Pacific Northwest NATIONAL LABORATORY

PNNL-29531

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May 2020

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U.S. DEPARTMENT OF ENERGY

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Abstract

In residential retrofit applications, ductless mini-split heat pumps (DHP) offer the potential for high-energy savings, depending on the system they are supplementing or replacing. However, of late, there have been a number of field studies indicating these energy savings are not being achieved, due to the interaction with existing HVAC systems. The primary goal of this project is to determine a cost effective (lowest cost for the most energy saved) and persistent (e.g. automated, hard to change, etc.) solution for controlling a ductless heat pump in a home with an existing central or zonal HVAC system. Various control strategies were evaluated at the Pacific Northwest National Laboratory Lab Homes in order to examine their energy savings and thermal comfort potential.

Acknowledgments

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Acronyms and Abbreviations

AC	Air Conditioner
CAC	Central Air Conditioning
CFM	Cubic Feet per Minute
DHP	Ductless Heat Pump
DMS	Ducted Mini-Split
DOE	Department of Energy
eFAF	electric Forced Air Furnace
EIA	Energy Information Administration
LR	Living Room
HVAC	Heating Ventilation and Air-Conditioning
IECC	International Energy Conservation Code
MB	Master Bedroom
Pa	Pascals
PNNL	Pacific Northwest National Laboratory
Wh	Watt-hour

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1.0 Introduction

Energy consumption consistently exceeds domestic production in the U.S. and forces utilities to purchase expensive imports. According to the Department of Energy (DOE) Energy Information Administration (EIA) in the “August 2019 Monthly Energy Review,” 81% of national energy consumption is produced domestically while the remaining 19% is imported [1]. When fuel is imported, it tends to raise the price of electricity for consumers. Additionally, most imports are petroleum, a fossil fuel that contributes to pollution and carbon emissions when burned for energy.

The EIA also reported that the residential sector makes up 22% of total energy use in the U.S. [2] and heating accounts for 15% of energy use in the residential sector (or 3.3% of America’s total energy consumption) [3]. Targeting residential heating to reduce energy consumption can be problematic, because efficiently controlling HVAC systems often requires optimized scheduling which may be unique to the home’s characteristics and occupants. The study to be discussed sought to identify control strategies for Ductless Heat Pumps (DHPs) as a retrofit addition to existing homes that already have central air conditioning (CAC) and an electric forced-air furnace (eFAF).

1.1 Ductless Heat Pumps

1.1.1 Hardware Overview

In a mini-split heat pump system, an outdoor unit (compressor, fan and coil) provides hot or cold refrigerant into a house to one or more various wall- or ceiling-mounted indoor fan units. The indoor units (or heads) contain a fan that blows air over the refrigerant filled heat exchanger, and hot or cold air is distributed throughout the room. Mini-split systems are different from conventional heat pumps in that they are typically smaller, are not connected to the whole-house ductwork, and can have more than one indoor fan coil unit served by a single outdoor condensing unit. In a ductless mini-split system, these heads are mounted on the finished wall surface, and are designed to be as unobtrusive as possible. Typically, one head is used per floor (~1,000 ft^2) if there is an open floor plan, or doors to rooms are typically left open. If the floor plan is not open, or doors are typically left closed, HVAC installers might recommend multiple indoor heads, even on the same floor.

In applications where aesthetics or other challenges restrict the use of the ductless head some manufacturers have developed a ducted mini-split (DMS) option. This places the head in an attic, basement, or dropped ceiling space to conceal the bulky components and allow installers to place the grille in “typical” ducted locations. These systems are also called “short-run ducted mini-split,” “mini-duct,” or “slim-duct” systems. Figure 1 shows different mini-split indoor units.

Figure 1. Various Indoor Units for Mini-Split Heat Pump Systems; a and b are ducted, c and d are ductless [1].

