of each mode during heating and cooling (compressor, fan-only, crankcase heat, and defrost).

Figure 18. Daily total heat pump heating and cooling energy vs daily average outdoor temperature, including the days when the ecobee setting was in "auto" mode

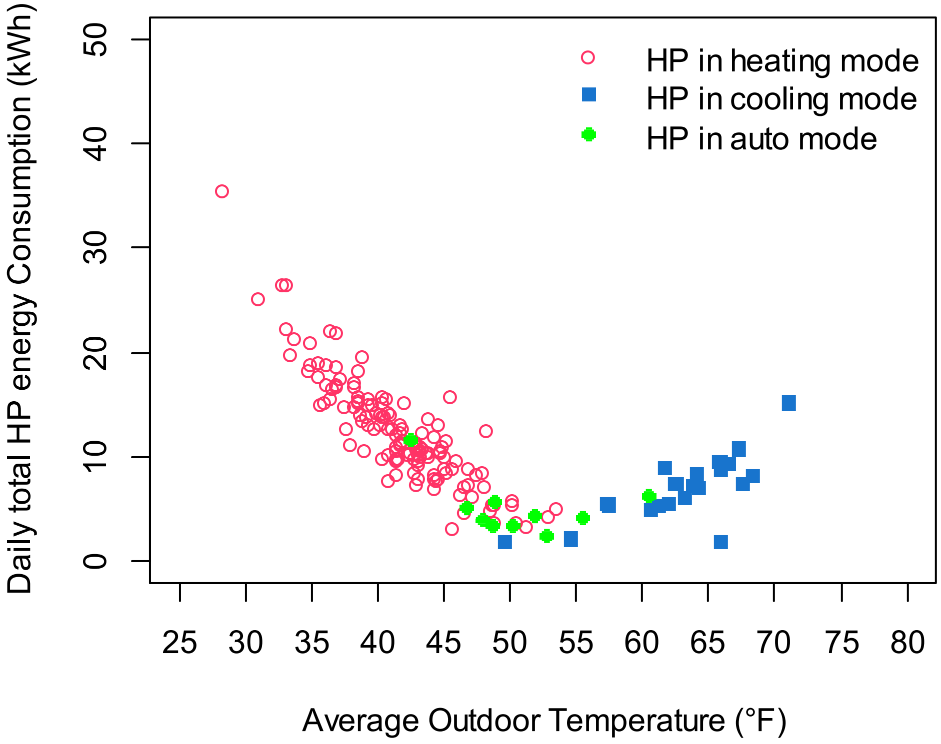


Table 4. Average daily energy consumption of each operating mode, including ecobee setting in auto mode days, and any auxiliary heat operation during normal heat pump heating and cooling operation. It includes the full data collection period except the period of intentional auxiliary heat operation.

Heat pump operating Mode	Compressor	Fan-Only	Defrost	Crankcase heat	Controls	Incidental auxiliary heat
Heating (kWh)	10.7	0.75	0.16	0.014	0.16	0.09
Cooling (kWh)	3.99	1.1	NA	NA	0.18	NA

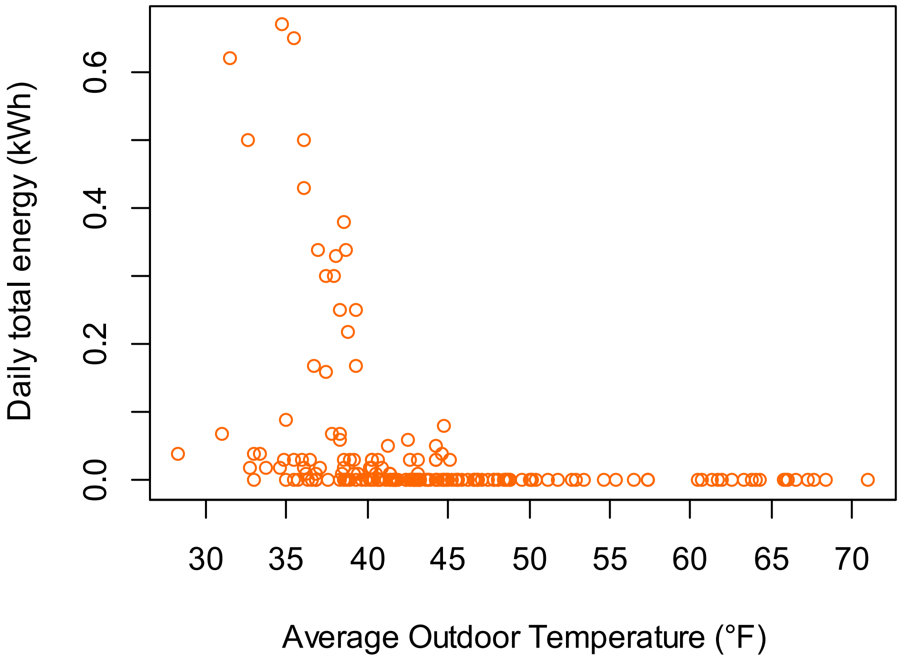
BREAKDOWN OF HEAT PUMP HEATING ENERGY CONSUMPTION

As previously shown in Table 2, we identified power consumption thresholds to classify the different parts of heat pump operation: crankcase, defrost, fan only, and compressor. Following is our analysis of daily energy consumption versus outdoor temperatures for crankcase, and defrost operating events.

Crankcase Operation

We identified heat pump power between 26 W to 75 W as the threshold for the crankcase heating mode. Crankcase heat mode includes the constant power consumption of controls. There were some occasional instances when the crankcase heat and indoor fan may have occurred simultaneously. For such instances we were not able to discern the crankcase heat operation from the fan operation. We found that during the entire heating operation the crankcase heater was in operation for 5% of the total heating time. This includes when the ecobee setting was in auto, heat, and auxiliary heating mode. Figure 19 shows the crankcase heat operation during the cold days (when the daily average outdoor temperature was <45ºF).

Figure 19. Daily total energy consumption (kWh) during crankcase heat operation vs average outdoor temperature



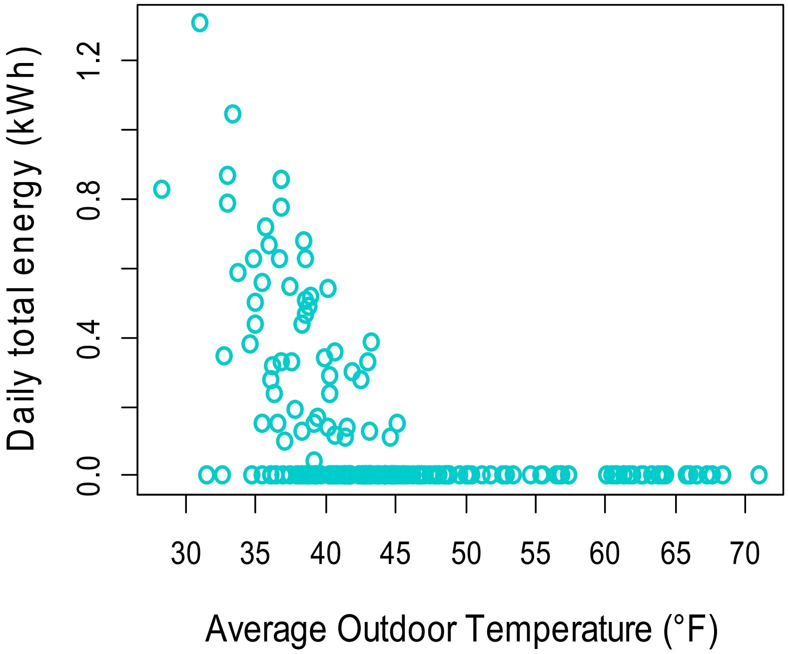
Automated Indoor Fan Operation

As demonstrated in Figures 3, 5, 6, and 8, the heat pump system would automatically cycle the indoor air handling fan on for about 7.5 minutes and off for 7.5 minutes consecutively between heating or cooling cycles. Possible explanations for this were previously discussed in the Heat Pump System Behavior section. The power of the indoor fan was 120 W and accounted for a daily average energy use of 0.75 kWh per day during heating period and 1.1 kWh per day during cooling period. The higher daily average during cooling is due to longer periods of time between cooling cycles compared to heating cycles.

Defrost Operation

Our analysis of defrost cycles found that they ranged between 1.5 minutes to 13 minutes. We identified 193 defrost cycles during the data collection period (September 24, 2022, to April 15, 2023). Figure 20 shows the defrost operation during cold days (when the daily average outdoor temperature was <45ºF). The circulation fan did not operate during defrost cycling. We also looked at the average daily defrost energy consumption versus the average dewpoint temperature. The results, however, were not significantly different from average daily defrost energy consumption versus outdoor temperature as shown in Figure 20.

Figure 20. Daily total energy consumption (kWh) during defrost cycling vs average outdoor temperature



HEAT PUMP AND AUXILIARY HEAT REGRESSION ANALYSIS

We used a regression analysis to further examine the energy consumption of the heat pump and the auxiliary heat system at this site. We used a simple linear regression to predict daily average heating energy consumption by the heat pump and auxiliary heat system, respectively.

Heat Pump Regression Analysis

We considered the following in our heat pump regression analysis:

- We excluded the following days from our analysis:
    - power outage days – 10/4, 10/5, 10/15, 10/19-10/21,11/05 to 11/15
    - auto mode days[11] – 10/23 to 11/4, 03/16 to 03/18
    - intentional period of heating with auxiliary electric resistance element – 02/22 to 03/14

- We considered daily heating energy kWh (total heat pump kWh[12] minus cooling kWh) as a dependent variable[13].
- We considered heating degree days (HDD) as an independent variable. We calculated HDD to a given base temperature (Tbase) for a given daily average outdoor temperature (Tout) as Tbase minus Tout where Tout is less than Tbase and zero if Tout is greater than Tbase. The analysis empirically found the best fit Tbase over a range from 48ºF to 63ºF as shown in Table 5.

Table 5. Regression trials to determine base temperature

T_{base}	Intercept	Coefficient	Adjusted R^2
48	3.87464	1.24824	0.8492
49	3.23678	1.19308	0.8656
50	2.63984	1.14141	0.8761
51	2.07589	1.09393	0.8829
52	1.58589	1.04659	0.8853
53	1.17246	0.99949	0.884
54	0.78346	0.95663	0.8814
55	0.44436	0.91554	0.8769
56	0.16128	0.87560	0.8705
57	-0.08857	0.83808	0.863
58	-0.34702	0.80501	0.8551
59	-0.58622	0.77422	0.8466
60	-0.78847	0.74450	0.8374
61	-0.98532	0.71729	0.8281
62	-0.98532	0.71729	0.8281
63	-1.49986	0.67536	0.8119

Table 5 shows the base daily average outdoor temperature of 52ºF has the highest R^2. While 52ºF seems like a low temperature when indoor heating would begin to occur, the indoor heating and cooling thermostat settings controlled by the occupants indicate a preference for relatively cooler indoor

---

[11] The exclusion of auto mode days is a judgment call. In this case, with regular fan cycling playing a role in "baseline" energy use when no heating occurs, the problem of how to establish a fair daily total of heating plus fan energy while excluding cooling energy presented a problem most easily managed by excluding the relatively small number of days with the system in ecobee auto mode.

[12] The total heat pump kWh was calculated from the measured "p_comp" variable from the egauge data. Any incidental auxiliary heating energy during the normal heat pump energy **was also added** to the daily total heat pump energy.

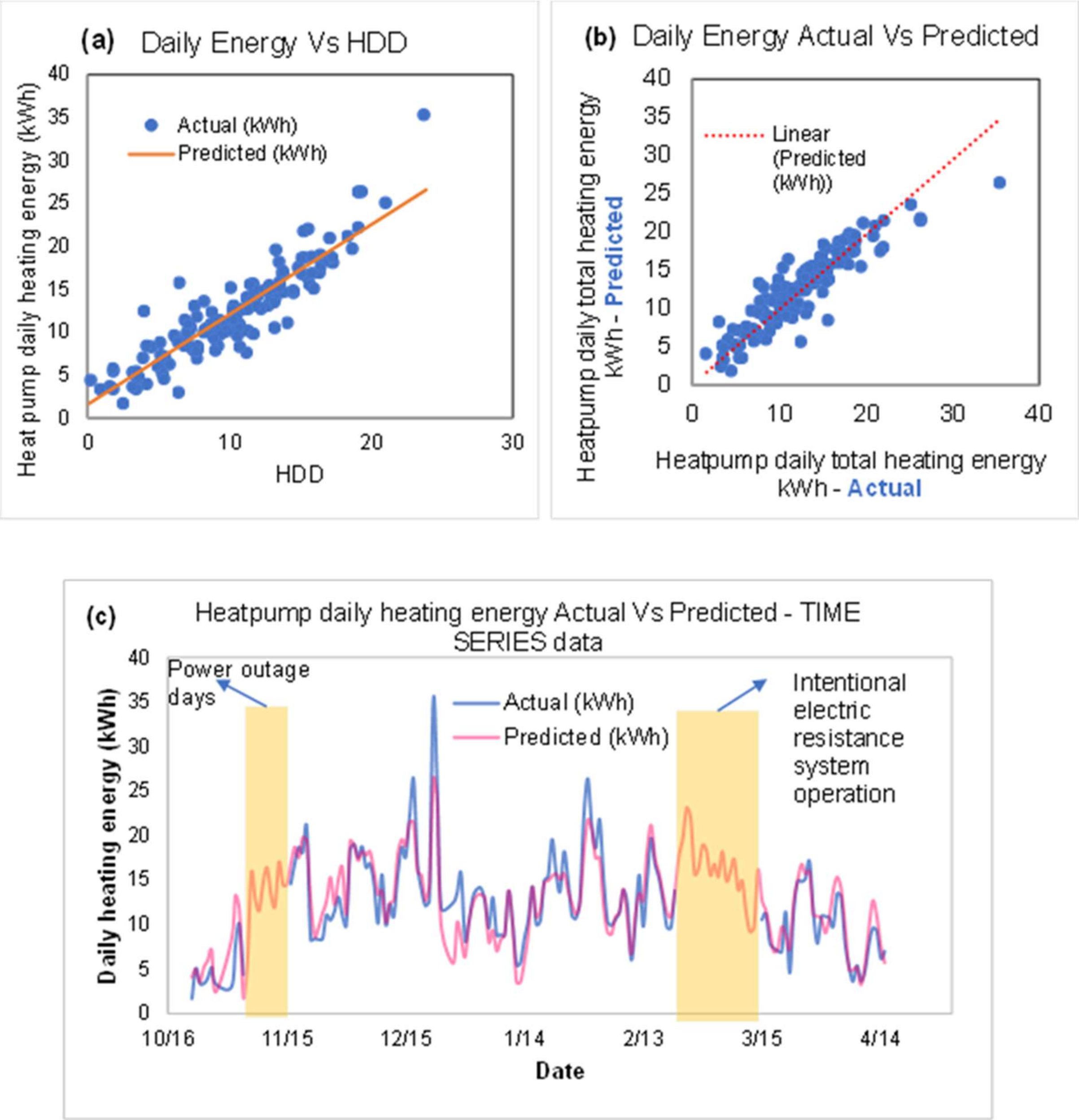
[13] Including non-heating days in the analysis helps establish baseline energy use by fan and controls when no heat is required.

temperatures. Accordingly, we used the intercept and coefficient obtained using 52ºF (as given below) to estimate the heat pump's daily heating energy.

