Dual Climate Case Study on HVAC Energy Efficiency and Comfort in Manufactured Housing

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ABSTRACT

Manufactured homes (MH) offer affordable homeownership, with 10 million units built in the U.S. since 1976. MH efficiency regulations are not as stringent as current IECC, typically resulting in nearly twice the energy use per square foot for space conditioning compared to a similar site-built home. While heat pumps in MH have the potential to reduce energy costs compared to electric resistance heating, their performance in meeting thermal comfort requirements is challenged in cold temperatures. In this context, experiments were conducted to understand the ability of a relatively new class of variable speed heat pump to satisfy thermal comfort and energy requirements in cold and hot climates. To achieve this, two identical heat pumps were installed in MHs in Oregon and Florida, and their behavior in terms of energy consumption and thermal comfort was examined. In Oregon, the heat pump's heating performance was compared to electric resistance heating, for a full season, revealing a potential of 63% reduction in heating energy while maintaining comfort. In Florida, cooling performance was assessed with two duct configurations (floor and attic ducts). The results showed that attic ducts increased the daily cooling energy by 11.5% for an average 80 ºF outdoor temperature day. The key lesson learned was that the selected heat pump maintained the desired thermal comfort, including indoor temperature and humidity, at both sites. Findings from this research could be useful to promote the adoption of variable-speed heat pumps in MHs and increase residents' confidence in using heat pumps even in cold climates.

Introduction

Manufactured homes (MH) have 60-70% higher energy cost /ft^2 compared to site built homes (NASEO, 2021). The energy use difference can be attributed to several factors: the manufactured housing industry market is extremely price sensitive; efficiency standards are set by the Department of Housing and Urban Development (HUD) code, which has not been updated since 1994; and sometimes damage can occur to insulation and duct systems during transportation and final installation. A basic MH is usually shipped from factory with a minimum efficiency gas or electric furnace as currently permitted by the current HUD code. Electric furnaces are popular lowest cost options for customers but have the highest operational energy cost creating a larger monthly cost burden. Heat pumps and variable speed heat pumps in particular are thought to be appliances that can reduce the amount of energy used in MHs for space conditioning, but research in the use of variable speed heat pumps with MHs is rare. A research study was conducted to investigate the performance of a high efficiency heat pump suitable for MH market and to investigate the potential energy savings.

Thermal comfort in buildings is crucial, and the method of achieving it depends on several factors. House type/characteristics, fuel type, equipment type, and their efficiencies play a substantial role in thermal comfort and home energy bills. In 2020, U.S. homes consumed more than half of the total energy consumption to meet their thermal comfort needs. Specifically, 42% of the household's end-use energy was consumed for space heating, with the highest (45%) and lowest (24%) consumption rates observed in detached single-family homes and apartments with 5 or more units, respectively (EIA, 2023a). Natural gas furnaces served as the primary source for space heating in 47% of U.S. households (EIA, 2017) and 70% of the mid-west homes rely on natural gas (EIA, 2023b). As renewable electric generation increases, there is a transition away from fossil fuel-based technologies. Many governments endorse the widespread adoption of heat pumps in a concerted effort to decarbonize buildings and enhance energy efficiency.

In recent years, the market share of heat pumps in 2022 has experienced 11% growth globally (IEA, 2023). In the U.S., 40% of new single-family homes utilize heat pumps for their space heating needs (IEA, 2022). Adopting heat pumps in U.S. households is considered a key strategy to reduce carbon emissions from the building sector and to achieve a net-zero energy system by 2050. The share of heat pumps in meeting space heating demand in the U.S. is expected to increase from 12% in 2022 to 25% in 2030 and 55% in 2050 (IEA, 2023). A recent study revealed that 62% to 95% of U.S. households will benefit from 31% to 52% of energy cost reduction based on the heat pump efficiency and energy efficient characteristics of the building (Wilson et al., 2024).

Among the different types (air, water and ground source), air source heat pumps (ASHPs) are preferred widely (Milev et al., 2023) and are capable of fulfilling both heating and cooling needs, representing an excellent alternative to fossil fuel-based systems. The U.S. introduced incentive programs in the Inflation Reduction Act (EnergyStar, 2022), to promote the adoption rate of ASHPs and make energy system upgrades more affordable for residents. It is envisioned that globally, the installation count of heat pumps will increase by 233% from 2020 to 2030 (IEA, 2023). Furthermore, continuous research efforts aimed at technological innovations within the domain of ASHPs have contributed significantly to the notable rise in their usage. For example, some of the recent studies focused on analyzing the coupled use of renewable energy sources for performance enhancement of heat pumps (Jin et al., 2023), impact of ASHPs on greenhouse gas (GHG) emissions and the cost-effectiveness (Wilson et al., 2024), impact of defrost cycles (Milev et al., 2023), use of refrigerant mixtures in ASHPs to improve their efficiency in cold climates (Hakkaki-Fard et al., 2015), and life-cycle analysis of ASHPs (Masternak et al., 2024). In IEA's Annex 49, simulation efforts were taken to understand the impact of integrating storage systems, photovoltaic panels, and dynamic setpoint settings on the ASHP performance and the respective results were reported (Wemhoener et al., 2017).

Besides on-site-built homes, ASHPs are excellent options for MHs, offering energy savings and achieving both heating and cooling needs. Serving as low-cost housing for approximately 19 million Americans, MHs are particularly appealing to first-time buyers (Talbot, 2012). Recognizing the importance of maintaining and upgrading these communities, HUD has recently allocated $225 million in financial aid for repairs, retrofits, and infrastructure improvements (HUD, 2024). The average electricity consumption in MHs (in 2021) was approximately 10,600 kWh per year (EIA, 2023c). American Council for an Energy-Efficient Economy (ACEEE) indicated that residents in MHs experience more energy burdens compared to on-site-built homes (Bell-Pasht & Ungar, 2022).

Despite the technological advancements and the availability of incentives, there are lingering concerns among MH residents regarding the suitability of ASHPs, particularly in cold temperatures. While ASHPs are known for their robust performance in milder regions, their heating output and efficiency drops in climates with low outdoor air temperatures. Residents face challenges such as higher initial costs compared to conventional heating systems, spatial constraints within MHs for installation, diminished energy efficiency in frigid conditions, and the complexities of the permitting process for outdoor units (IEA, 2022). In a bid to enhance the acceptance of heat pumps, the U.S., Department of Energy (DOE) has forged partnerships with six collaborators for the development and commercialization of cold climate heat pump technology (DOE, 2021). However, the above-mentioned challenges hinder the transition or adoption of ASHPs among MH residents.