1.1.2 Implementation

DHPs are an emerging HVAC technology that offer retrofit installation options and are relatively energy efficient compared to most existing systems [4]. DHP adoption is increasing in both residential and commercial sectors with the expectation of energy savings of up to 60% [5]. However, the actual energy savings being realized are not meeting the prospective figures. Some people hypothesize that the lack of performance could be due to backup heat sources being over-used from a lack of combined control strategy. To test some possible control strategies, the Pacific Northwest National Laboratory (PNNL) installed DHPs in the PNNL Lab Homes to study how the systems could be run most efficiently.

1.2 PNNL Lab Homes

1.3 Previous Research

A recent modeling study by PNNL shows that DHPs can save up to 77% of heating energy over electric resistance heat (or up to 19% of heating energy over a typical air source heat pump) in typical Northwest homes [4]. At the least, this suggests that retrofitting DHPs into homes that already have either kind of heat source installed will yield savings. Another study quantified the savings and found that installing DHPs in the central zone of 14 homes in the Pacific Northwest saved an average of 4,442 kWh per year [6]. A continuation of this study with 11 of the previous 14 homes showed an average per-site savings of 4,204 kWh in the second-year post-installation [7]. In the Northeast, a study of 152 homes retrofitted with DHPs showed that a lack of proper controls resulted in the ductless mini-split only being used for 51-64% of its total potential operating hours [8]. The study recommended that development of controls that allow ductless systems and primary thermostats to interact and share information would lead to increased DHP savings [8].

Similar experiments which studied DHPs installed in homes with forced air furnaces in the Pacific Northwest resulted in an average savings of 5,500 kWh per year [9]. This study also found that if the furnace could operate on its own control logic, it would overwhelm the operation of the DHP and result in little to no savings. These findings suggest that in order to produce significant savings where DHPs are retrofitted, the original furnace should be controlled so that the DHP acts as the primary heat source. Further studies in the Pacific Northwest by Ecotope show a similar imbalance with baseboard heaters. Ecotope suggests that even though DHPs are capable of providing most of the heat necessary for a home, the overall energy use remains higher than anticipated because the electric resistance heating is still acting as the primary heat source at night. [10]. These findings show that a significant amount of energy can be saved by targeting *the times* when the electric resistance heating comes on, which is largely based on the installation location of the DHP. If the DHP is installed only in the living room then during the night when it is the coldest bedrooms typically require electric resistance heating to maintain temperatures at a comfort level that is not achievable by the DHP alone. One solution would be to add additional indoor heads to bedrooms to provide supplemental heating so that electric resistance heating would not be required at all. However, adding additional DHPs or heads would add to the cost of the installation. PNNL Lab Homes Test Setup

PNNL initiated the Lab Homes project in 2011 to conduct experiments that evaluate the potential energy efficiency impact of new building technologies that are designed to reduce energy use. The lab homes are two identical 1,500 sq. ft., 3BR/2BA, all electric, manufactured homes located (side-by-side) on the PNNL campus in Richland, Washington (IECC Climate Zone 5/EIA Climate Zone 2). Figure 2 shows the floor plan of the Lab Homes with each of the rooms, their orientation, and their dimensions.