Daily heat pump heating energy (kWh) = 1.58589 + (1.04659*HDD_{52})

Error! Reference source not found. (a) shows the regression results comparing actual and predicted daily heating energy (on the y-axis) against the HDD (on the x-axis). **Error! Reference source not found.**(b) directly compares the actual and predicted kWh. **Error! Reference source not found.** (c) compares actual and predicted heat pump energy with respect to each day. There is a linear fit that results in reasonably close agreement between predicted and actual energy use up to about 18 HDD. This point was also when actual heating energy was up to 20 kWh. The regression appears to underpredict energy as heating load increased above 18 HDD, perhaps due to a reduction in compressor COP as outdoor temperature drops. A polynomial regression may have improved prediction if there were more data available at higher HDD.

Figure 21. Actual vs Predicted heating energy for heat pump



For our regression analysis of the auxiliary heating system, we considered the daily auxiliary heating system’s energy[14] and HDD (for the base temperature of 52ºF) during the intentional auxiliary heating system test period (02/22 to 03/14) as dependent and independent variables, respectively.

---

[14] The daily auxiliary heating system is obtained by adding auxiliary heating system power and eheat pump power. During the intentional auxiliary heating system operation, heat pump power includes crankcase heat energy, fan-only and control energy. Including crankcase heating, which would not be present in a system using only electric resistance heat, slightly increases the estimated energy use in auxiliary heating.

Due to a small data set without a wide variation in outdoor temperatures, we were not able to develop a reasonable regression intercept from the regression analysis for the intentional auxiliary heating period. Therefore, we used the regression intercept calculated from linear regression analysis using the heat pump operation for the electric auxiliary heating as well. We used the regression equation given below to estimate the daily auxiliary energy.

Daily electric resistance heating energy (kWh) = 1.58589+ (3.0916 *HDD_{52})

Once we determined the regression equations to predict both the heat pump and electric resistance heating system daily energy, we estimated heating energy for the data collection period (from September 24, 2022, to April 15, 2023) for both the heat pump and electric resistance heating system. Figure 22 shows the predicted daily heating energy for the heat pump and the electric resistance heating system for the days with HDD > 0, and the corresponding results are shown in

Table 6. Our analysis predicted that the heat pump would consume 63% less energy compared to conventional electric resistance heating over the heating season.

Figure 22. Predicted heating energy for heat pump and electric resistance heating system during the local heating season period

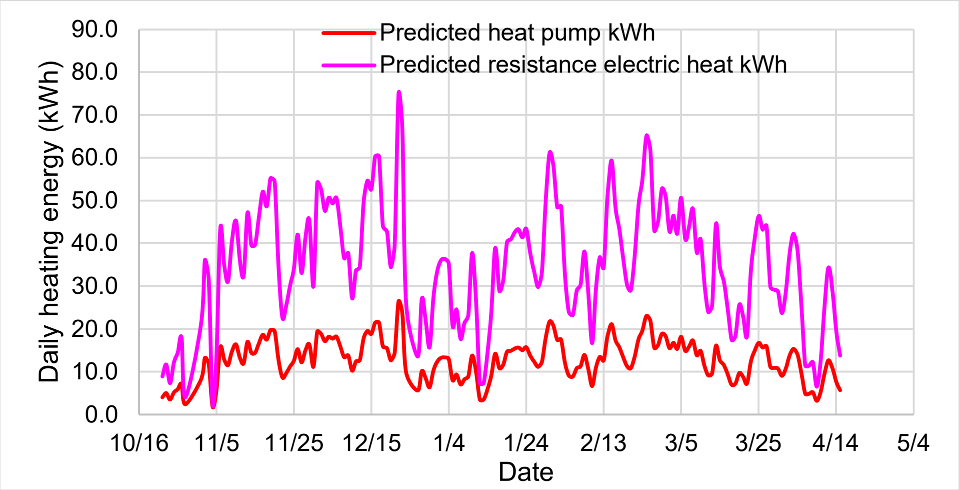


Table 6. Seasonal heating energy comparison for heat pump and electric resistance heating system over the data collection period

System	Estimated total seasonal heating energy (kWh)[15]
Heat pump	2,204
Electric resistance heating system	5,979
Savings for heat pump	63.2%

THERMAL COMFORT

Customers of manufactured homes are more accustomed to gas or resistance heating. Supply air temperature from heat pumps is often cooler than that from gas furnaces or electric auxiliary resistance

---

[15] The days for which HDD >0, from September 24, 2022 to April 15, 2023.

heat, which can result in dissatisfaction for some individuals. We evaluated thermal comfort metrics of indoor air temperature and supply air temperature during heating and cooling operation of the heat pump.

All the points mentioned in the notes of Figure 12 are applicable to the boxplots for the thermal comfort analysis. We used one-minute egauge data merged with the five-minute omni and ecobee data for our analysis. In our analysis, the term **stable setpoint temperature** means 1-hour periods during which the ecobee thermostat setpoint remained unchanged. This is intended to reduce the effect of setpoint changes on observed room temperatures. We analyzed the variations in the supply air temperature for the heat pump heating mode, defrost mode, and auxiliary heat system (during the intentional auxiliary heating period) in different hourly average outdoor temperature bins.

Room Temperature Deviations

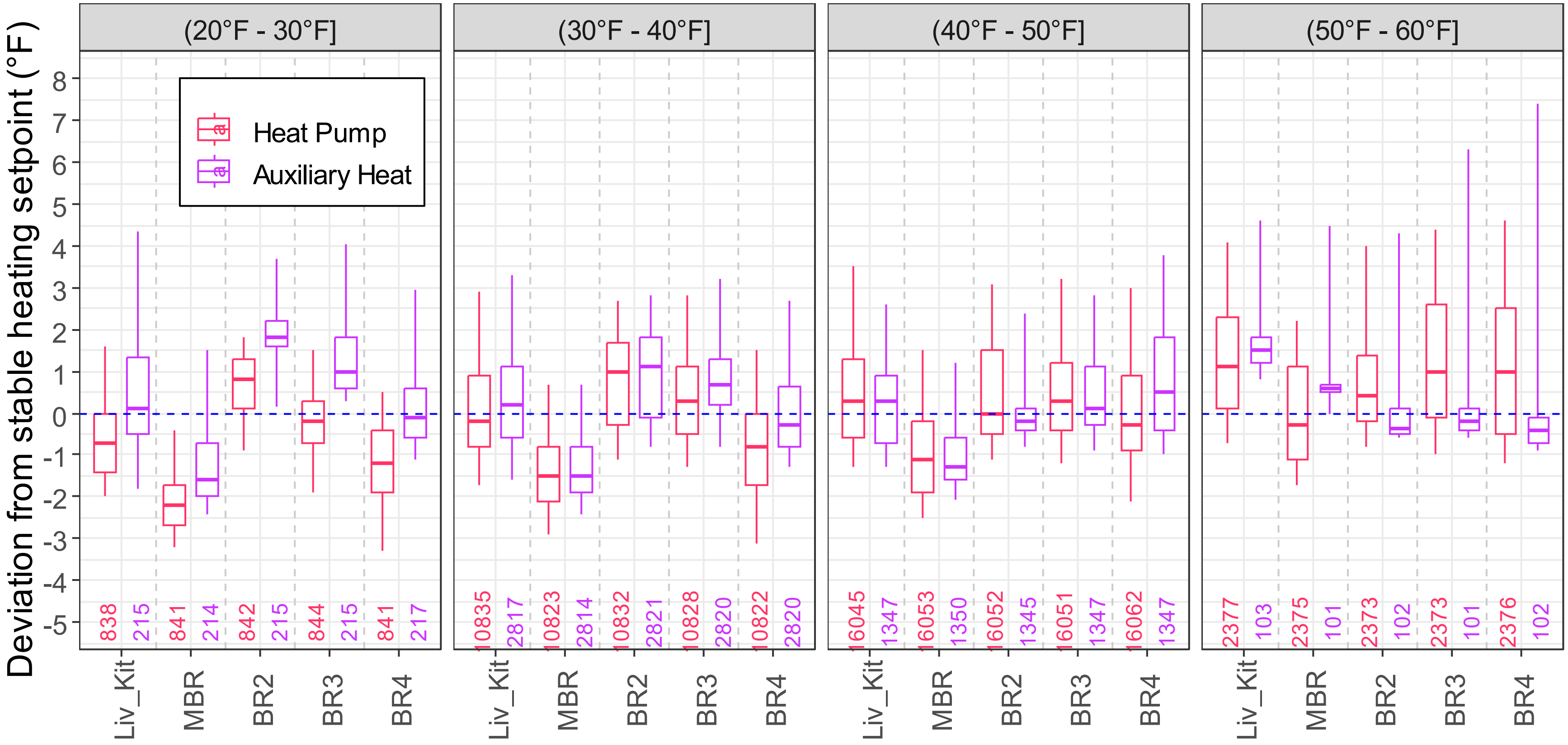
For the heat pump heating period, we present the temperature difference between individual room temperatures and the stable heating setpoint temperature averaged over hourly periods, including defrost cycling in 10ºF hourly average outdoor temperature bin as shown in Figure 23. The blue dashed line at 0ºF in the y-axis is a reference to exactly matching temperature between any given space and the desired setpoint. Figure 23 shows a systematic variation in temperature across the rooms, with the master bedroom having the lowest temperatures (generally slightly below setpoint) and bedroom #2 having the highest (often slightly above setpoint)[16]. The pattern changes somewhat in the highest temperature bin, with increased high-end room temperatures—likely driven by incidental heating from solar energy and internal gains when no heat is required. In the lowest temperature bin (20 to 30ºF), room temperatures maintained by the heat pump were slightly lower than temperatures maintained by auxiliary heat. In general, however, most of the temperature observations for both the heat pump and auxiliary heating system across all temperature ranges were within ± 2ºF of the stable heating setpoint temperature. In summary, it appears that reasonably comfortable conditions were maintained most of the time based on the Air Conditioning Contractors of America (ACCA) Manual RS, which establishes a desired temperature difference[17] from room to setpoint not to exceed +/- 2ºF during heating and +/- 3ºF during cooling.

---

[16] Temperature variation across rooms may result from HVAC supply air volumes relative to room loads, but also from differences in internal gains (e.g. appliance use), solar gains, and from the placement of temperature sensors.

[17] Rutkowski, H. (1997). Manual RS—Comfort, Air Quality, and Efficiency by Design. Arlington,VA: Air Conditioning Contractors of America.

Figure 23.Hourly average room-wise temperature deviation from stable heating setpoint temperature in outdoor temperature bins – heat pump and auxiliary heat. Includes data for days with the thermostat set to heating control mode.

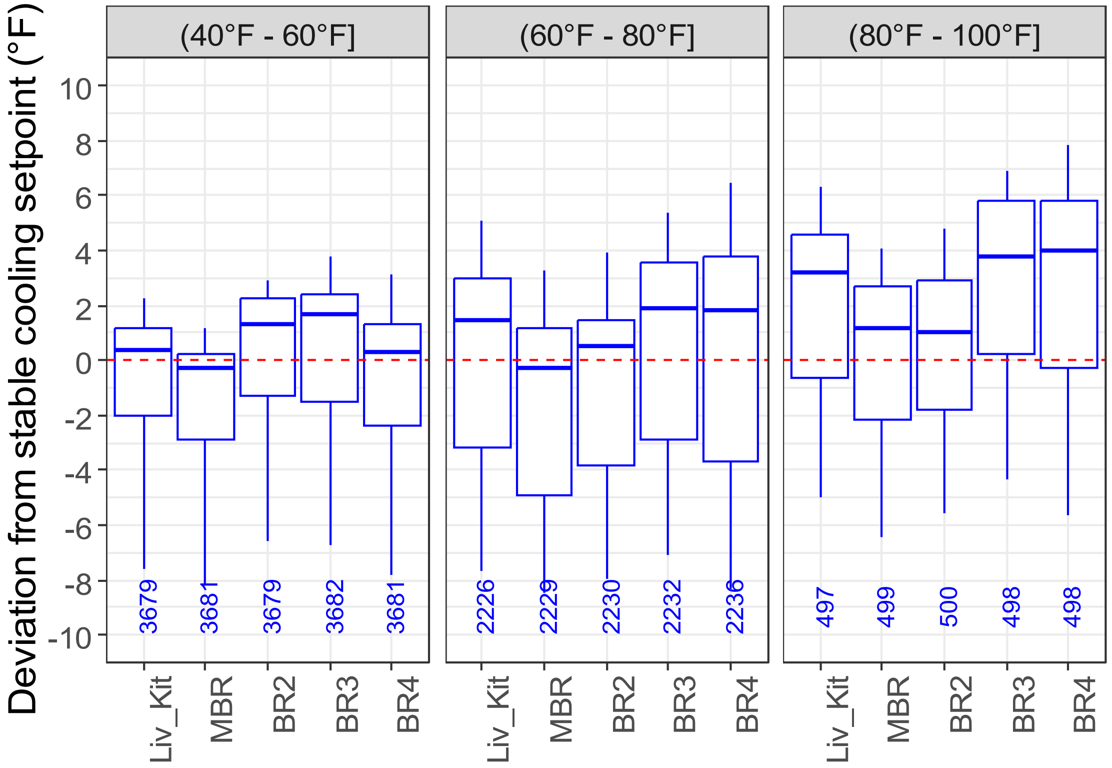


The room temperature deviations from the stable cooling setpoint temperature using the hourly average values for the outdoor temperature bins are shown in Figure 24). We did not present the room temperature deviation from the stable cooling setpoint temperature for the outdoor temperature bin (100ºF – 120ºF] since there were fewer than 50 data points.