While numerous studies in the literature have concentrated on technological advancements, estimating cost-effectiveness, and assessing GHG emission reductions due to ASHPs, most of these analyses primarily rely on simulation and research specifically focused on MHs is scarce. Although winter-proof or cold climate heat pumps have been promoted (NEEP, 2015), their performance in lower ambient conditions, particularly in MHs, remains largely unreported. Addressing this gap, the paper's primary objective is to examine the heating and cooling performance of an energy efficient ASHP installed in MH located in diverse climates (Oregon and Florida), focusing on its capacity to maintain thermal comfort and energy savings. To accomplish this, an ASHP was selected based on criteria such as energy efficiency, ease of installation, compatibility with conventional thermostats, and no need for specialized skills for outdoor unit installation. Since Oregon is a heating dominated site, investigating the heat pump's heating performance was prioritized in Oregon and heat pump's cooling performance analysis was prioritized at the Florida site. It should be noted that the intention of the study was not to compare the performance of the selected heat pump between the Oregon and Florida sites, but rather to assess the performance of the heat pump under two different climatic conditions. The findings will provide valuable insights into ASHP performance in varied climates and advocate for its broader adoption in cold climates, particularly within the MH community.

Methodology

This section provides comprehensive details on the selected heat pump, an overview of the manufactured homes (MHs) in both Oregon and Florida sites, the data utilized for the analysis, and the methodology employed to obtain the results. For the evaluation, an ASHP with AHRI-certified SEER: 21.00, EER 12.50, HSPF 11.60 was chosen. The manufacturer product data indicated a cooling capacity range from 7,500 Btu/h up to 26,000 Btu/h. This cooling capacity range and turn-down ratio of 3.5 were envisioned to work well particularly during low cooling load. The heating capacity was specified as 5,600 to 31,000 Btu/h. The same model and capacity heat pump were used in both locations (Oregon and Florida). The capacity was sized correctly for each location (ANSI/ACCA Manual J 8^{th} Edition 2016). The heat pump selected for this study has an air handler that can be configured with electric strip heat and set to operate as an electric furnace independent from the compressor. It can also use any third-party thermostat. This flexibility allows for partial heat pump installation in MH factory and for the home to ship with a functioning heating system, even before heat pump's installation that occurs on final site.

The MH used in Oregon was located in Lane County which comes under the mixed marine 4C climate. The house is occupied and has two sections with a conditioned space of 1,782 ft^2. The Oregon site MH was equipped with an Ecobee 3 lite programmable thermostat and set back temperature is enabled during nighttime. The thermostat adjusts the setpoint based on various schedules, including home, sleep, and away modes. Occupants have the option to override the default setpoint temperature individually for each mode. Figure 1 (left) represents the pictorial view of MH located in the Oregon site. The other MH used in the study is located at the Florida Solar Energy Center (FSEC) campus in Cocoa, Florida (Climate Zone 2A). This 1,600 ft^2 MH was an unoccupied, furnished MH laboratory (double-wide) and was built to 2001 ENERGY STAR standards. The occupancy in the MH lab is simulated, where the sensible and latent loads are generated internally. In the FSEC's MH lab, a constant cooling setpoint of 75 ºF and heating setpoint of 70 ºF was maintained. This is one of the notable differences between the two sites considered in the study. Figure 1 (right) shows FSEC's MH lab.

Figure 1. Pictures of MH located in Oregon (left) and Central Florida (right).

Data Description

The data analysis in the Oregon site was carried out from September 24, 2022, to April 15, 2023. This test period includes an intentional electric resistance heat system operation between February 22, 2023, to March 14, 2023. The limited data collected during intentional resistance heating energy was used to develop a regression equation that was compared to conventional heat pump energy regression to estimate seasonal energy use of each type of heating. Oregon data collection measured heat pump total power use, air handler and electric strip power use, thermostat set point temperature, different room temperatures and relative humidity (RH), as well as temperature and RH outdoors, in crawlspace and within the floor cavity. Table 1 shows the source and resolution of data collected at Oregon site. In the Florida site, the heat pump performance was studied between June 30, 2022, to November 5, 2022, and from December 24, 2022, to March 31, 2023. In the FSEC's MH lab, Campbell Scientific dataloggers were used to collect the indoor and outdoor environmental data as well as internally generated sensible and latent loads data, heating, and cooling energy use. More details on the parameters used to study the performance of the heat pump installed at the FSEC site are presented in Table 1. The delivered heating and cooling energy was measured by temperature and humidity sensors located before the air-handling indoor coil and just after the coil and fan (return and supply). All data was sampled at 10-second intervals by the Campbell dataloggers. The environment-related parameters (temperatures, RH, solar insolation, and air handler total static pressure) were averaged at 15-minute intervals. Energy usage, runtime and rainfall were summed at 15-minute intervals. The heat pump performance data was only recorded if there was active heating or cooling and was stored at 1-minute intervals.

Table 1. Parameters measured and used in the study.

Data relevance	Parameter	Storage Interval
Oregon Site – Data collection		
Performance related data	Total heat pump power (W)	1 second
	AHU and Electric resistance system power (W)	
	Voltages Phase A & B (V)	
	Supply and return air temperature (ºF)	5 minutes

Data relevance	Parameter	Storage Interval
MH & environmental (MHE) data	Outdoor air temperature (ºF)	
	Indoor temperature – Living room/kitchen, and four bedrooms (ºF)	
	Supply, return air, outdoor, room relative humidity (RH%)	
Thermostat data	Ecobee setting (heat/cool/auto/off)	5 minutes
	Ecobee mode (compressorHeatStage1On, compressorCoolStage1On, etc.)	
	Ecobee program mode (home/sleep/away)	
	Heating and Cooling setpoint temperature (ºF)	
Florida Site – Data collection		
Heat pump performance (HPP) data	Heat pump compressor, Air handler unit run time (seconds)	1 minute
	Supply and return air temperature (ºF)	
	Total heat pump energy, Air handler unit energy (Wh)	
	Heat pump air flow rate (cfm)	
MH lab & environmental (MHE) data	Outdoor Temperature (ºF)	15 minutes
	Indoor Temperature (Hall, living, 3 bedrooms) (ºF)	
	Thermostat temperature (ºF)	
	Outdoor and indoor RH (Hall, living, 3 bedrooms.) (RH%)	
	Horizontal Solar Insolation (W/m^2)	