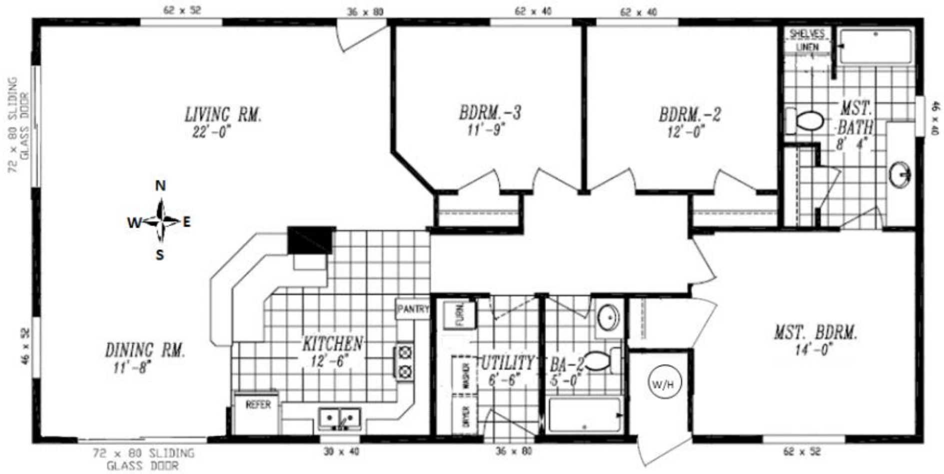

Figure 2. Lab Homes Architecture

PNNL, in partnership with Silicon Valley Power/American Public Power Association, Northwest Energy Efficiency Alliance, and Bonneville Power Administration, launched experiments in the PNNL Lab Homes to test various control schemes that would minimize heating and cooling energy use by optimizing the control of ductless mini-split heat pumps in conjunction with existing equipment.

Typically, the Experimental Home has the energy efficient product installed, while the Baseline Home has the standard efficiency counterpart installed. In this case, both homes had exact same type and size of a DHP installed in the living room (see Figure 3). The variation between the two homes in this study was not the hardware used, but the strategy in which the homes were controlled. The homes were constructed to represent typical existing homes including R-11 wall and floor insulation and R-22 ceiling insulation. Energy use is monitored at all 42 breakers in each home and recorded using a Campbell Scientific CR1000 data logger that collects data at 1-minute intervals. A second CR1000 collects temperature readings at the same interval using 37 thermocouples that are distributed throughout the home, including in every room, the hallway, and on both surfaces of all the windows.

The outdoor unit was installed in the back of the house on a 2’ X 2’ cement slab on stands and was about 1’ away from the house near the water heater closet access door. Figure 3 shows the location of the indoor and outdoor components of the DHP as well as the central system. The indoor head was mounted to the wall between the dining room and living room about 1’ from the ceiling. The indoor and outdoor components connect using insulated refrigerant piping that was attached to the lower exterior walls. A hole was drilled through the wall behind the DHP for the piping to be attached to the indoor unit. An (Ecobee) thermostat for the central system was installed in the hallway on the wall across from the utility room, as marked by T1 in Figure 3. A remote temperature sensor for the thermostat was placed in the master bedroom for some of the experiments. The controller for the DHP was mounted on the wall below and to the side of the air handler unit, which is also the temperature sensor for the DHP, and is indicated by T2.

The DHP was sized to meet about 65% of the whole building load capacity that was calculated using an EnergyPlus model. The cooling design load is about 25,000 Btu/h and the heating design load is about 18,000 Btu/h. The rated capacity of the Mitsubishi MUZ-FH18NA is 17,200 Btu/h for cooling and 20,300 Btu/h for heating at 47 °F.

The central system ducts are located in the crawlspace of these homes. The ducts are not used at all in the DHP system. The duct leakage was tested just before the heating season experiments in September 2018. The Baseline Home had leakage around 230 cfm at 25 Pa and the Experimental Home had duct leakage of about 145 cfm at 25 Pa. The contractor who measured the duct leakage (and also checked for any disconnections or other impactful issues) mentioned that a lot of leakage did seem to be coming from the air handler cabinet itself.