In general, there is less data for the heat pump cooling period than for the heating period, so we grouped the outdoor temperature bins in a 20ºF interval. Though the number of data points in (40ºF - 60ºF] seems higher, 95% of those points fall into (50ºF - 60ºF]. Note that we also included the data during the days when the ecobee setting was in “auto” mode, for the temperature deviation analysis. In both Figure 23 and Figure 24, the room temperatures were subtracted from the respective stable setpoint temperatures.

Furthermore, Figure 24 shows a trend of slightly increasing room temperature difference from the setpoint as the weather gets warmer and the cooling load increases. Deviations of room temperature below the setpoint may be the result of natural (e.g. overnight) cooling during periods when the thermostat was set to enable cooling. Thermal comfort appears to have been maintained at most times despite the living room/kitchen, BR3, and BR4 medians exceeding the desired cooling limit of +/- 3ºF from setpoint (Rutkowski 1997) during the warmest weather bin (80ºF - 100ºF].

Figure 24. Hourly average room-wise temperature deviation from stable cooling setpoint temperature in hourly average outdoor temperature bins—heat pump cooling period. Includes data for days with the thermostat set in cooling mode.

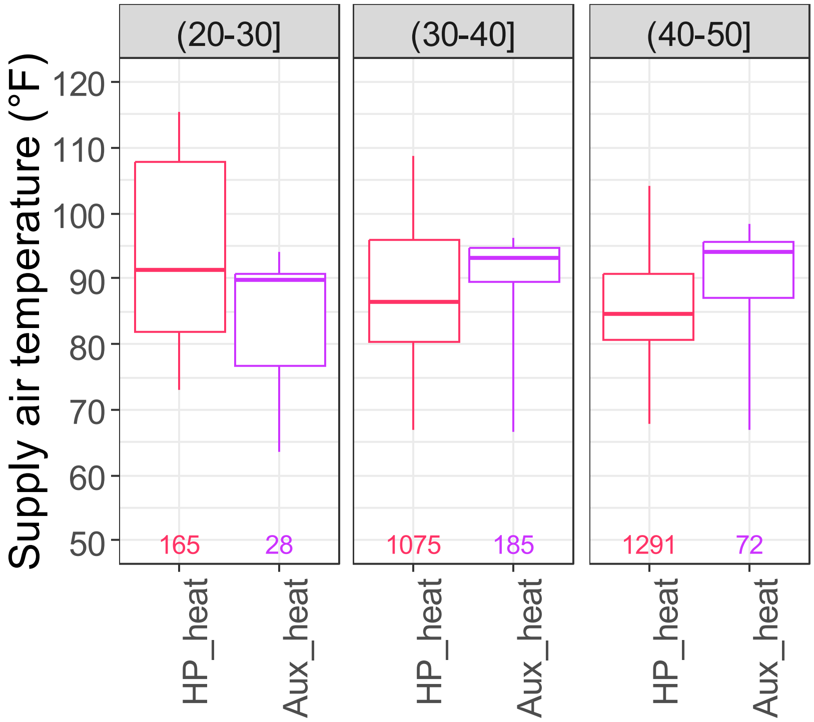


Heating Supply Air Temperature Variation We analyzed the supply air temperature variations during heat pump heating, defrost modes, as well as intentional auxiliary heating. Figure 25 shows heat pump and auxiliary heating supply air in hourly average-based 10ºF outdoor temperature bins. We do not show data for the outdoor temperature bin 50ºF - 60ºF] because there were fewer than 50 data points. We have less data for the auxiliary heating system due to the more limited monitoring period.

The most important outcome from this analysis is that, during the coldest outdoor temperature bin (20ºF - 30ºF], the median of the supply air temperature for the heat pump was not only adequate for maintaining comfort but also slightly greater than the auxiliary heating system. In the other two warmer outdoor temperature bins, the median auxiliary heat supply air temperature was 8ºF- 10ºF warmer than the median heat pump supply air temperature. While the heat pump supply air was not as hot, the runtime was substantially longer allowing it to meet the heating load. There is the possibility of local discomfort where supply grille discharge may be directed to sedentary occupant locations (commonly termed “cold blow”), but there were no known occupant complaints of such issues did not arise at this test location.

Supply air temperature could not be evaluated for defrost operation since the air handler did not operate at those times.

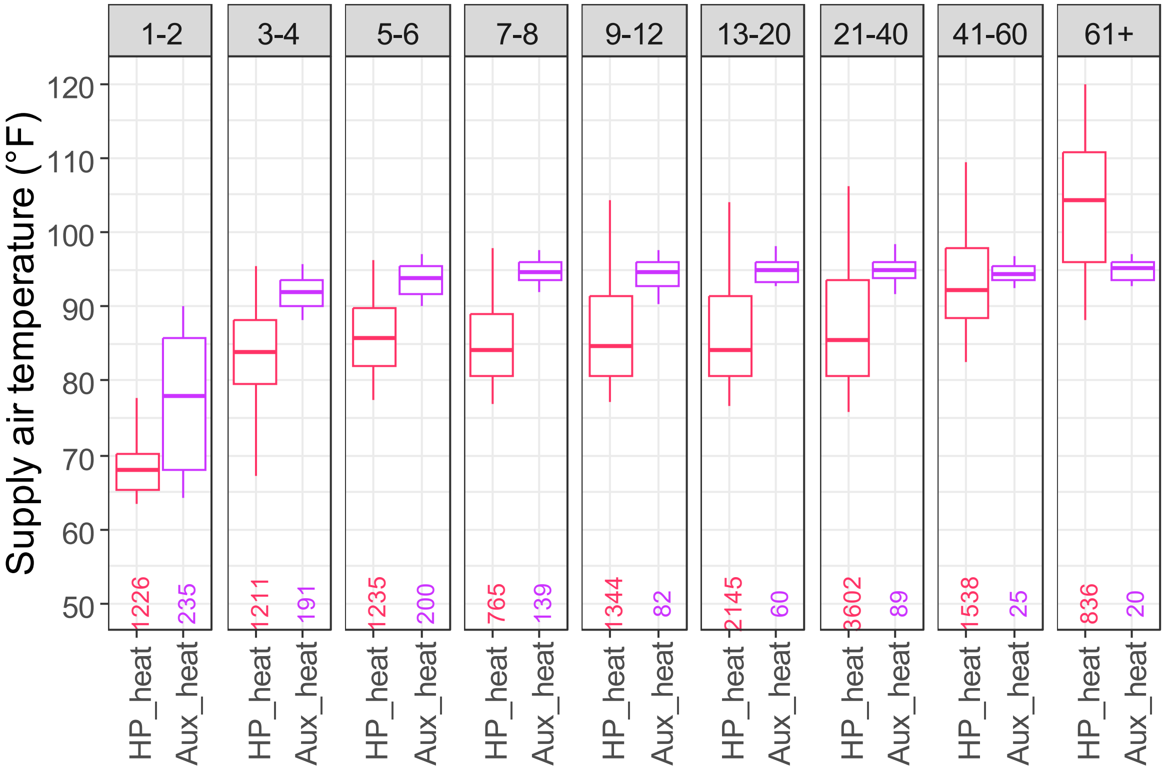
Figure 25. Supply air temperature variations during different modes in 10ºF hourly average outdoor temperature bins



Generally, we expect supply air temperature to rise over the first few minutes of any heating cycle, then may remain stable (if energy inputs and fan speed are constant) or it may vary over time based on compressor and fan control algorithms. We compared the variation in the supply air temperature with elapsed time in individual cycles. The results are shown in Figure 26. The bin numbers at the top of each boxplot denote the minutes into each heating cycle. For example, the “1-2” bin in the boxplot indicates the supply air temperature variation during the first two minutes of the heating cycle. Likewise, 61+ denotes conditions after at least 61 minutes of continuous heating operation.

Figure 26 illustrates the variability of supply air during heat pump and auxiliary heating for different runtimes. It shows an initial increase in the supply temperature after two minutes for both types of heating, then relatively stable temperature until about 60 minutes when there is another increase in temperature for only the variable capacity heat pump. There is no significant change in supply air of auxiliary heating after two minutes. We expect that the heat pump supply air temperature in the first two minutes of heating is influenced, in part, by reheating of the coil and ductwork after defrost operation—we did not evaluate that effect separately as there were very few cases of defrost observed. We also note that after the first two minutes of a heating cycle, the supply air temperature increases by approximately 17ºF (considering the medians of 1-2 minutes and 3-4 minutes cycle duration bins). From the 4th minute of the cycle, there is a gradual/slight increase in the supply air temperature. Compared to the heat pump, the auxiliary heating system showed less variation in the supply air temperature with different runtime bins. This is explained best by the fact the auxiliary heat does not vary its heat capacity output with varying heat load and runtimes, whereas this variable capacity heat pump, by design, could vary output heat capacity with varying heating load. Note that supply air temperature rise during the 60+ minutes period occurred by design, where highest power and capacity output are called upon after 60 minutes of continuous heating operation.

Figure 26. Supply air temperature variations during various time steps (in minutes) of the heat pump heating cycle



DATA COLLECTION AND ANALYSIS – FSEC MH LAB

DESCRIPTION

We analyzed the cooling and heating performance of the same heat pump model used in the Oregon site (variable-capacity Carrier 40MBAAQ24XA3/38MARBQ24AA3 ducted heat pump), but with no electric resistance heating elements, at FSEC's manufactured home (MH) lab. This test site is located in Central East Florida on the FSEC campus. The MH lab was built in 2002 and designed to meet EnergyStar Homes' requirements at that time. Figure 27 shows the floor plan of the FSEC's MH lab. It has a total living area of 1620 ft^2 with three bedrooms and 2 bathrooms. Unlike the Oregon site, FSEC's MH lab is unoccupied but has internal sensible and latent loads automated to simulate some occupancy impacts. The daily internal sensible load is about 3500 btu/h on average, and the internal latent load is about 12 lb./day. The other main difference between the Oregon site and FSEC's MH lab is the setpoint temperature setting of the thermostat. At the Oregon site, the thermostat setpoint was managed by the programmable ecobee thermostat but could be changed at will by the occupants. The Oregon test site thermostat used the night setback temperature and temperature recovery modes, and the occupants, at times, manually adjusted the thermostat setpoints. The MH lab thermostat settings were constant heating at 70ºF and a cooling setpoint temperature at 75ºF. There were no setbacks, recovery, or manual adjustments. Figure 28 is a pictorial representation of FSEC's MH lab and shows the location of the heat pump's outdoor unit. Table 7 summarizes the parameters of the data from the FSEC site. The indoor air handling unit was located in a utility room in a horizontal orientation that enabled testing using either an attic supply duct system or a supply floor duct system. Our analysis focused on the attic supply duct system since this is more common for manufactured homes in cooling-dominant regions.