Data Processing and Analysis

The overview of the steps involved in data processing is briefly outlined in Figure 2. Data processing on both sites mainly involved data cleaning, data aggregation, and data merging. In the Oregon site, data cleaning was performed for power measurement data (for both heat pump and electric resistance heater), which included eliminating days with no data during power outages, data outside the voltage range 105V to 130V, and minutes lacking 60 seconds of power data. For consistency, the days or hours eliminated in the power data were also eliminated in the MH & environmental (MHE) data. After data cleaning, one-second power data was aggregated into minute data. Subsequently, minute-wise power data was merged with 5-minute data containing data on temperature (both indoor and outdoor), relative humidity, and thermostat-related data. The heat pump mode was determined using the ecobee setting. While in the Florida site, data preparation primarily involved converting Julian date to a calendar date, data merging (combining 1-minute heat pump power-related data with temperature and relative humidity data), and identifying heat pump mode, based on the difference between supply and return air temperature. All the data analysis was performed using libraries from R programming (RDevelopementCoreTeam, 2010). In both sites, data analysis includes investigating the heat pump's power modulation during heating, cooling modes, cycle durations and the heat pump's ability to meet thermal comfort requirements. The thermal comfort ability is represented in terms of deviation from setpoint temperatures. In addition to the above, at the Oregon site, heat pump energy consumption during heating mode is compared with the conventional electric resistance heating system and accordingly, the energy-saving potential of the heat pump is reported. Regression analysis was performed to estimate the heat pump's energy-saving potential. As part of the research conducted at the Florida site, the heat pump's cooling performance was investigated under two different duct configurations (floor and attic) and the results are reported.

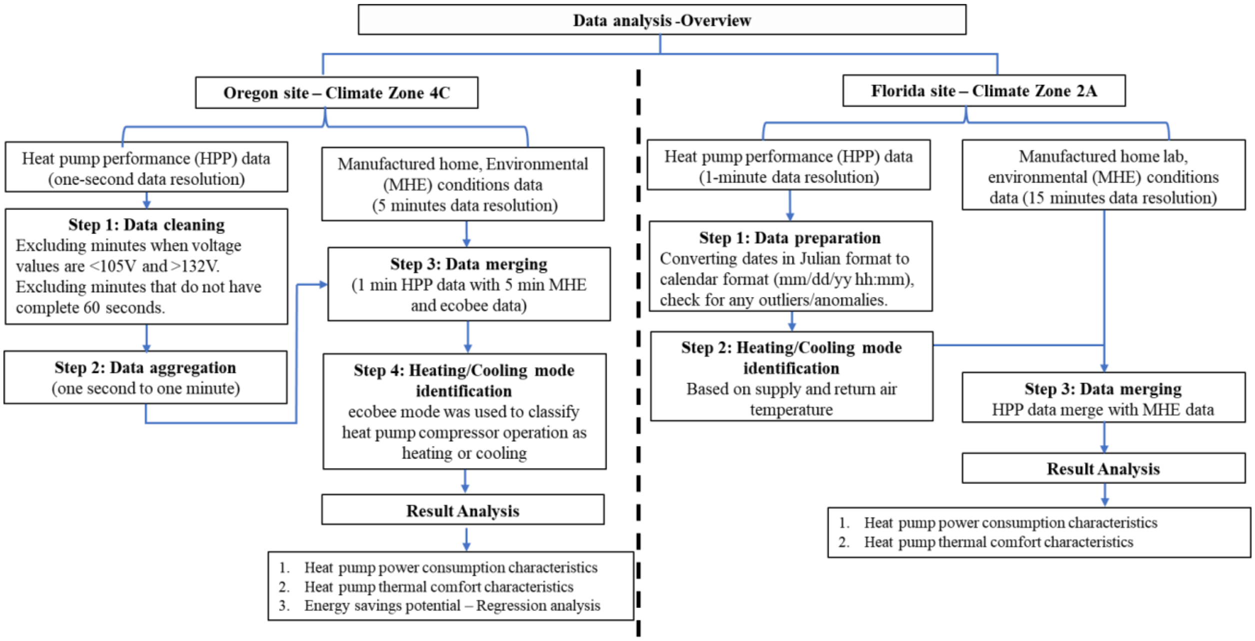

Figure 2. Data analysis framework – Overview.

Oregon Site - Results

Heat Pump Power Variation in Heating And Cooling Modes

Figure 3 depicts a boxplot illustrating the operating wattage of the heat pump compressor during heating (left) and cooling (right) operations, categorized into 10 ºF outdoor temperature bins. Although outdoor temperatures were recorded at five-minute intervals, hourly average values were utilized to mitigate potential rapid fluctuations caused by events such as cloudbursts (rainfall).

Within each boxplot, the numbers denote the data points[1] within each outdoor temperature bin. The minimum and maximum lines represent the 5th and 95th percentiles, respectively. The median value is depicted by the middle horizontal line, while the lower and upper horizontal lines represent the 25th and 75th percentiles, respectively. These definitions apply uniformly to all boxplots presented in this paper. It can be seen from the figure that during heating, the heat pump typically operated at higher power levels during periods of colder outdoor temperatures compared to higher outdoor temperatures. The compressor's power ranged from 700W to 4,680W. Since the boxplots were set to display data from the 5th to the 95th percentile, the maximum value is not explicitly shown. On the other hand, the power consumption of the electric resistance system (not shown in Figure 3) ranged between 9,000W to 10,000W. During cooling, the heat pump did not demonstrate as much variability between low cooling load and high cooling load as expected from a variable capacity system. This may be due in part to relatively small amount of data in some bins and some impact of varied thermostat settings at

[1] In Oregon, data points for power measurements represents one-minute intervals, while temperature and relative humidity data points represents five-minute intervals. In Florida power measurements represent one-minute intervals, but temperature and relative humidity datapoints represent 15-minute intervals.

this occupied home. Fundamentally, split- DX cooling systems use more power as outdoor temperature increases. Based on this system's performance data the increase from 47ºF to 95ºF outdoor would expect 1,420 W increase, which explains most of the increase shown. .