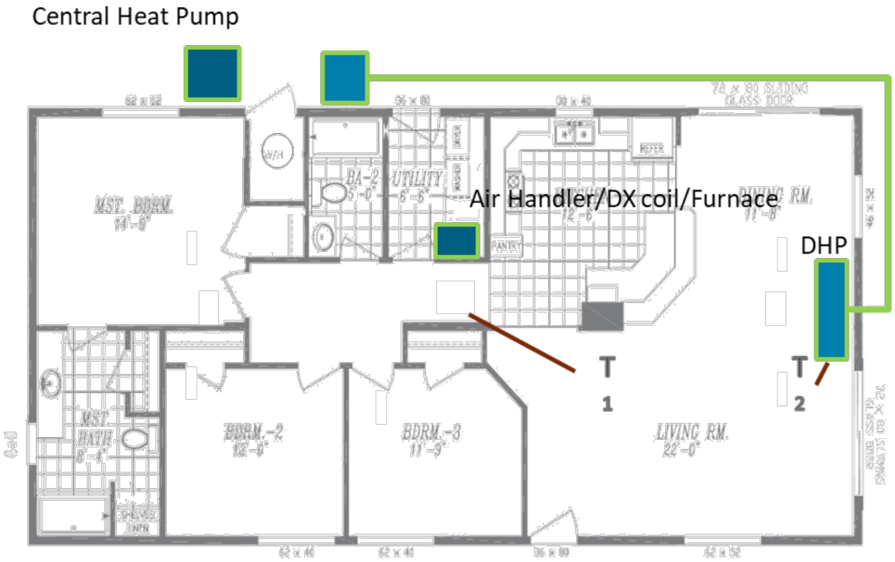

Figure 3. Central Heating/Cooling Lab Homes Setup

The zonal heating and cooling experiments had a slightly different setup. The DHP was kept the same as in the central experiments, but the CAC was no longer used. Window ACs (Air Conditioners) and space heaters were installed in each of the bedrooms, and powered transfer fans were installed above the bedroom doors. This setup is shown in Figure 4 below.

Figure 4. Zonal Heating Lab Homes Setup.

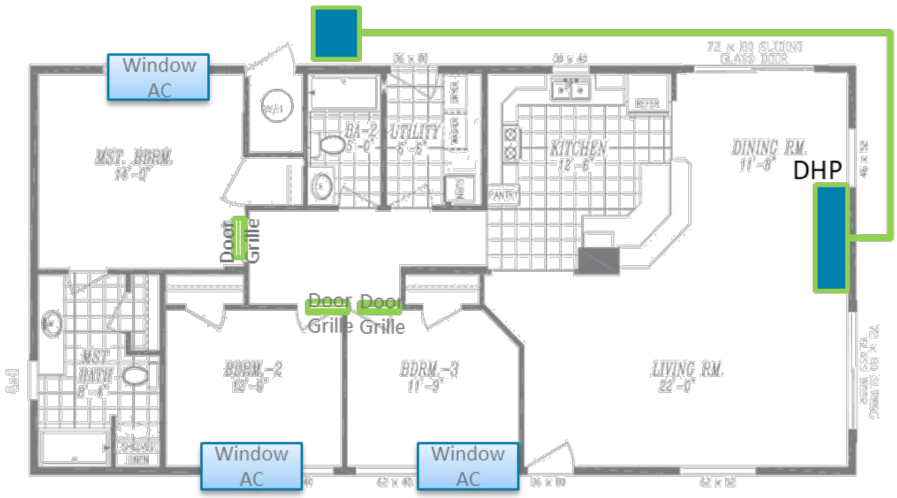

Figure 5. Zonal Cooling Lab Homes Setup.

These experiments were designed to replicate typical installations in people's homes. Each experiment discussed in the subsequent sections has been decided upon by the advisory committee for this work, that are the most promising and cost-effective solutions available at the time this experiment was conducted. The experiments are conducted in a controlled environment so that the results of each experiment are comparable to each other. Results in actual homes would be comparable as well, although, it is unlikely that all the indoor and outdoor conditions would exactly match up.

1.4 Heating Experiment – Central

1.4.1 Heating Experiment - Central: Test Condition

The study took place during Winter and Spring 2019. During the period that the experiments were conducted, February and March, outdoor air temperatures varied between a high of 57 °F, a low of 16 °F, and an average of 33 °F. The Baseline Home was configured the same for all heating experiments: the eFAF was set to 72 °F with the fan set to auto, and the DHP was turned off. All interior doors were open and the fan was set to auto. The setup of the Experimental Home is described in detail in the sections below.

The indoor temperatures reported throughout this paper are measured in each room or location (e.g. hall) with a sensor that is in the middle of that space, hanging about two feet down from the ceiling vertically.