Figure 27. FSEC Manufactured housing laboratory floor plan

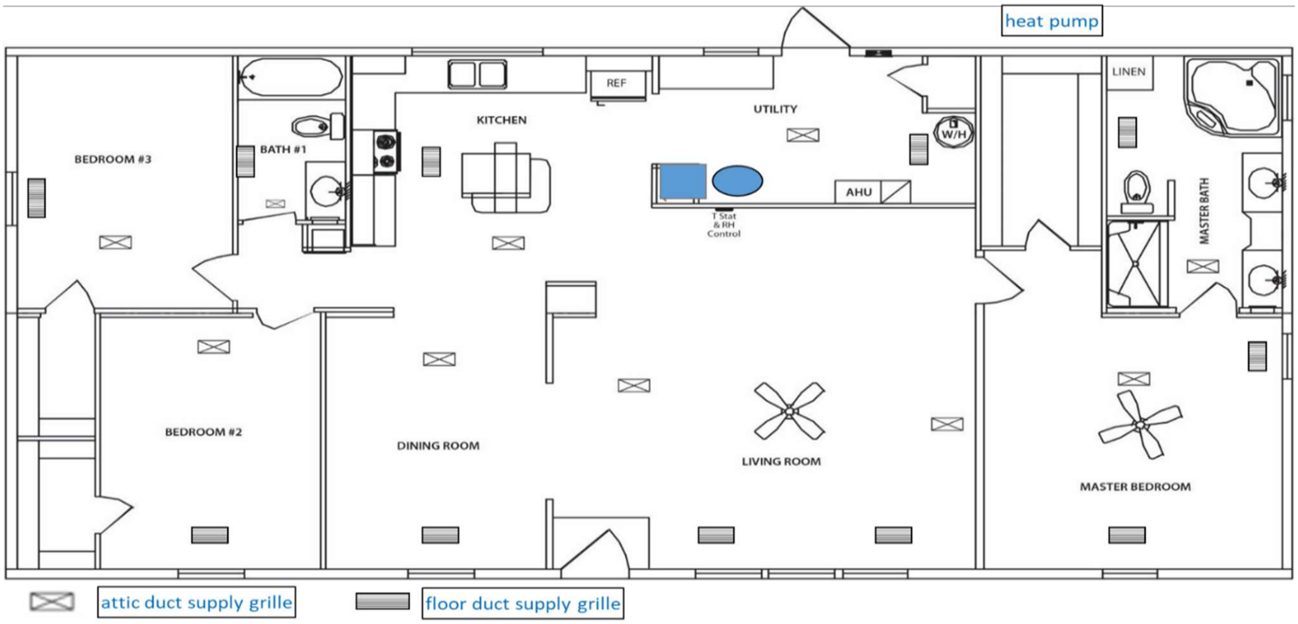


Figure 28. Picture of FSEC MH lab and the heat pump's outdoor unit

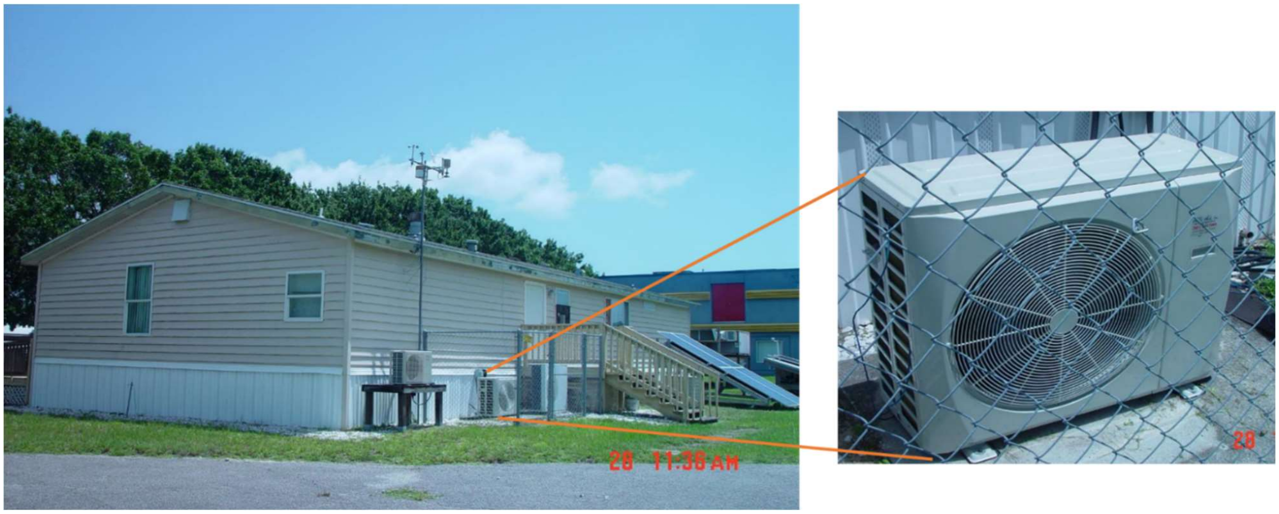


Table 7. Parameters used in the study from FSEC's site

Parameter	Data resolution	Sample value/Options
Heat pump performance data		
Julian date	1 minute	2022181
hours and minutes		0:00:00
Compressor (outdoor), Air handler unit (indoor) run time in (seconds)		30
Supply air temperature (ºF)		54.5
Return air temperature (ºF)		72.4
Total system energy (Wh)		13
Air handler unit energy (Wh)		1
Manufactured home (MH) lab environmental conditions data		
Julian date	15 minutes	2022181
Hour and minute		0:00:00
Hallway temperature (ºF)		79.8
Northeast and southeast bedroom temperatures (ºF)		79.1
Thermostat temperature (ºF)		82.3
Master bedroom temperature (ºF)		82.6
Northeast and southeast bedroom RH (%)		55.13
Master bedroom pillow RH (%)		55.21
Outdoor temperature (%)		70.1
Outdoor RH (%)		89.4
Solar radiation (W/m^2)		587.7

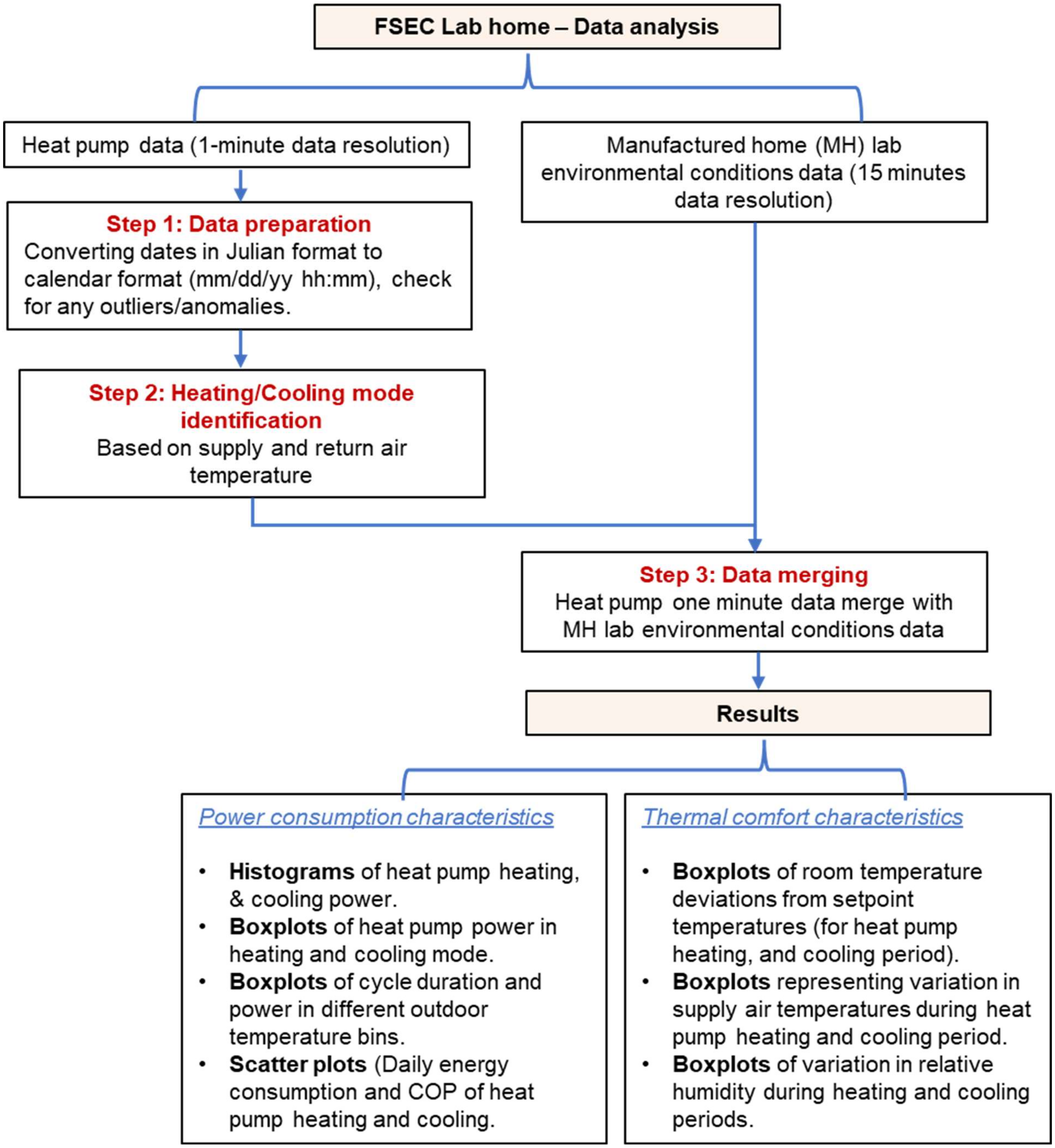
Campbell Scientific dataloggers were used in the FSEC's MH lab to collect the indoor and outdoor environmental data, as well as internally generated sensible and latent loads data, and heating and cooling energy use. Table 7 provides more details on the parameters used to study the performance of the heat pump installed at the FSEC site. We measured the delivered heating and cooling energy with temperature and humidity sensors located before the air-handling indoor coil and just after the coil and fan (return and supply). Heat pump central airflow was also monitored. All data was collected at 10-second intervals managed as follows:

- We averaged the environment-related parameters (temperatures, RH, solar insolation, and air handler total static pressure) at the intended time storage interval (15 minutes).
- We totaled energy usage, runtime, and rainfall at storage intervals.
- We only recorded eat pump performance data if there was active heating or cooling.
- We excluded crankcase heat or stand-by energy from the metrics collected for heat pump performance so that temperatures and RH weren’t averaged at storage intervals if only very low power stand-by or no energy was consumed at a 10-second interval sample rate.

APPROACH

Figure 29 show the steps we followed to analyze the heat pump performance at the FSEC's MH lab.

Figure 29. Data analysis procedure for FSEC lab home data



FSEC Lab home – Data analysis

Heat pump data (1-minute data resolution)

Manufactured home (MH) lab environmental conditions data (15 minutes data resolution)

Step 1: Data preparation
Converting dates in Julian format to calendar format (mm/dd/yy hh:mm), check for any outliers/anomalies.

Step 2: Heating/Cooling mode identification
Based on supply and return air temperature

Step 3: Data merging
Heat pump one minute data merge with MH lab environmental conditions data

Results

Power consumption characteristics

- **Histograms** of heat pump heating, & cooling power.
- **Boxplots** of heat pump power in heating and cooling mode.
- **Boxplots** of cycle duration and power in different outdoor temperature bins.
- **Scatter plots** (Daily energy consumption and COP of heat pump heating and cooling.

Thermal comfort characteristics

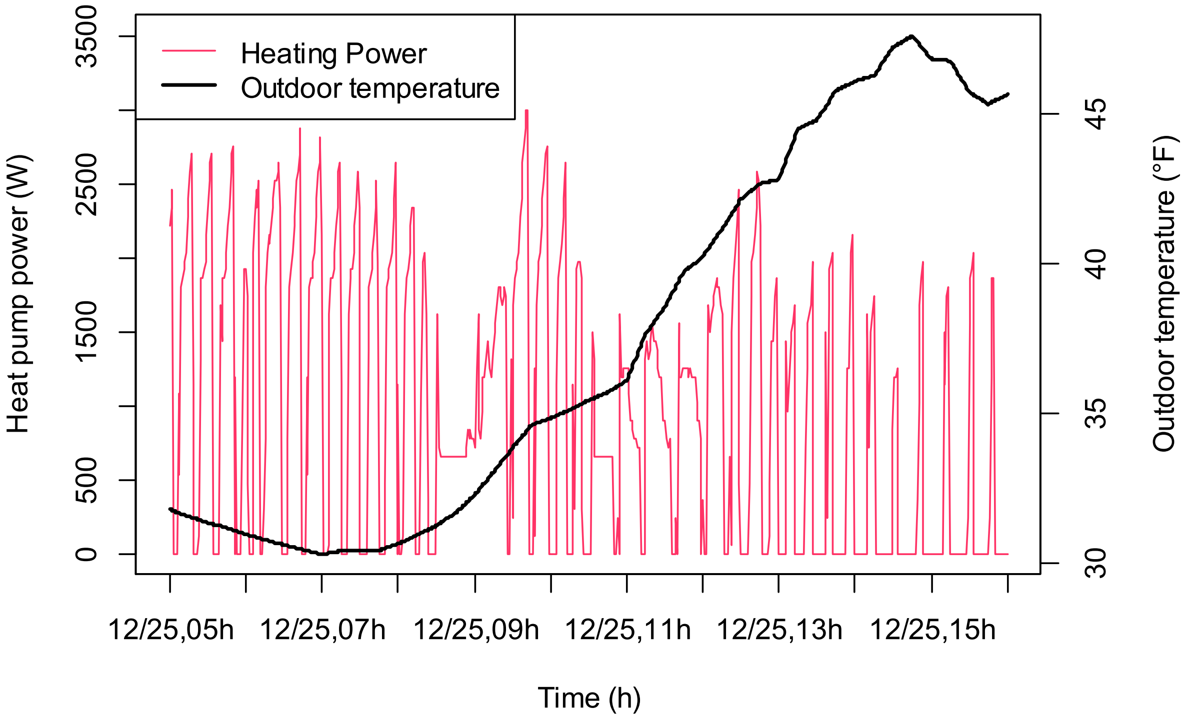
- **Boxplots** of room temperature deviations from setpoint temperatures (for heat pump heating, and cooling period).
- **Boxplots** representing variation in supply air temperatures during heat pump heating and cooling period.
- **Boxplots** of variation in relative humidity during heating and cooling periods.

HEAT PUMP SYSTEM BEHAVIOR

The heat pump characteristic of periodic indoor fan cycling on and off for 7.5 minutes between heating and cooling cycles was also observed in the MH Lab testing just as it was noted for the system tested in the Northwest. The heat pump heating and cooling power characteristics were evaluated the same way as the Northwest system looking at power use over time of day. Here we present the power profile and cycling behavior during early morning to afternoon of seasonal heating and cooling days.

Figure 30 and Figure 31 demonstrate the typical heat pump operation during cooling and heating modes. They characterize typical operation during seasonal conditions for a partial day with varying loads to demonstrate the range in power and cycling. Figure 30 shows heating power use during several hours of the coldest day. During the coldest conditions between 5:00 a.m. and 8:30 a.m., there was high power consumption and short cycles of about 10 minutes each. Then, there was one long cycle (for 55 minutes) with lower power consumption between about 8:30 a.m. and 9:25 a.m. We would expect this type of system to exhibit the longer cycle and lower power consumption during cold conditions and are at a loss to explain the high-power consumption, short-cycles period. As the heating load decreased throughout the day, the heat pump transitioned back to more frequent shorter cycles and relatively lower power use than in the previous hours.

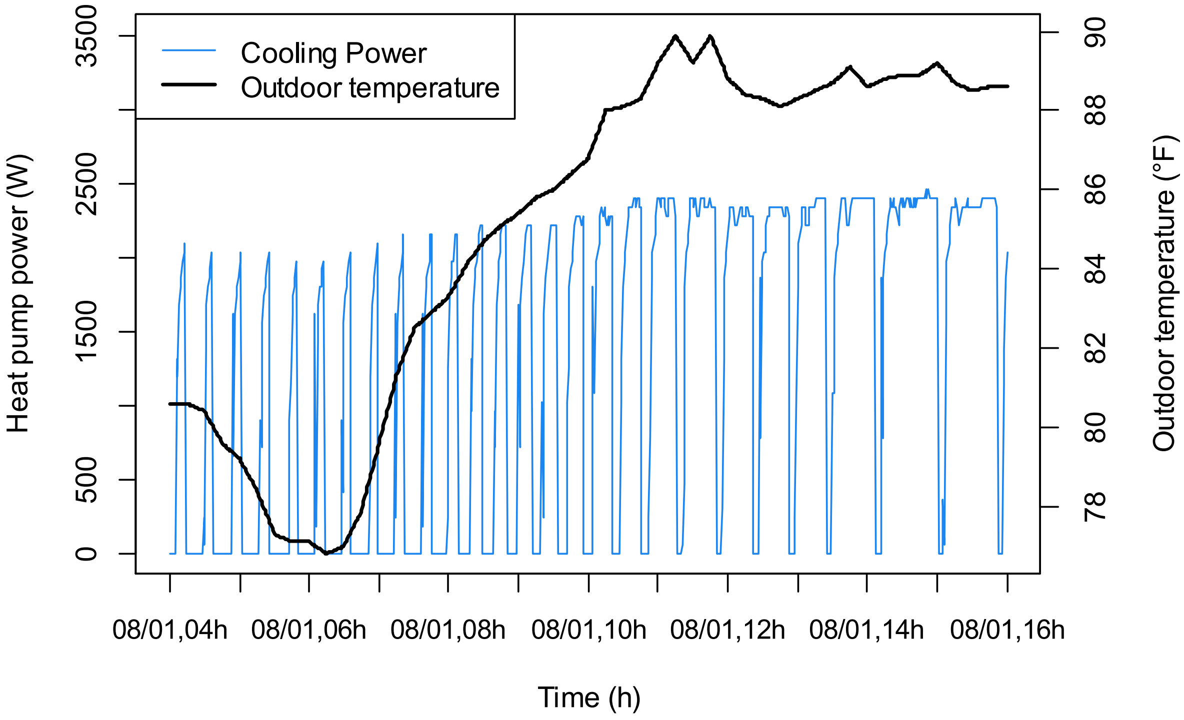
Figure 30. Example of heat pump operation in heating mode at FSEC site



The heat pump heating characteristics at the Florida site were different from those we observed at the Northwest site. The Northwest test site had noticeably longer and fewer heating cycles, as previously shown in Figure 3 due to colder weather with less warming breaks between. The outdoor and indoor conditions of the first several hours of Figure 3 were similar to those on December 25 in Florida (Figure 30). The cold weather (< 35° F) period shown in Figure 30 only lasted several hours, after which there was a prolonged period of continuous heating for a few hours with some modulation from about 8:30-9:30 a.m. With light heating load, there was more cycling observed. Winter in Central Florida consisted primarily of mild weather where cooling is needed until a brief cold front may require heating.