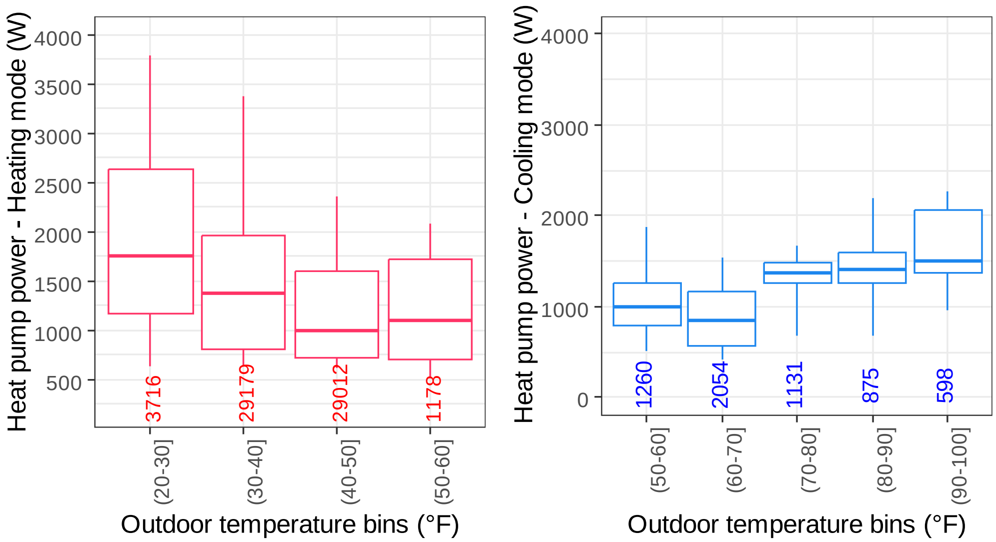

Figure 3. Heat pump heating (left) and cooling (right) power modulation with respect to hourly average outdoor temperature ranges. Note: The values inside the boxplot denote the number of data points (one-minute data) within each outdoor temperature bin.

Heat Pump and Conventional Electric Resistance System Daily Energy Consumption

Figure 4 shows the daily total heating energy used for two different sets of evaluation settings over time from late September through mid-April. The first evaluation was with the system set to a typical heat pump operation. The second evaluation was with the system intentionally set to electric resistance heating only, thereby eliminating compressor heating and any of its associated operations. The last part of the figure (after March 14) shows the return to heat pump operation. The electric resistance test period was chosen to test the power drawn from the electric resistance heat equipment, compared to the heat pump, and to evaluate the ability of the heat pump to meet the heating demand. As mentioned earlier in the data description, the electric resistance heat test period started on 2/22/2023 at 19:08 PDT and ended on 3/14/2023 at 13:30 PDT. During the electric resistance system test period, the heat pump compressor was not allowed to operate, however, there was some small parasitic stand-by power draw of the heat pump.

Figure 4 shows the higher energy consumption pattern of the electric resistance heating system compared to the heat pump. The other main inference is for most of the days, the heat pump could heat the space without the electric resistance heating system. In the course of normal heat pump operation, electric resistance heating was active for 10 brief periods on 8 separate days as shown in Figure 4. In just one case, the electric resistance system appears to have been triggered during normal programmed thermostat recovery from night setback when the outdoor temperature was about 24ºF. In all the other cases, the thermostat had been placed in a manual hold, and in most of these cases, the temperature setting had been manually increased shortly before auxiliary heat was called. This suggests that if manual thermostat changes had been avoided, almost no auxiliary heat would have been used. In any case, during the normal heat pump operation test period, the maximum daily electric energy consumed by the auxiliary heating system was less than 2.5 kWh.

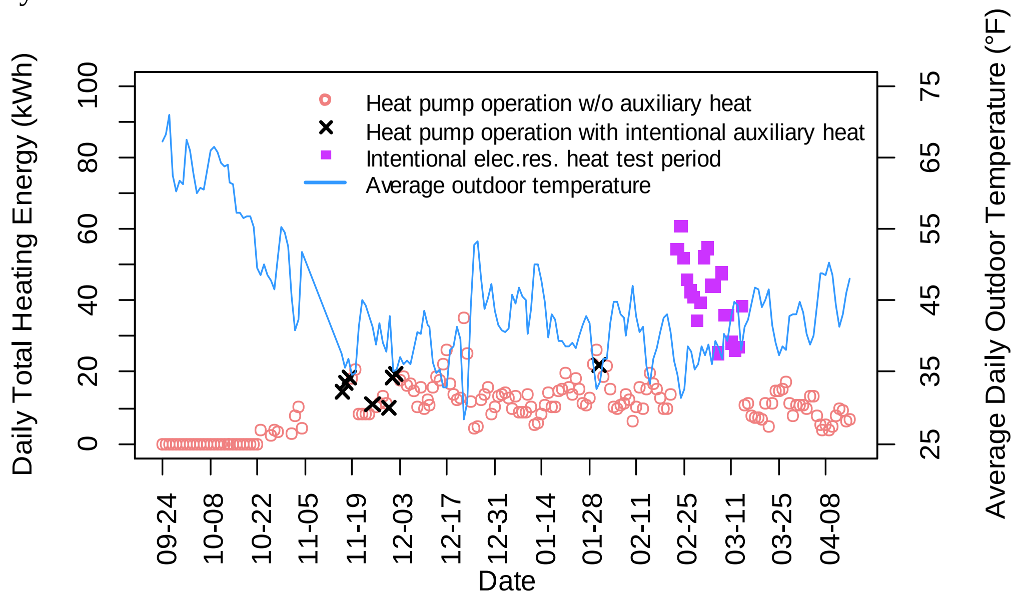

Figure 4. Total daily energy consumption (kWh) during heat pump operation and electric resistance heating test period. Note: Heat pump heating started on October 22, 2022.