1.4.2 Heating Experiment - Central: Experiment Calibration

This preliminary test determines the difference in performance between the two homes under the same conditions so that the variance could be applied as a correction factor to the results of the subsequent experiments. This is the same process used for all previous Lab Homes experiments where the percent variation during this calibration period is added to the percent savings in the results. This ensures that the embedded variance of the two homes/setup/equipment is factored into the results appropriately compared to a kwh adjustment, which would vary much more than the percent difference depending on the outdoor conditions. The calibration process includes a blower-door test procedure to assess the tightness (infiltration rate) of each home. This is followed by a period of null-testing whereby each home's HVAC system is set and maintained at a constant temperature and the daily HVAC energy use is recorded, analyzed, and compared.

There were three different home calibration experiments: eFAF only, DHP only, and dual use. The eFAF only baseline testing had both homes set up with the eFAF set to 71°F heating and with the DHP set to fan only. The DHP only calibration was completed in both homes with the eFAF turned off and the DHP set to 71 °F heating with the fan set to high. The dual-use baseline had both homes setup with the eFAF set to 72 °F heating with the fan set to auto with the temperature being sensed remotely in the master bedroom. In this case, the DHP was also set to 72 °F heating with the fan on high. All bedroom doors were left open during these experiment calibrations. For the dual-use baseline, the remote temperature sensor was used in the master bedroom to be consistent with the requirements for the model as well as to minimize the interaction of the air flow between the two heating devices.

1.4.3 Heating Experiment - Central: Fan Only

The goal of this control strategy was to determine if energy could be saved with the DHP as the only heat source, while maintaining comfort by using the eFAF fan as a circulator. The Experimental Home was configured with the eFAF set to only use the fan and to have it always on, and the DHP was set to 72 °F with the fan set to auto.

1.4.4 Heating Experiment - Central: Central Offset (a.k.a. Droop Control)

In this strategy, the DHP is forced to act as the primary heat source and the eFAF only turns on if the indoor temperature drops below 5 °F of the setpoint. The Experimental Home was configured with the DHP set to 72 °F and the eFAF set to 67 °F with both fans set to auto. The DHP used the onboard temperature sensor to control the setpoint and the eFAF system used the remote temperature sensor in the master bedroom to try to force the DHP to do most of the work, and to ensure some level of comfort at night in the master bedroom. This experiment was conducted in two ways, first with all the grilles in the house open and second with the grilles (furnace vents) in the living room closed, to try to minimize the amount of double-heating in that space and determine if there was any extra energy savings associated with this strategy.

1.4.5 Heating Experiment - Central: Complex schedule

The complex schedule represents a strategy which uses the quasi-zoning of the house to save energy by following typical occupancy patterns. The advisory committee discussed the setpoints and schedule. They decided to use typical setpoints for occupants during the day in the main living area where the DHP was located, and a 5 °F set-back at night, with one hour overlaps in schedule to ensure comfort during occupant transitions. The schedule was as follows:

- DHP: 72 °F from 6am to 10pm, and 66 °F 10pm to 6am
- eFAF: 55 °F from 7am to 9pm, and 66 °F from 9pm to 7am.

1.5 Heating Experiment – Zonal

1.5.1 Heating Experiment – Zonal: Test Conditions

The study took place in March and April 2019. During the period that the experiments were conducted, outdoor air temperatures varied between a high of 80 °F and a low of 11 °F. The Baseline Home was configured similarly for all zonal heating experiments and used electric space heaters with web-enabled controls to turn on and off like a baseboard heater with a thermostat. The sensor that acted like a thermostat was placed near the door to the bedroom about mid-way up the wall, like a typical zonal thermostat. The web-enabled device had to be triggered to turn on and triggered separately to turn off. So, the desired setpoint was programmed to be the turn-off point, and the turn-on point was made 2 °F below that.