Figure 31 shows cooling operation during a transition from low outdoor to high outdoor temperature on a typical summer day. Figure 31We saw relatively little variation in power from the coolest to the hottest time of day, which seemed unusual for a variable capacity system. While we observed a small amount of variable power and cooling output, the cooling system operated more like a single capacity system using nearly maximum power within about two minutes of a cycle, and the runtime increasing with increases in cooling load. Based on manufacturer rated performance data, the lower cooling power shown during cooler outdoor temperatures in Figure 31 is primarily due to lower outdoor temperature resulting in decreased load on the compressor.

Figure 31. Example of heat pump operation in cooling mode at FSEC site



HEAT PUMP POWER CONSUMPTION

A breakdown of crankcase heat, automated indoor fan circulation, and defrost energy was not evaluated due to very limited heating season data.

The datalogger recorded the total system runtime and AHU runtime in intervals of 10 seconds (0, 10, 20,…60) based on a counter mechanism. The counter was based on the measured energy use value and therefore the runtime resolution was limited to 10 seconds. On some occasions, the compressor might start to operate at the end of the minute or might end at the very beginning of the minute. This could result in a one-minute representation of “operation” when the system only operated for 10 seconds of that minute. To avoid poor representations of heat pump operation, we applied the following conditions to identify the heat pump event as the "compressor" operation:

- **There was heating or cooling operation** if the total system run time was ≥10 seconds and total system power was > 60 W**.**
- **There was negligible heating or cooling operation** if the total system run time was ≤ 20 seconds and total system power was = 60 W.

We easily knew the conditioning mode at the lab house because it was not occupied and the thermostat was set to either heating or cooling at specific setpoint temperatures. Heating and cooling status was also verified based on the difference between the supply and return air temperatures. If the difference between supply temperature and return temperature was positive, the mode was "Heating." If it was negative, then it was "Cooling." We made exceptions when the system was confirmed to be in heating mode and brief periods of lower supply air temperature were measured. These periods were determined to be very infrequent defrost events. Figure 32 shows the power distribution (in 60 W bins) of the heat pump (total system) during cooling (left) and heating modes (right). The maximum power of the heat pump unit during cooling and heating was 2,580 W and 3,600 W, respectively. The power under 500 W shown in the cooling power frequency distribution of Figure 32 is due to a typically measured characteristic where the compressor started up for about 1 minute, then turned off for about 30 to 40 seconds while the outdoor condensing fan cycled down, then compressor and condenser fan quickly increased to nearly full speed.

Figure 32. Frequency distribution of heat pump's outdoor unit power in cooling mode (using one-minute data) in 60 W power bins

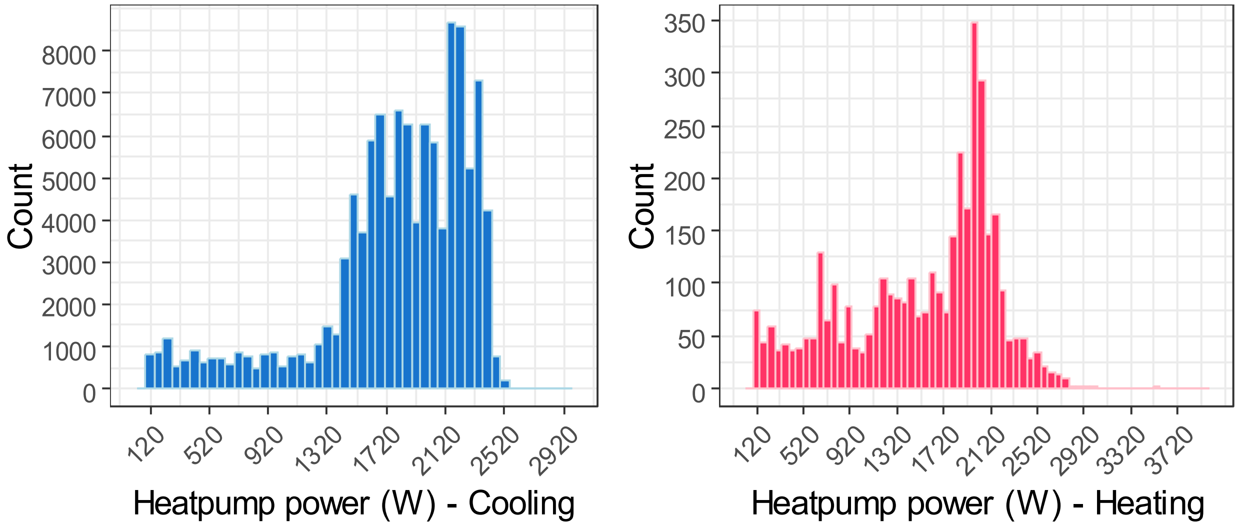


Figure 33 shows the variation in the heat pump's power (total system including AHU power) with respect to hourly average outdoor temperature (grouped in 5ºF bins) during cooling (left) and heating (right). In cooling mode during the coldest outdoor temperature bin in the plot (low cooling load), the heat pump power median value was ~1500 W, whereas, during the high outdoor temperature bin (90ºF - 95ºF], the median was ~ 2300 W (high cooling load). Cooling power use increased as the cooling load increased. However, the increasing trend is almost entirely due to the increased load on the compressor and not from variable capacity at part load. Based on manufacturer data, the expected full capacity power use at 63ºF would be about 1,544 W and 2,570 W at 95ºF outdoors. The median cooling power is relatively close to the full capacity manufactured data. The full capacity delivered during the lowest temperature bins was not expected for a variable capacity system since such systems typically modulate power and output more to meet actual load.

We believe that the mild heating load conditions and nature of heating load patterns in Florida did not offer adequate opportunity to evaluate the heating effectively.

Figure 33. Heat pump power in 5ºF hourly average outdoor-temperature bins during cooling (left) and heating (right) modes[18]

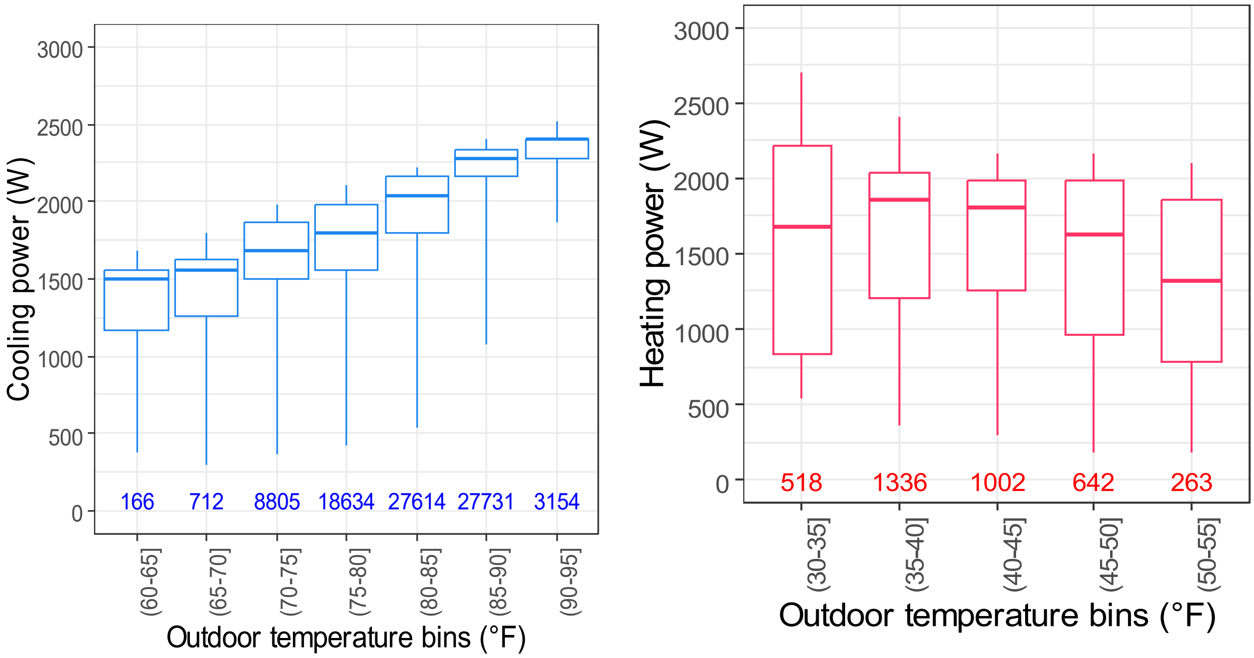


Figure 34 shows the heat pump cycle length (in minutes) during cooling in different outdoor temperature bins (left) and the frequency distribution of cooling cycle lengths (right). As seen in the boxplot, the cooling cycles in the outdoor temperature bins from 60º F - 80º F lasted for less than 10 minutes most of the time. To meet the cooling demand at higher temperatures, the cycle durations were longer, as expected.

The vast majority (77%) of cooling cycles were shorter than 15 minutes (as seen in the boxplot). We did not expect to see an inverter-driven compressor, variable capacity heat pump with so much short cycling, as it would not be surprising for a single-speed heat pump. Most of these short cycles occurred overnight when the cooling load was lowest. Short cooling cycles are often associated with poor

---

[18] Note that the boxplot minimum and maximum represent the 5th and 95th percentiles. The horizontal line denotes the median value. The boxplot's lower and upper horizontal lines represent the 25th and 75th percentiles, respectively. The numbers inside the boxplots show the number of data counts in each temperature bin. This explanation is applicable to all the boxplots used in the FSEC lab data analysis.

dehumidification; however, humidity control was good under the specific test conditions as will be discussed later.

Figure 34. Heat pump cooling cycle duration in 5ºF hourly average outdoor-temperature ranges (left) and frequency distribution of cycle duration during (in minutes) cooling mode (right)

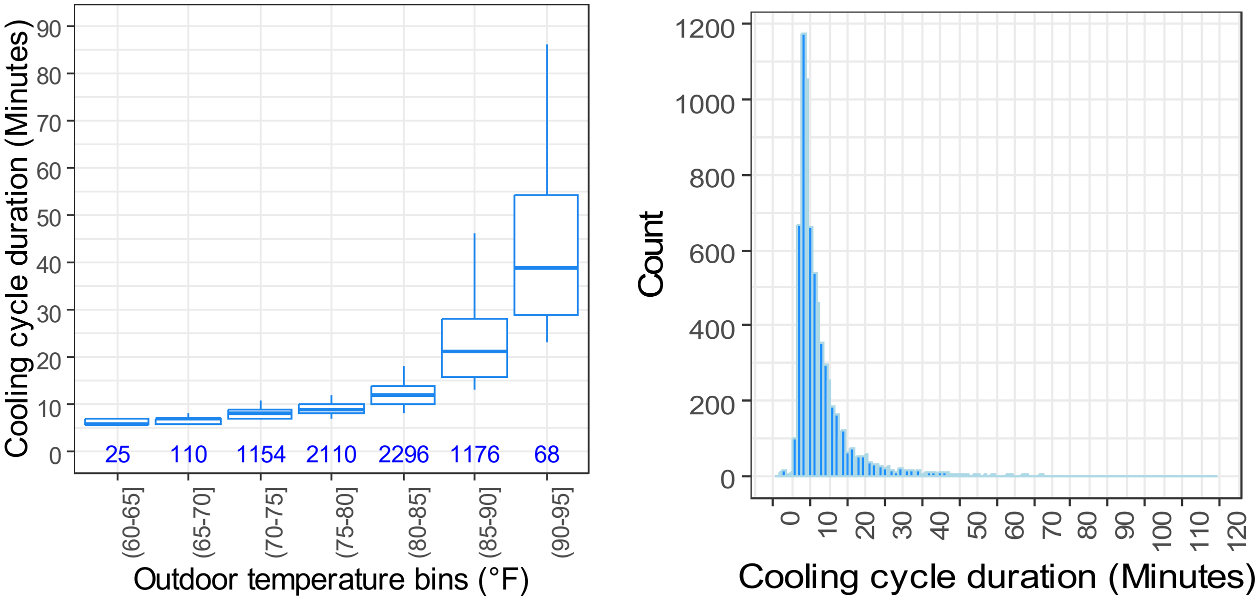
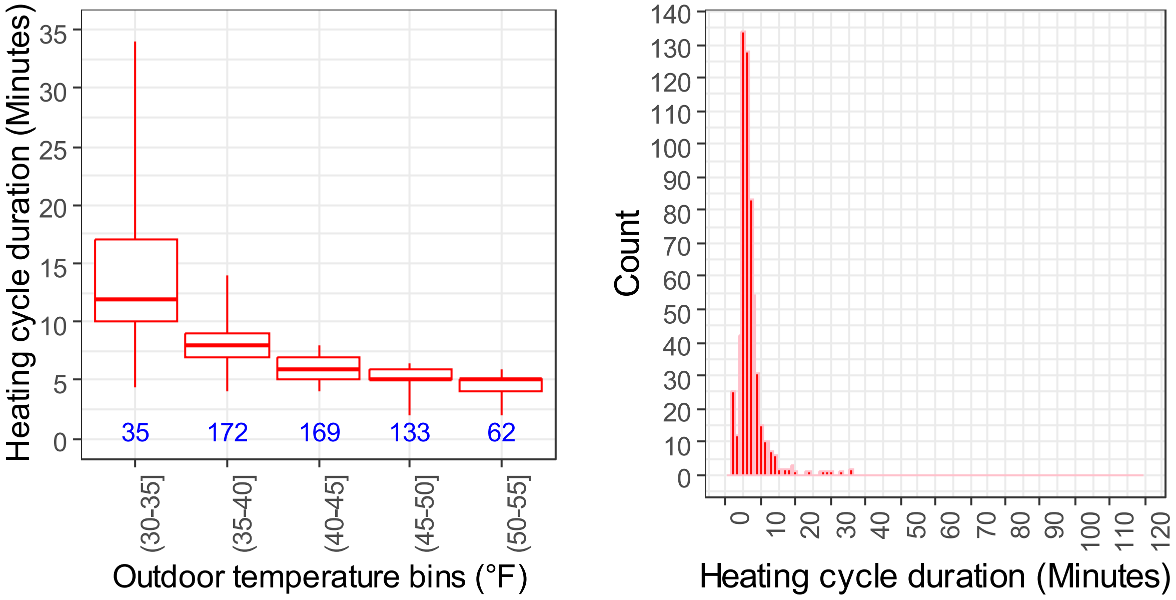


Figure 35 is a boxplot showing heating cycle duration in different outdoor temperature bins (left), and a bar chart showing the frequency distribution of the cycle lengths (right) during heating mode. The heating cycles were mostly under eight minutes long for outdoor temperatures between 35ºF to 55ºF. It wasn't until temperatures dropped to 30ºF – 35ºF that runtime increased to about 10-16 minutes most of the time. The median runtime of the system at the Northwest site (Figure 14) was about 15-minutes, which was 3 minutes (25%) longer than the FSEC median for periods with outdoor temperatures between 30ºF - 35ºF.