Thermal Comfort Analysis

Thermal comfort was evaluated as the difference between measured room temperature and the stable thermostat setpoint. We used the term 'stable setpoint temperature' to mean 1-hour periods during which the ecobee thermostat setpoint remained unchanged. Figure 5 represents the deviation from the heating setpoint temperature for the heat pump and electric resistance heating system, respectively. The blue dashed line at 0º F in the y-axis is presented as a reference to the ideal difference from any given space to the desired setpoint. The terms 'Liv_Kit', 'BR 1, 2, 3 and 4' represent Living room/Kitchen, and four bedrooms, respectively. Figure 5 shows a systematic variation in temperature across the rooms, with BR1 having the lowest temperatures (generally slightly below the setpoint), and BR2 having the highest (often slightly above the setpoint)[2]. The pattern changes in the highest outdoor temperature bin, with increased high-end room temperatures – this is likely driven by incidental heating from solar energy and internal gains when no heat is required. In the lowest outdoor temperature bin (20 ºF to 30 ºF], room temperatures maintained by the heat pump were slightly lower than temperatures maintained by the electric resistance heating system. In general, however, the majority of temperature observations for both the heat pump and auxiliary heating system across all temperature ranges were within ± 2 ºF of stable heating setpoint temperature. In summary, it appears that reasonably comfortable conditions were maintained most of the time based on Air Conditioning Contractors of America (ACCA) Manual RS which establishes a desired temperature difference from room to setpoint not to exceed +/- 2 ºF during heating and +/- 3 ºF during cooling (Rutkowski, 1997).

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[2] 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.

Similar results were obtained for the heat pump's cooling operation where thermal comfort appears to have been maintained at most times.

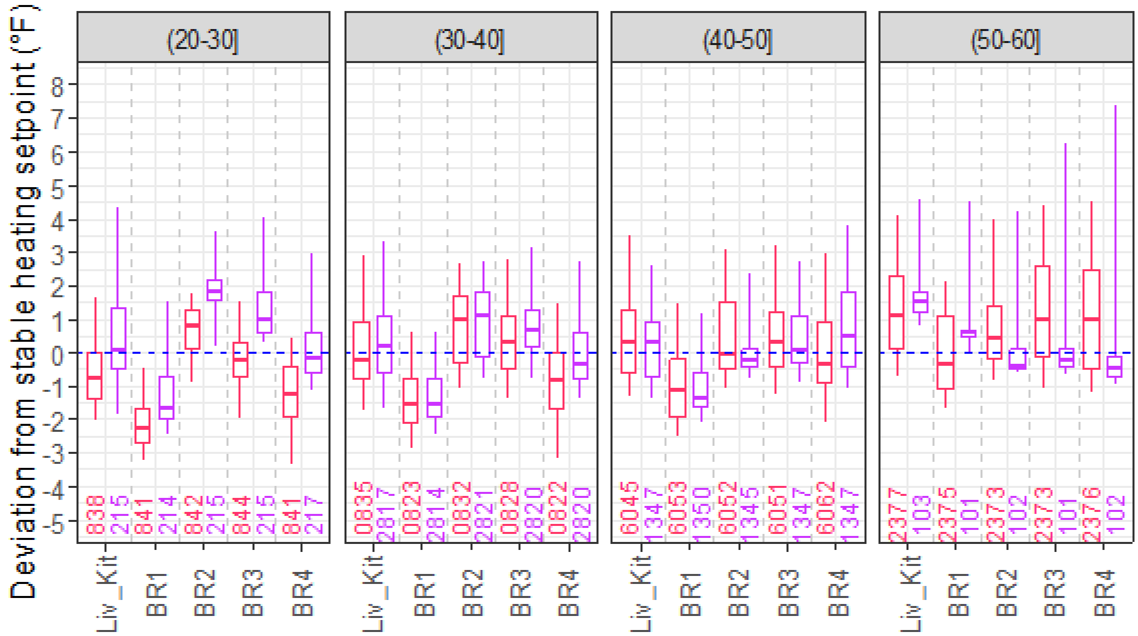

Figure 5. Hourly average room temperature deviation from stable heating setpoint temperature in outdoor temperature bins – heat pump and electric resistance heat. The values inside boxplot denote the number of data points (five-minute data) within each outdoor temperature bin.

Regression Analysis

To estimate the energy-saving potential of a heat pump compared to an electric resistance heating system, the linear regression method was used in this study. To predict the daily heat pump heating energy, the daily total heating energy, represented in kWh, and heating degree days (HDD) was considered as the dependent and independent variable, respectively. HDD with respect to a specified base temperature[3] (Tbase) was calculated by subtracting the daily average outdoor temperature (Tout) from Tbase. When Tout was greater than Tbase, the HDD is regarded as 0. Subsequently, simple linear analysis was conducted to determine the optimal Tbase within a range from 48 ºF to 63 ºF. The highest R^2 value (0.8853) was achieved for Tbase at 52 ºF, thus establishing it as the threshold temperature below which the heat pump operates in heating mode. Accordingly, the intercept and coefficient (shown in Equation 1) obtained using 52 ºF was used to estimate the heat pump's daily heating energy.

$$\textit{Daily heat pump heating energy (kWh)} = 1.58589 + (1.04659 * HDD_{52}) \qquad (1)$$

To estimate the electric resistance heating system daily energy, daily electric resistance system heating energy (kWh) was considered as the dependent variable and HDD (for the base temperature of 52 ºF) was considered as the independent variable. Since the data availability was

[3] Tbase represents the outdoor temperature, below which, the heat pump will operate in heating mode. With the experimental data collected, it was hard to find out at exactly what outdoor temperature, heat pump operated in heating mode. Hence regression analysis was used to find the base temperature.

limited (between February 22 to March 14, 2023) for the intentional electric resistance system heating period, R^2 was not good. Therefore, an assumption was made that the regression intercept is the same for electric resistance heating as for heat pump heating. Subsequently, regression analysis was performed using a fixed intercept of 1.58589. The regression equation given below was used to estimate the electric resistance heating system's daily energy consumption.

*Daily electric resistance heating energy (kWh) = 1.58589+ (3.0916 *HDD_{52})* (2)

Once the regression equations to predict both the heat pump and electric resistance heating system daily energy was determined, 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 was estimated. Figure 6 shows the predicted daily heating energy for the heat pump and the electric resistance heating system for the days with HDD > 0. Using the regression equations, for the period between September 24, 2022, to April 15, 2023, and when HDD >0, the total heating energy for the heat pump and electric resistance heating system was estimated as 2,204 kWh and 5,979 kWh respectively. This indicates that the selected heat pump is projected to consume 63% less energy compared to the conventional electric resistance heating system over the analyzed heating season.