Figure 35. Heat pump heating cycle duration in 5ºF hourly average outdoor-temperature ranges (left) and frequency distribution of cycle duration during (in minutes) cooling mode (right)



THERMAL COMFORT INDICATORS

Thermal comfort was evaluated based on the room temperature deviation from the cooling and heating setpoint temperature. Temperatures were measured in three bedrooms, a short hallway, and in the living room.

Figure 36 and Figure 37 show the room temperature deviations from the cooling and heating setpoint temperatures in different hourly average outdoor temperature bins, respectively at four locations. The deviation of living room from setpoint is not shown to avoid crowding in the figures. The living room temperature deviation was within ± 2ºF from setpoint. The bedrooms are labeled NEBR (northeast bedroom), SEBR (southeast bedroom), and MBR (master bedroom). We show the heating data in Figure 37 in ten-degree bins instead of five-degree bins since the mild weather limited the amount of heating data we collected.

The MBR is located on the west side of the building, and the temperature sensor is located at pillow height on the bed located near the west wall. Thus, the deviations were relatively higher in MBR compared to the other rooms. Other than MBR, the deviation from the setpoint temperature is within the range of ± 2ºF for all the outdoor temperature bins during both heating and cooling. This shows that, during cooling, the attic supply duct system maintained reasonably comfortable conditions.

Figure 36. Room-wise temperature deviation from cooling setpoint temperature in different hourly average outdoor temperature bins – heat pump cooling period

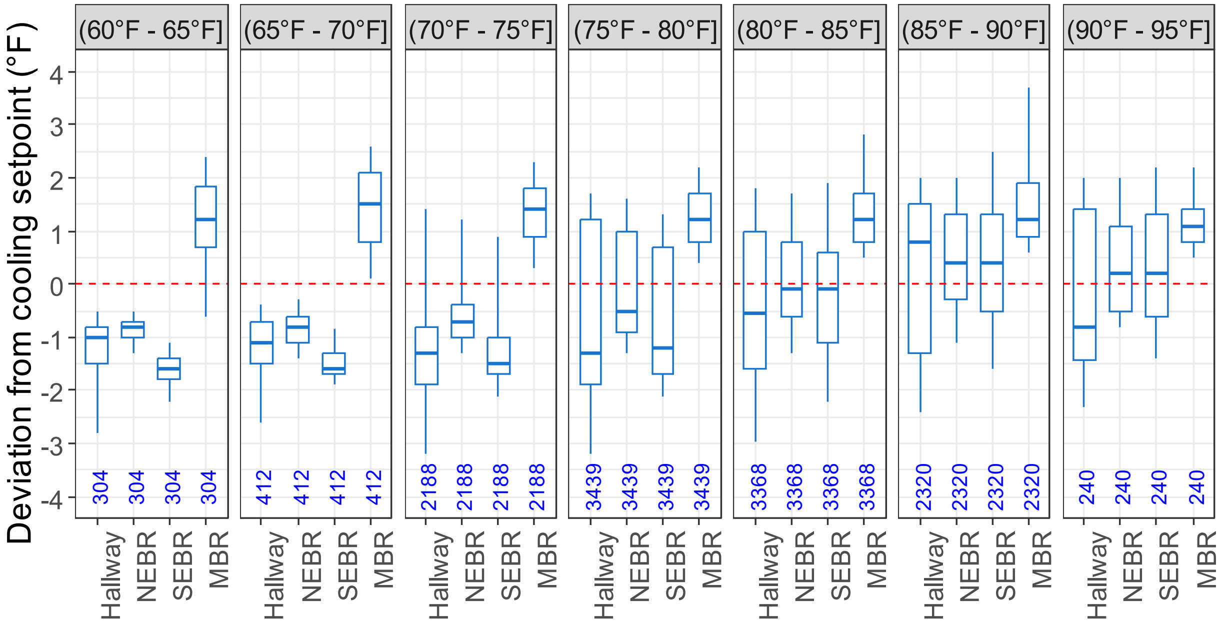


Figure 37. Room-wise temperature deviation from heating setpoint temperature in different hourly average outdoor temperature bins – heat pump heating period

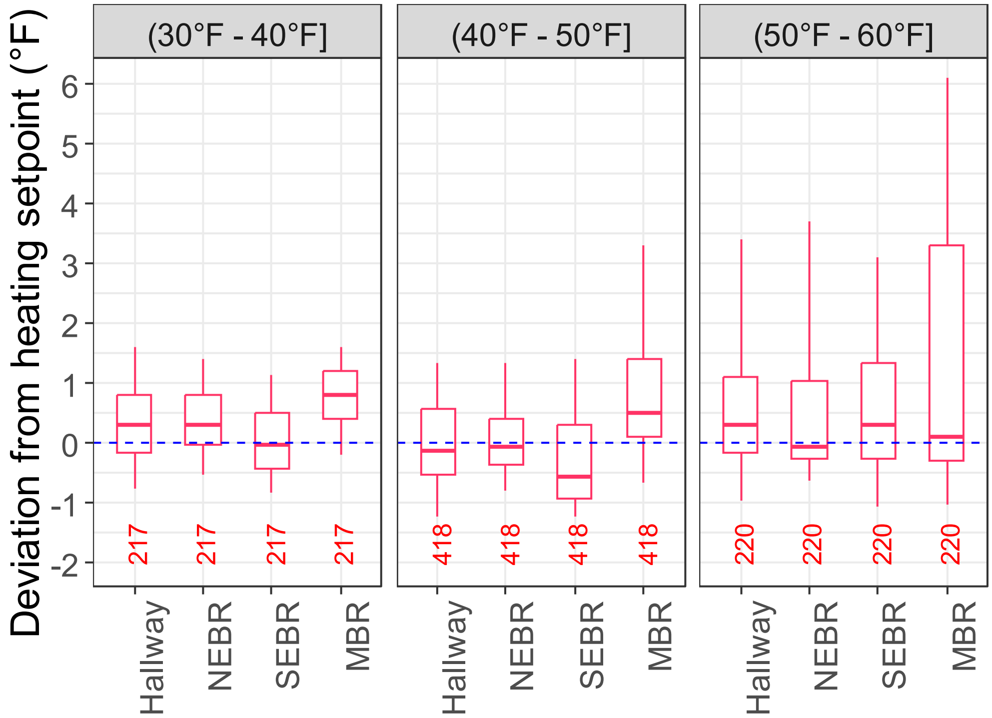
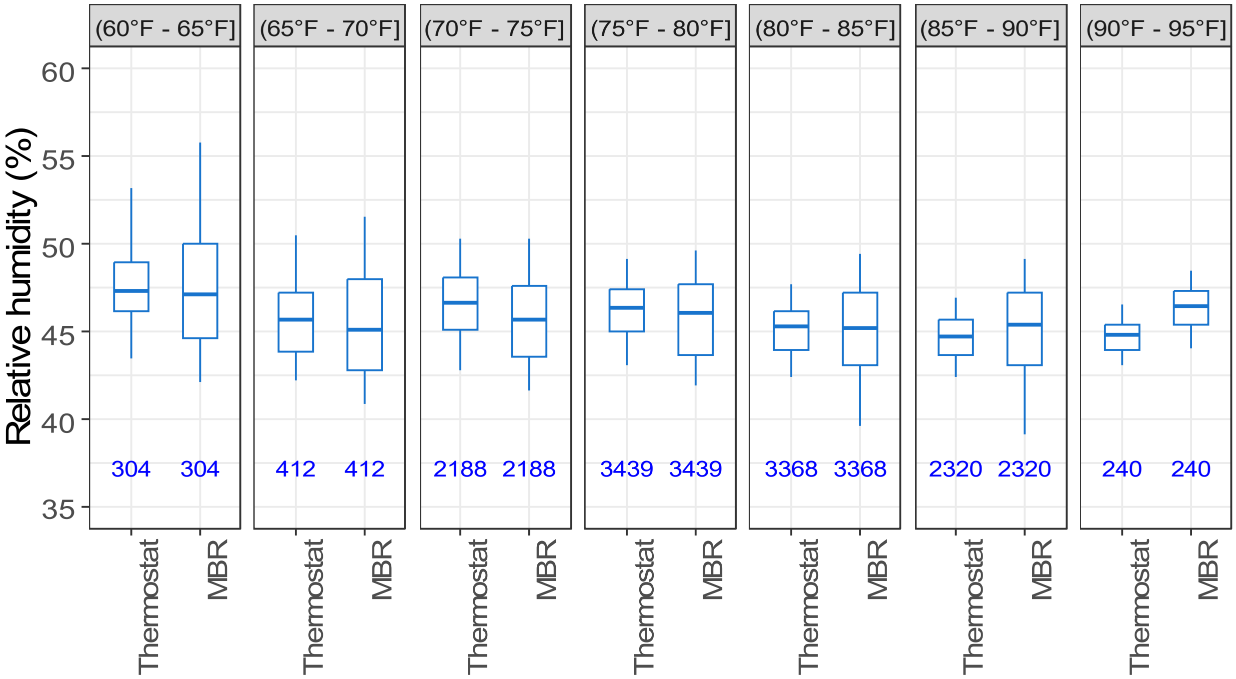


Figure 38 and Figure 39 show variations in the relative humidity (RH) in two locations in the FSEC's MH lab in different outdoor temperature bins during cooling and heating, respectively. At the location labeled "Thermostat" we measured RH next to the thermostat on an interior wall in the living room. Despite a lot of relatively short cooling cycles, the heat pump maintained the RH well within the range of 42% to 50% most of the time across a wide range of outdoor temperatures.

We did not measure RH under the ASHRAE 62.2 minimum ventilation standard, which would have required about 55 cfm continuous mechanical ventilation. As tested, there was no mechanical ventilation, only natural ventilation due to wind and stack effect. This vastly reduced the latent load on the cooling system during summer conditions. Based on past experiments in the MH lab, with and without ventilation, we believe that the observed indoor RH during summer testing was about 10% RH lower than it would be under ASHRAE 62.2 ventilation.

We deliberately chose not to ventilate to the ASHRAE standard in the MH lab because the outdoor latent load varies over the season giving us less control during cooling performance evaluations and it was also desirable to represent more typical operational conditions in occupied manufactured homes. It is unlikely that occupied manufactured homes maintain levels of ventilation that meet ASHRAE 62.2 since it makes humidity control more difficult. Humidity control in MHs in the Southeast has been a well-known occupant complaint and industry issue.

Figure 38. Variation in relative humidity at different measurement locations and different hourly average outdoor temperature bins – during cooling



During heating season, RH varied between 35% and 45% in all outdoor temperatures.

Figure 39. Variation in relative humidity at different measurement locations and different hourly average outdoor temperature bins – during heating

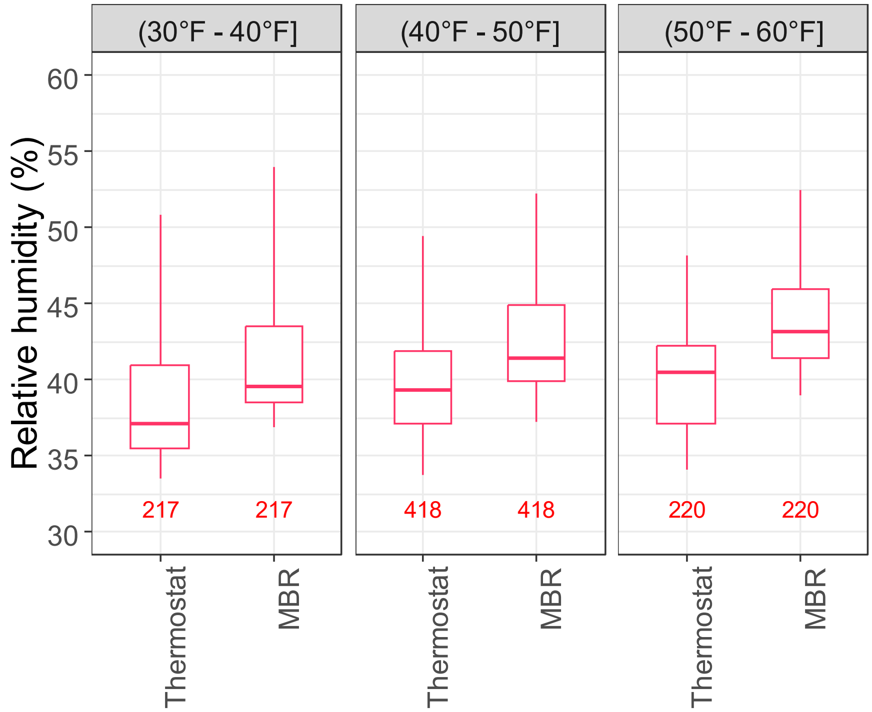
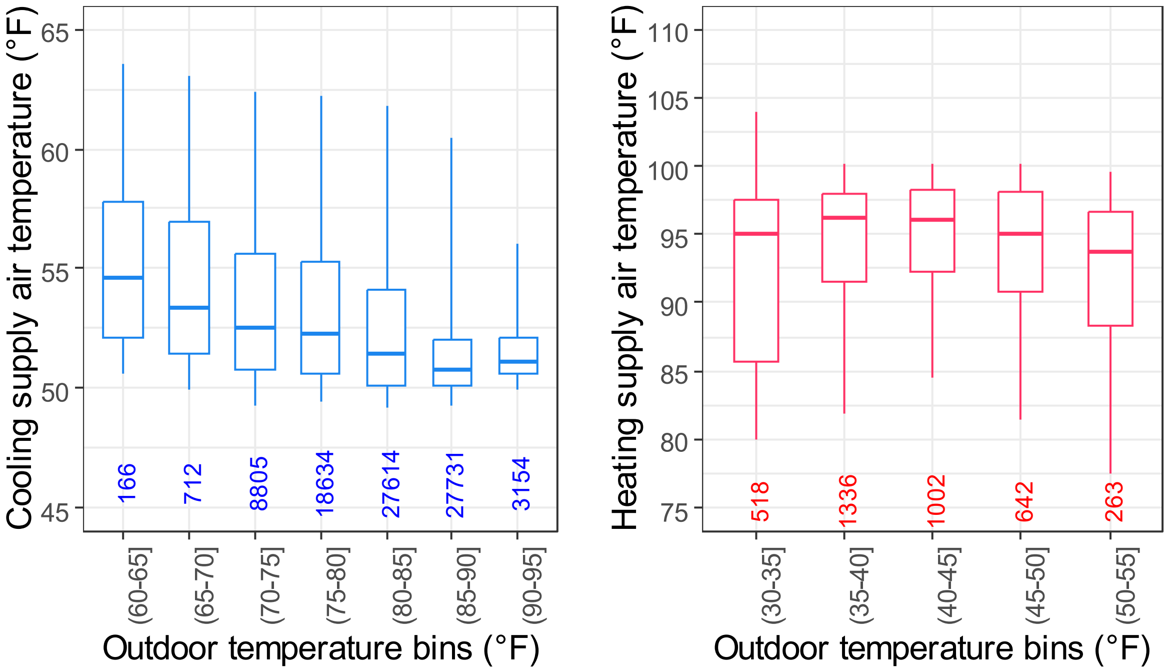