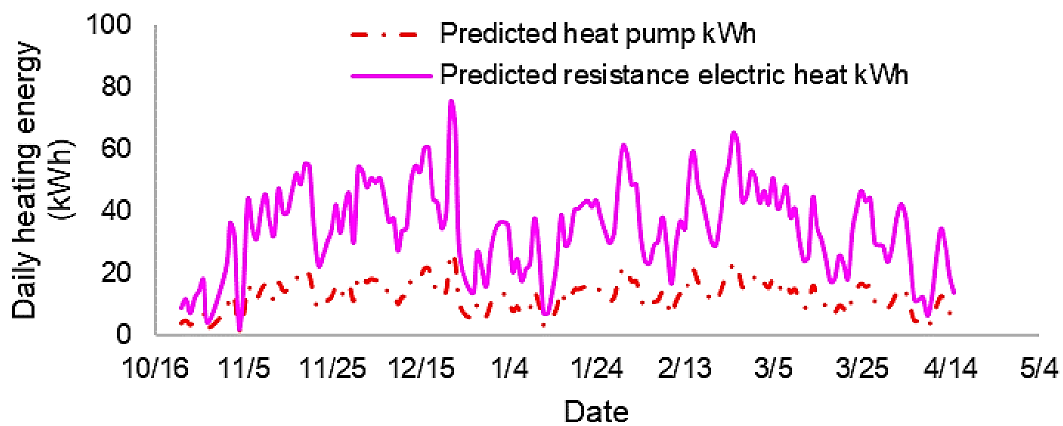

Figure 6. Predicted heating energy for heat pump and electric resistance heating system during the considered heating season period (October 22, 2022, to April 15, 2023)

Florida Site – Results

Heat Pump Power Variation in Heating and Cooling Mode

The variation in the heat pump's power with respect to hourly average outdoor temperature (grouped in 5 ºF bins) during cooling (left) and heating (right) is shown in Figure 7. The inference from the figure is that in heat pump cooling mode, during the coldest outdoor temperature bin in the plot (low cooling load), the heat pump power median value was ~1,500W, whereas, during the high outdoor temperature bin (90ºF-95ºF] (high cooling load), the median was ~ 2,300W. The cooling power increase is attributed to the increasing power demand on the compressor at higher outdoor air temperatures. 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 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 performance effectively.

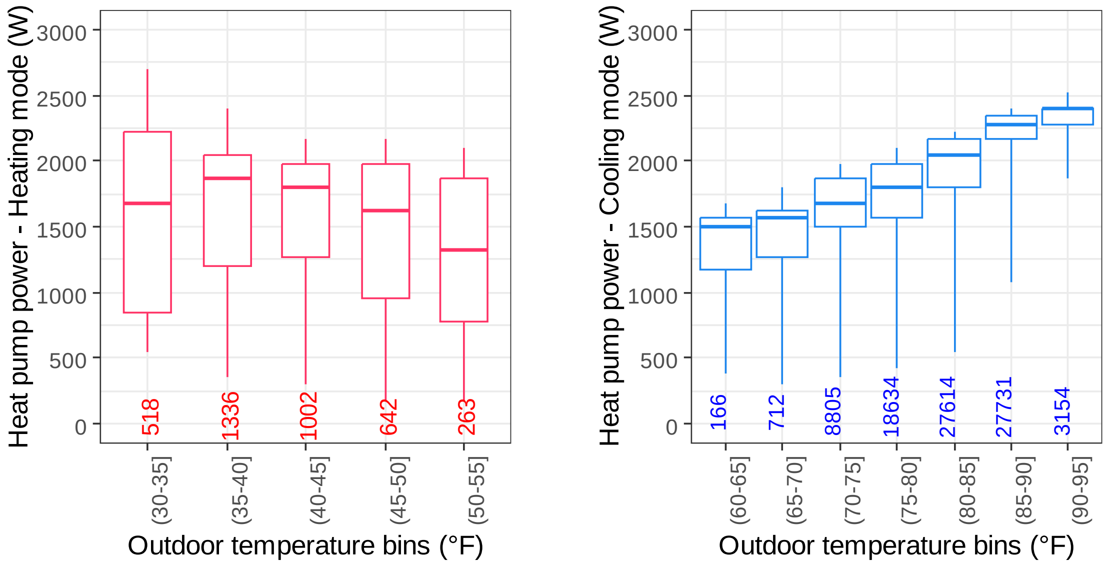

Figure 7. Heat pump power modulation in 5 ºF hourly average outdoor-temperature bins during heating (left) and cooling (right) modes. Values inside boxplot denote the number of data points (one-minute data) within each outdoor temperature bin.

Heat Pump Daily Energy Consumption

The cooling system did not variably modulate according to load as one would expect from a variable speed system. Figure 8 shows the measured cooling power during a hot summer day. The system ran short cycles overnight at about full capacity output instead of longer cycles at lower output. In fact, measured input power and output energy showed that the cooling system reached near full capacity within about two minutes into a cycle and demonstrated short cycles during low load periods during summer evenings. The vast majority (81% of the total) of cooling cycles were shorter than 15 minutes and 59% of the cooling cycles were between 7 to 11 minutes.

Figure 9 exhibits the daily total energy against the daily average outdoor temperature for both heating and cooling. It can be seen that heating and cooling converge in the outdoor temperature range between 60 ºF to 65 ºF and the daily total cooling energy varies from 5 kWh to 30 kWh. In general, the measured heating and cooling COP was about as expected when conditions were similar to rated conditions, however, the cooling operation performed more like a single capacity system than variable capacity, and daily cooling energy use was higher than expected for the rated efficiency. The slope of cooling energy use in Figure 9 was similar to SEER 13 systems than SEER 21 systems tested in prior research in the same MH lab. The manufacturer was contacted and verified proper installation, but could not explain lack of cooling modulation in our system. They indicated that they discontinued the air handling unit model in our test and replaced it with another model.

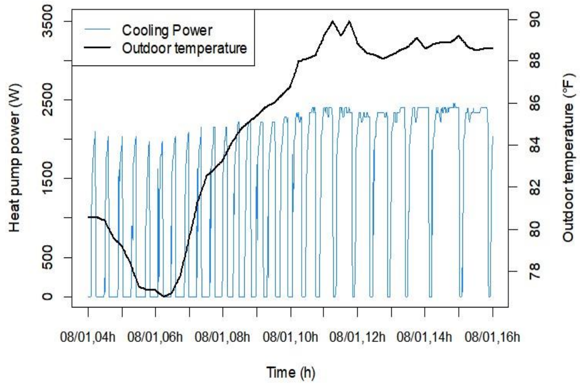

Figure 8. Cooling power measured each minute on a hot summer shows unexpected very short cycles during early morning low load and cycles on off even during hottest time of day.

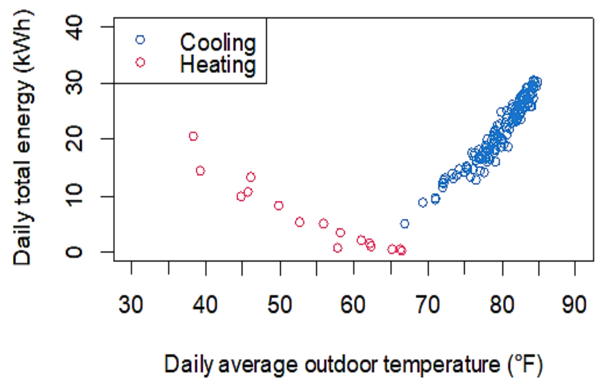

Figure 9. Daily total heat pump heating and cooling energy vs. daily average outdoor temperature.

Thermal Comfort Analysis

The room temperature deviations from the cooling and heating setpoint temperatures in different hourly average outdoor temperature bins are depicted in Figure 10 and Figure 11, respectively. The red dashed line at 0º F in the y-axis is presented as a reference to the ideal difference from any given space to the desired setpoint (75 ºF for cooling). In the figures, NEBR, SEBR and WBR represent the northeast bedroom, southeast bedroom and west bedroom, respectively. The temperature sensor in WBR was located at the pillow height on the furnished bed located near the west wall, hence the deviations were relatively higher in WBR compared to the other rooms. Other than WBR, it can be seen from Figures 10 and 11 that the deviation from the setpoint temperature is within the range of ± 2 ºF for all the outdoor temperature bins during both heating and cooling. This demonstrates reasonably comfortable conditions maintained using the attic supply duct system during cooling.

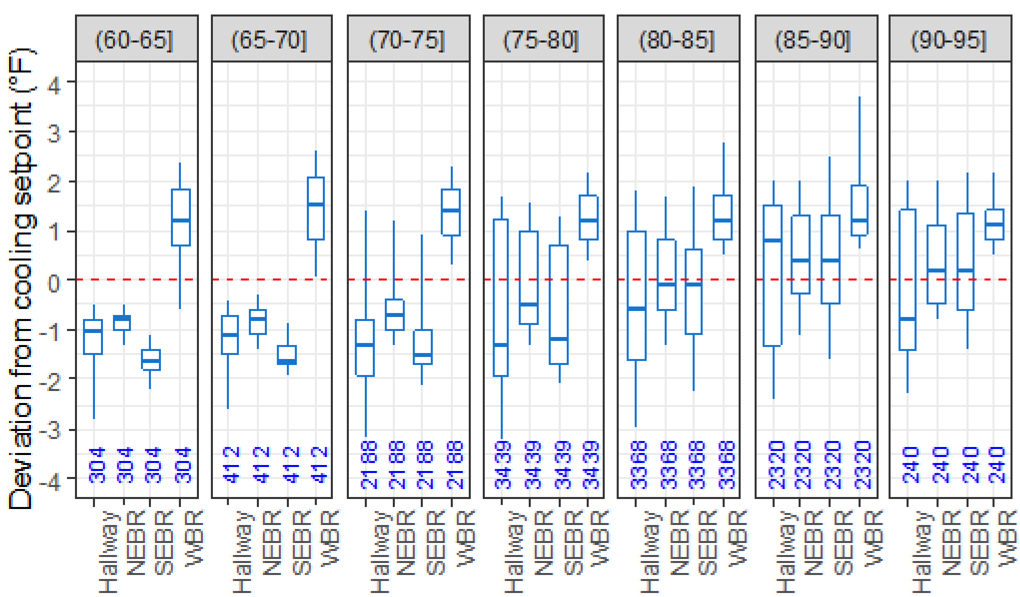

Figure 10. Room temperature deviation from cooling setpoint temperature in different hourly average outdoor temperature bins – heat pump cooling period.

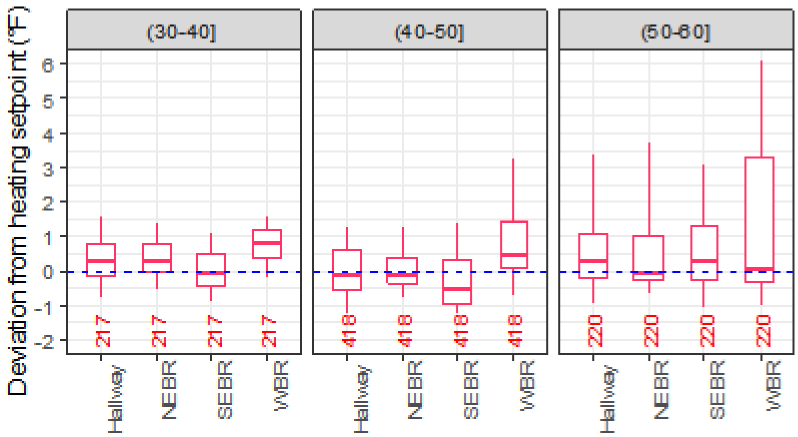

Figure 11. Room temperature deviation from heating setpoint temperature in different hourly average outdoor temperature bins – heat pump heating period.

In the Florida site, the selected heat pump's ability to maintain the relative humidity during cooling operation was studied and the respective results are presented in Figure 12. For illustration, the relative humidity measured at two locations was considered. The location 'Thermostat' in the figures denotes the RH measured next to the thermostat on an interior wall of the living room. The WBR RH was measured at the same location as the temperature at pillow height near the west wall. Figure 12 indicates that the heat pump air conditioning maintained the RH well within the range of 42% to 50% most of the time across a wide range of outdoor temperatures. This lab home did not have any mechanical ventilation during this experiment and if it had the RH would likely be a little higher. RH control during heating periods in Florida is less problematic than during cooling and measurements showed that RH fluctuated between 35% and 45% across all outdoor temperatures during the heating season.