Figure 40 shows the variation in the cooling (left) and heating (right) supply air temperature of the heat pump installed at FSEC MH lab. We were able to collect sufficient supply air temperature data during both heating and cooling modes. Cooling at higher outdoor temperatures >85ºF demonstrated the least variation and coldest supply air temperature due to longer continuous runtime cycles and more maximum cooling output.

While in heating mode, the median of the supply air temperature was around 95ºF for all the outdoor temperature bins.

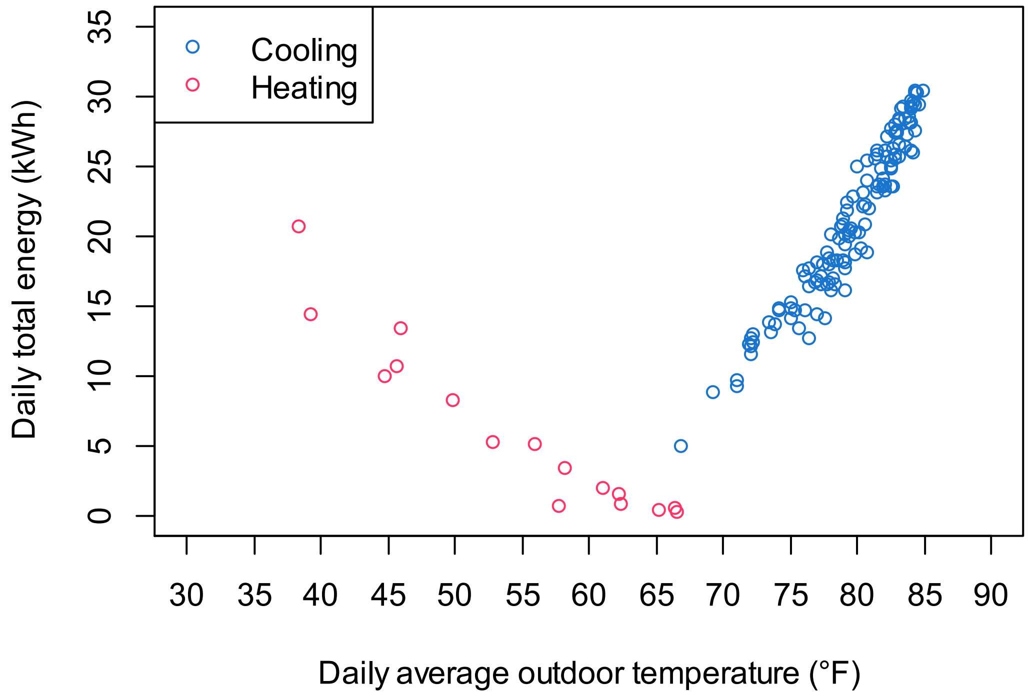
Figure 40. Variation in supply air temperature in different daily average outdoor temperature bins – during cooling (left) and heating (right)



ENERGY CONSUMPTION

Figure 41 shows the daily total energy against the daily average outdoor temperature for both heating and cooling. It shows that heating and cooling converge in the outdoor temperature range between 60ºF to 65ºF. The daily total cooling energy varied from 4.95 kWh to 30.49 kWh. The minimum daily total cooling energy occurred when the average daily temperature was 66.8ºF, whereas the maximum cooling energy was recorded for the average daily temperature of 84.2ºF.

Figure 41. Daily total heat pump heating and cooling energy vs. daily average outdoor temperature



HEAT PUMP EFFICIENCY

We analyzed heating and cooling efficiency using the measured system electric energy consumption and the delivered heating or cooling output energy leaving the indoor coil. We calculated the delivered cooling energy using the temperature and relative humidity of the air entering and leaving the indoor coil. Temperature, relative humidity, runtime, and the measured air flow rate were sampled at ten-second intervals and then averaged during one-minute measurement intervals. The ten-second interval samples were only included in the average if the system was in an active heating or cooling operation. Figure 42 shows the results for measured daily average cooling and heating COP versus daily average outdoor temperature. We reported the heating and cooling COP values only for the instances when the compressor was running 100% during each minute interval.

Cooling

The cooling data shows an expected trend of greater efficiency as the outdoor air temperature drops. The daily average COP for cooling ranged from ~ 3.5 to 5.1 across a wide range of outdoor test conditions. Interior sensible and latent loads remained the same through automated controls. While the daily average cooling COP is not directly comparable to manufacturer-rated COP, it could be useful to consider available manufacturer data at conditions similar to our test conditions. We used an outdoor temperature of 77ºF as a seasonal basis for comparison since there was manufacturer data at this temperature, and this also represents a seven-month (April-October) cooling season average for central Florida. Based on an outdoor condition at 77ºF and entering air conditions of 75.2ºF and 62.6ºF, the manufacture data indicated a COP of 4.1. Based on our testing, the daily average COP (shown in Figure 42) appears to be about the same even though our data consists of a wide variability in outdoor conditions over the course of a day, and the daily average entering air conditions were about 75ºF and 61ºF wet bulb.

Heating

The results of the daily average heating COP were not what we expected—they were relatively lower, particularly at outdoor temperatures greater than 47ºF, and the measured COP was relatively flat, as seen in Figure 42. The measured daily average COP does not represent steady state rated conditions. However, it is still interesting to see how our measured data compared to manufacturer rated data. The measured heating COP at 47ºF was 3.3 at best. Manufacturer data shows a positive slope of COP increasing as outdoor temperatures increase: COP =3.18 at outdoor temperature of 44.6ºF, COP=2.69 at outdoor temperature of 39.2ºF, and COP=1.89 at outdoor temperature of 17ºF.We did not see this trend in our measured data.

We do not know the exact cause of flat COP performance over a variety of outdoor conditions. However, we see some influence from observations of the cycle time and overall lower heating degree days. During the heat pump's heating operation at FSEC, the daily average outdoor temperature varied between 38.4ºF and 62.9ºF. One major reason for such unexpected low COP for a variable capacity heat pump operation during heating could be the shorter-than-expected heating cycle duration experienced at the FSEC site. Figure 43 shows the heat pump's cycle durations while heating at the lowest outdoor temperatures during the test period. For the time frame shown in Figure 43, the maximum heating cycle duration was only about 15 minutes, and the one-minute interval heating COP was between 3.5 to 2.5. These results reflect our observation of short heating cycles with a median active heat cycle of only 12 minutes when the outdoor temperature was between 30ºF and 35ºF shown in Figure 35. Most of the heating cycles were only 5-8 minutes long for outdoor temperatures between 35ºF and 50ºF, and the indoor temperature was stable during the heating period.

Figure 42. Average daily heat pump COP in cooling and heating mode against the average daily outdoor temperature

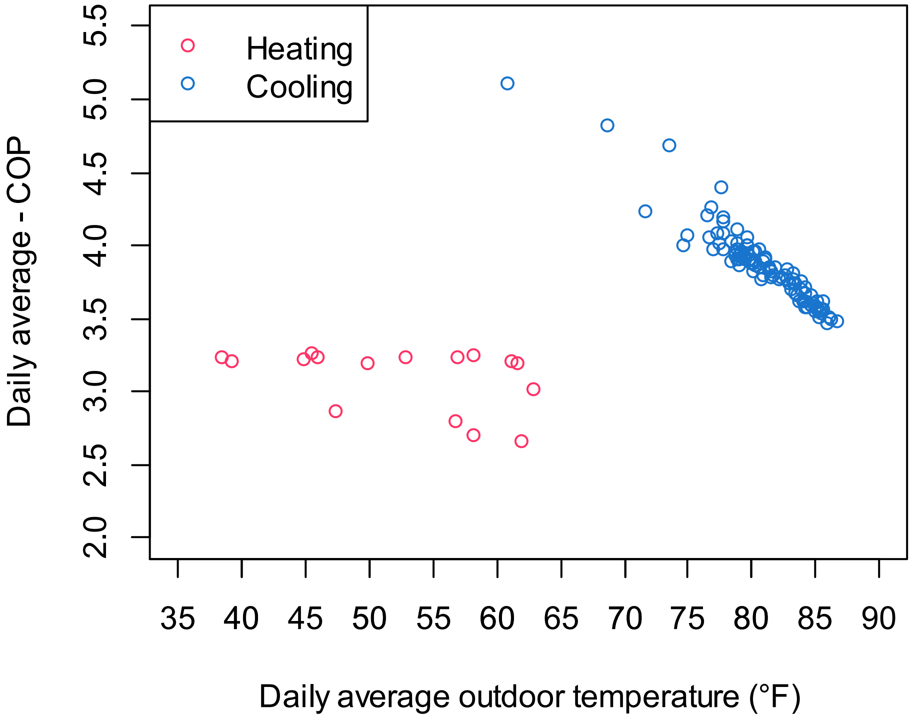
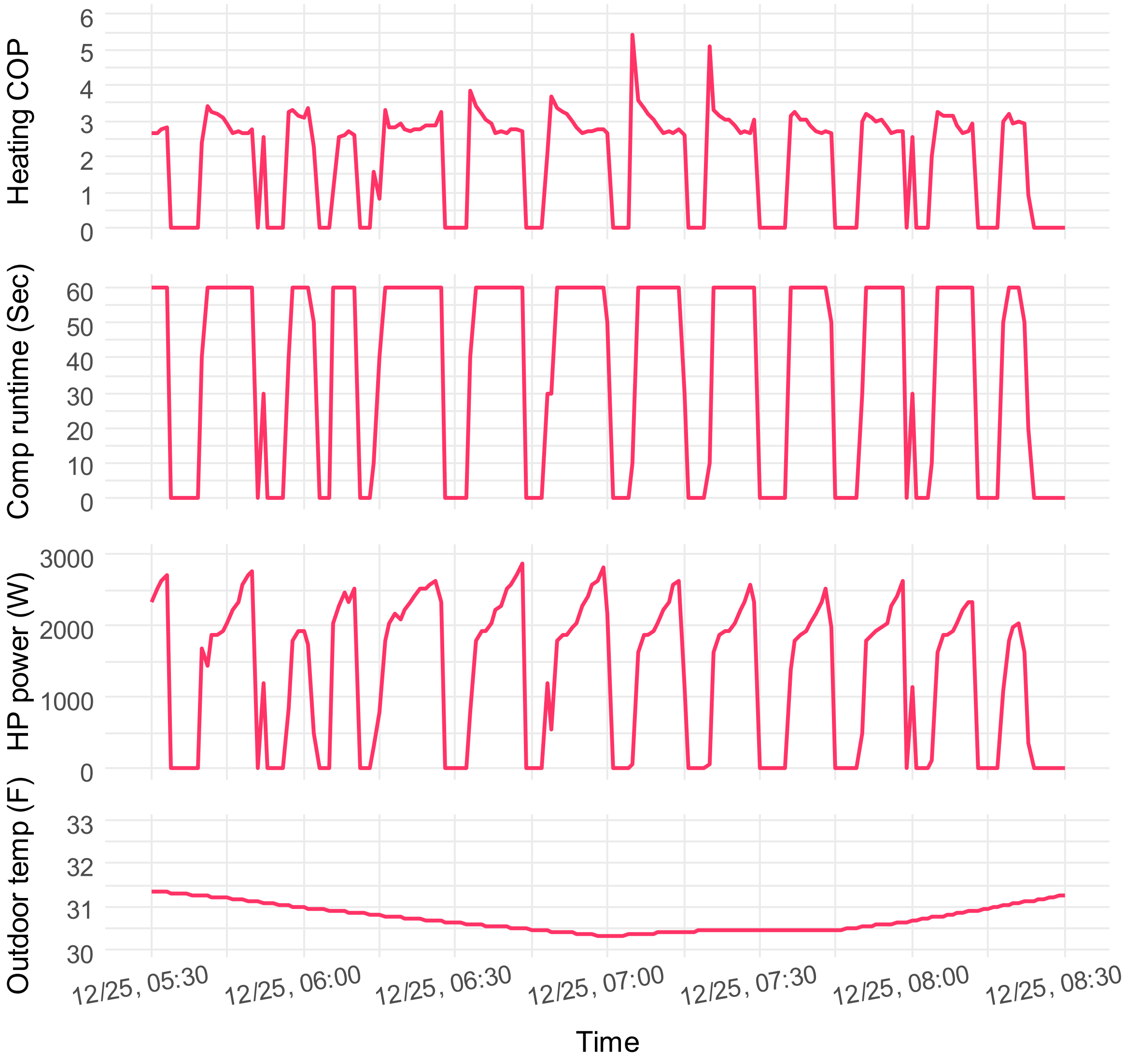


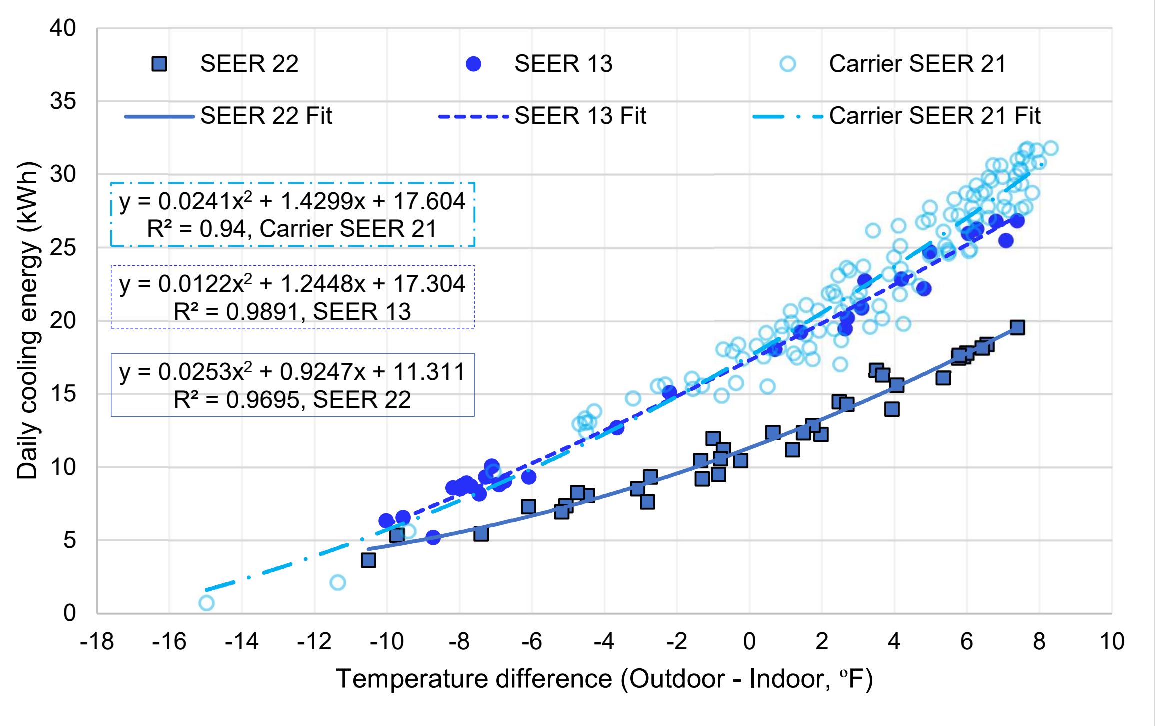
Figure 43. Heat pump heating cycle operation during the coldest outdoor temperature of the test period at the FSEC site



While the measured cooling COP was not surprising, the actual daily cooling energy use over various outdoor conditions was surprising, when compared to two other heat pumps in cooling mode tested in previous projects. Each of those systems were also two-ton heat pumps with similar indoor loads. One was a SEER 13 and the other a SEER 22. Our earlier analysis of the SEER 13 system used the same thermostat that we used on this project (Carrier SEER 21 system). The SEER 22 system had its own proprietary communicating thermostat. Indoor cooling setpoints were the same at 75ºF for all systems. Figure 44 shows the results. The daily total cooling energy is plotted against the daily average temperature difference between outside and inside. The plot clearly shows the Carrier SEER21 uses a bit more energy than the SEER 13 system. An average summer day is about 80 degrees, and the indoor setpoint of 75ºF would result in a temperature difference of 5ºF. Using delta temperature of 5ºF for a basis of comparison, the SEER 22 system used 16.6 kWh/day, SEER 13 used 23.8 kWh/day, and Carrier

SEER 21 from this project used 25.4 kWh/day. The Carrier SEER21 system used 6% more daily cooling energy than the SEER 13 unit and 35% more daily cooling energy than the SEER 22 unit.

Figure 44. Comparison of daily cooling energy versus dT for three different heat pump systems tested in the same facility using the same attic duct system



ENERGY CONSUMPTION WITH FLOOR DUCTS

The FSEC MH Lab has the option of using either an attic or a floor supply duct system. All the data we've presented up to this point has been based on using the attic duct system. Attic duct systems are very common in Southeast manufactured homes, but floor duct systems might be more prevalent in other regions, such as heating-dominated climate zones. We looked at the difference in energy consumption between attic and floor duct systems.

From June 1, 2023, to September 10, 2023, we collected data using the same heat pump, but connected to the floor duct system instead of the attic. The floor ducts consisted of a typical straight metal trunk line run longitudinally within each half of the double-wide lab manufactured home. A reasonably sealed cross-over connected the two main trunks. Floor register boxes were connected to main trunk lines by short flex ducts. The floor ducts were located between the floor deck and the belly insulation and air retarder membrane.

Figure 45 compares daily energy use between the attic and floor duct systems using the same heat pump. The attic supply ducts resulted in 11.5% higher daily cooling energy use for an average 80ºF outdoor temperature day (this is representative of 6-7 months of cooling season average temperature for central Florida). The attic duct location was much hotter and there were more conductive gains compared to the floor duct system. It is important to mention that the attic duct system had more duct leakage than the floor ducts. Based on duct pressurization tests using a DuctBlaster, the attic duct leakage to outdoors was 4.9 cfm25 per 100 ft^2 of conditioned floor area. The floor duct system leakage to outdoors was 2.8 cfm25 per 100 ft^2 of conditioned floor area. While the attic duct leakage is 75% greater than the floor duct, the amounts are small to modest. An energy simulation of the MH lab (EnergyGauge USA v 7.0) indicates the difference in duct leakage would only result in 1% more annual cooling energy use. This would indicate that without any difference in duct leakage, the attic duct system may use 10.5% more cooling energy than the floor duct system.

We analyzed the room temperature deviation from the cooling setpoint temperature (75ºF) in 5ºF outdoor temperature bins for the floor duct configuration, as we had for the attic ducts (Figure 37). Figure 45 and Figure 46 show the results for the floor duct system. The floor duct system maintained the indoor air temperature within a reasonable comfort level. The largest majority of hall and bedroom temperatures did not exceed ±2ºF deviation from cooling setpoint, and there were no significant deviations greater than ±3ºF. One notable difference is that the hallway temperature using floor ducts was consistently cooler for different temperature bins than when using the attic duct system. The hallway sensor was located at mid-wall height within four feet of the bathroom floor register which directed some air toward the sensor, likely resulting in cooler hallway temperatures at the sensor. Furniture in the MH Lab was arranged so that floor registers were not blocked. Thermal distribution from floor ducts in occupied homes may be quite different than these results depending upon furniture arrangements.

Figure 45. Daily total cooling energy versus daily average outdoor temperature for the same heat pump when connected to either attic supply or floor ducts

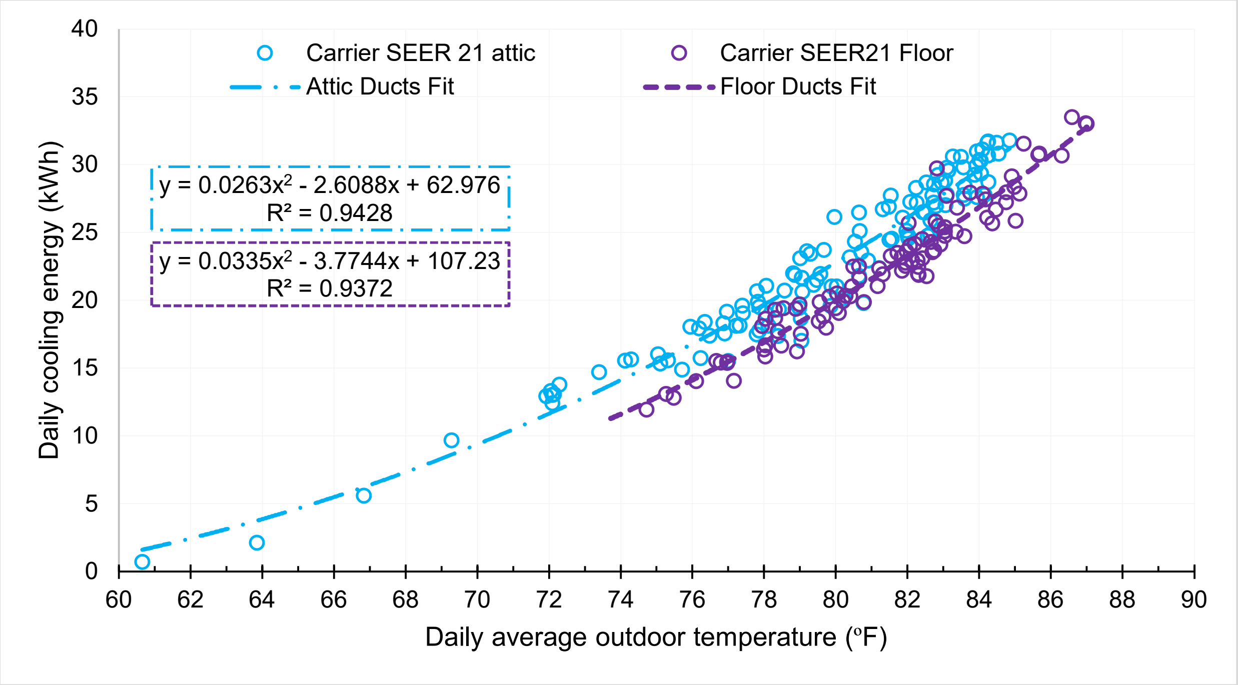
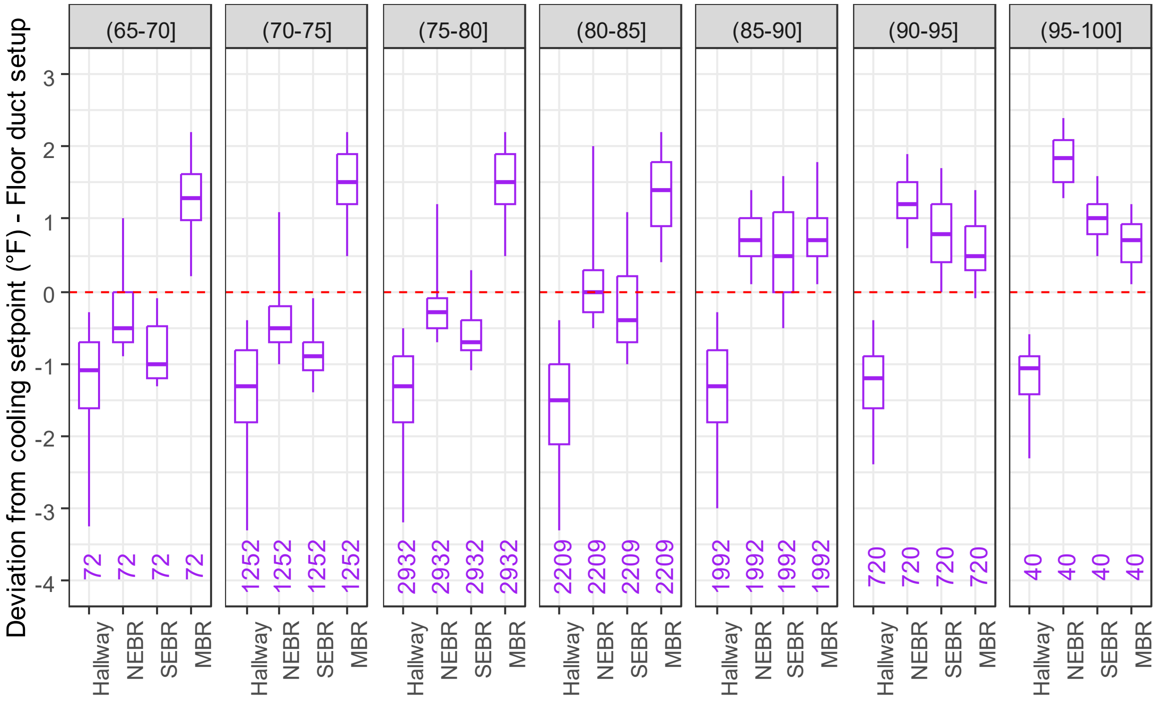


Figure 46. Room temperature deviation from cooling setpoint temperature in different hourly average outdoor temperature bins – heat pump cooling period with floor duct setup



UNEXPECTED COOLING PERFORMANCE OF THE TESTED HEAT PUMP

This heat pump model showed power modulation in heating mode as expected from variable capacity systems. In cooling mode, the system could readily deliver full output capacity, but there was very limited power modulation. The FSEC MH lab allowed us to observe cooling output and runtime in a controlled setting in a hot and humid climate. We did not expect to see the cooling system operate more like a single-stage system with short cycles during low cooling load periods. Given the observed cooling output and relatively short runtimes for a variable capacity system, we were not confident that the system would perform at its rated seasonal efficiency. Our analysis did not use actual rated test conditions compared to the AHRI rating. Instead, we used the daily cooling energy use over a wide variety of weather conditions to compare to previously tested systems (Figure 45). Our results showed that the Carrier 40MBAAQ24XA3 / 38MARBQ24AA3 combination, rated at SEER 21, did not use energy as efficiently as we would have expected compared to previously tested SEER 13 and SEER 22 rated systems. Interestingly, the measured cooling EER (tested at full capacity operation) was similar to manufacturer rated EER.

We confirmed that the system was installed properly and the manufacturer could not determine a cause for the difference in cooling performance that we observed. Sometime after the study began, Carrier discontinued the air handler unit model that we tested in this study and replaced it with a new model. Carrier was unaware of this study at the time they made changes to the air handler unit, and we, (project staff) were unaware of the planned product change at the time we selected the heat pump model for our study.

According to Carrier, “The 40MBAA series control algorithm utilizes a correlation between the 24V thermostat sensed temperature and measured return air temperature at the AHU to establish a setpoint. The delta between the system setpoint and the sensed return air temperature determines the cooling or heating output of the system. Loss of correlation between thermostat sensed temperature and return air temperature may adversely impact system performance. The 40MBAB series control algorithm uses revised hardware and software to improve system operation when used with either the (provided) communicating wired controller, or a third party 24V thermostat. Use of the provided communicating wired controller is recommended for optimal system performance.”