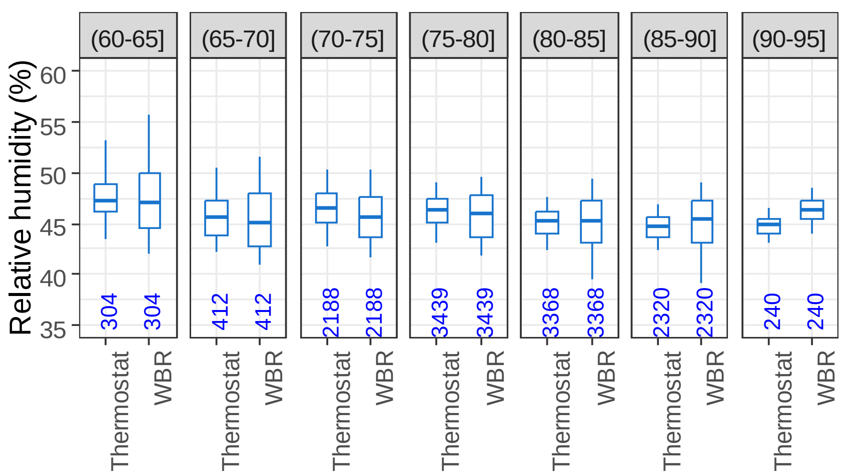

Figure 12. Variation in relative humidity at different measurement locations and different hourly average outdoor temperature bins – during heat pump operation in cooling mode.

Cooling Energy Comparison Between the Floor and Attic Duct System

The FSEC's MH Lab has the option of using either an attic or a floor supply duct system. Ducts in a vented attic are outside the primary thermal barrier, but ducts in MH floor space are between the finished floor and floor insulation. Attic duct systems are very common in southeast manufactured homes, where there may be a preference for floor duct systems in other regions such as heating-dominated climate zones. During the experimentation, data was also collected using the same heat pump connected to the floor duct system during the summer of 2023. Figure 13 shows a comparison of daily cooling energy use versus daily average outdoor temperature for the attic and floor duct systems using the same type of heat pump. The attic supply ducts resulted in 11.5% higher daily cooling energy use for an average 80 ºF 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 to it compared to the floor duct system. While the attic duct system had more duct leakage to the outdoor than the floor ducts (4.9 cfm25 per 100 ft^2, and 2.8 cfm25 per 100 ft^2 of conditioned floor area, respectively), both ducts would be designated at Grade I leakage based on ANSI/RESNET/ACCA Standard 310-2020. The room temperature deviation from the cooling setpoint temperature (75 ºF) in 5 ºF outdoor temperature bins was analyzed for the floor duct configuration and showed that the largest majority of hall and bedroom temperatures did not exceed ±2 ºF deviation from setpoint and there were no significant deviations greater than ±3 ºF. The reader is reminded that the MH Lab was furnished with furniture that was arranged in a way that floor registers would not be blocked. Thermal distribution from floor ducts may vary more than these results in occupied homes depending upon furniture arrangements.

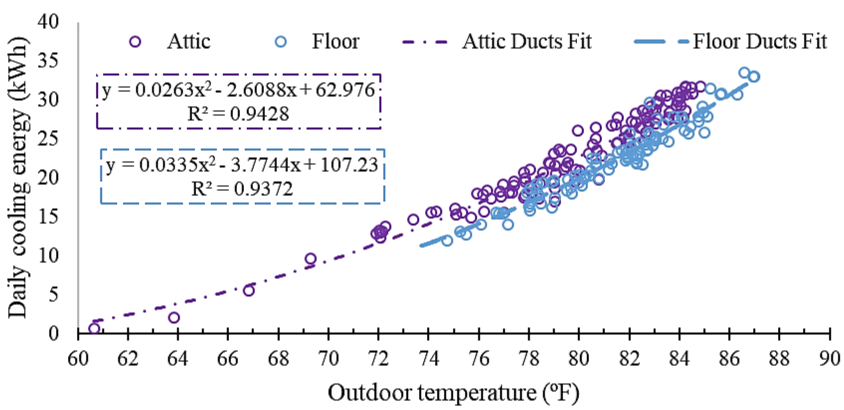

Figure 13. Daily total cooling energy versus daily average outdoor temperature for the same heat pump when connected to only attic supply ducts and only floor ducts.

Conclusion

This study evaluated the same heat pump model installed in two different MH in two different climate zones in Oregon and Florida (4C and 2A, respectively). Based on data from both test sites, it demonstrated that properly sized electric heat pumps can effectively meet heating and cooling loads in these climate zones and maintain reasonable thermal comfort in terms of indoor temperature and relative humidity. Heating loads were met with outdoor low temperatures as low as 23 ºF in Oregon and cooling loads met with outdoor temperatures as high as 94 ºF in Florida. The hot and humid climate in Florida found good humidity control in the MH lab home as tested but did not have ventilation meeting ASHRAE 62.2 minimum standard, which would have created a bigger challenge for RH control during summer. The longer heating season in Oregon allowed a comparison of heating energy using the heat pump and only the electric resistance heating which indicated a heating season energy savings of 63% for the heat pump. Oregon testing also found that the heat pump effectively managed the entire heating load throughout the winter, with minimal reliance on backup electric resistance heat. Florida testing demonstrated that attic central system ducts require about 11.5% more daily cooling energy use due to greater thermal losses compared to when only a typical MH floor duct system is used based on the Florida MH lab test house using the same heat pump. The findings from the study can be useful to understand the heat pump performance (in terms of energy consumption and meeting thermal comfort requirements) in diverse climates (such as Oregon's cold winter and Florida's hot and humid summer). Furthermore, the result validates the ability of chosen heat pump to meet the thermal comfort in both heating and cooling mode and reported its energy saving potential compared to the conventional electric resistance system. The scope for future works may include conducting a comparative analysis of the selected heat pump's performance against other baseline models, against different MHs and climates.

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