For the calibration experiments, the DHP was set to 72 °F with the fan set to auto, and the bedrooms had space heaters which represented baseboard heaters that turned on from 70 °F to 72 °F in each bedroom (outdoor lows around 20 °F). As the experiments went on and the weather got warmer, it became evident that it would be best to increase the setpoints for the experiments so the heaters were all working hard enough to distinguish a large energy use signal compared to the typical error between the homes. So, starting on April 1st, 2019, and for all of the rest of the zonal heating experiments the Baseline Home had the DHP set to 85 °F on heat mode with the fan set to auto, and the bedrooms had space heaters set to turn on from 83 °F to 85 °F (outdoor lows around 45 °F). In all of these cases, the central system was turned off.

1.5.2 Heating Experiment – Zonal: Experiment Calibration

The test was conducted under two variations of test conditions: all bedroom doors closed and all bedroom doors open in both houses. Bathroom doors always remained open.

1.5.3 Heating Experiment – Zonal: Bedroom Setback

The goal of this scenario was to understand how much energy could be saved if a zoned home could use a large bedroom setback during the day when no one would be in that space, and a smaller setback during the night when occupants were sleeping. The magnitude of the setbacks were determined by the advisory committee for this project. In this case, the Experimental Home had the DHP set to 85 °F with the fan on auto at all hours of the day, with the resistance heaters in the bedrooms set to remain on from 58 °F to 60 °F from 6am - 10pm, and set to remain on from 78 °F to 80 °F from 10pm-6am. In occupied homes, this could be implemented through a schedule or occupancy sensors. In this and all subsequent zonal heating experiments, the doors were closed.

1.5.4 Heating Experiment – Zonal: Transfer Fans

This experiment tested if the use of motorized transfer fans above the doorway to each bedroom would help push enough warm air to the bedrooms to help offset the use of the zonal resistance heat. The Experimental Home had the DHP set to 85 °F at all times, and used transfer fans that were on only during night hours of 10pm - 6am (schedule determined after initial modeling showed that all-day energy use from the transfer fans would not save energy). The resistance heaters in the bedrooms were not used in this case because the most important research question in this case was understanding it was important to understand how comfortable the transfer fans could keep the bedrooms without backup heat.

1.5.5 Heating Experiment – Zonal: Complex Schedule

The goal of the complex schedule experiment was to take advantage of the zoned home to save energy, assuming occupants spend the day in the living room and the night in the bedrooms. In this case, the Experimental Home had the DHP set to 85 °F from 6am - 10pm, and 80 °F from 10pm - 6am. The electric resistance zonal heaters were set to remain on from 58 °F to 60 °F from 6am - 10pm and 78 °F to 80 °F from 10pm - 6am.

1.6 Cooling Experiment – Central

1.6.1 Cooling Experiment – Central: Test Condition

The central cooling experiments ran in the Summer from June 19th, 2019 to August 1st, 2019. June temperatures were in the range of 48 °F to 89 °F with an average of 69 °F, and July stayed between 47 °F and 100 °F with an average of 75 °F. For all experiments in this section, the Baseline Home was set with the central system at 76 °F in cooling mode and with the DHP off. In this case, the combined baseline was not attempted due to the known variability from the heating season experiment. Bedrooms doors remained open during the central cooling experiments to keep the DHP conditioning as much of the bedroom air as possible.

1.6.2 Cooling Experiment – Central: Experiment Calibration

The home calibration for the central cooling experiments ran from July 21st to July 27th, 2019. Due to a need to share the homes with two other summer experiments, the home calibration set temperature was a compromise between the different experiments. In this experiment, both the homes had the central system set to 72 °F cooling in heat pump mode with the fan set to auto, and the DHP was off.

1.6.3 Cooling Experiment – Central: Central Fan Only

For this experiment, the Experimental Home had the central system set to use the fan only as a circulator, with the DHP set to 76 °F cooling in heat pump mode with the fan set to auto. The goal for this experiment was to understand if the central system would work well as an air circulator with the DHP doing all cooling for the home.

1.6.4 Cooling Experiment – Central: Central Offset

For this experiment, the Experimental Home had the central system set to 80 °F cooling with the fan set to auto and using the external temperature sensor located in the master bedroom. The DHP was set to 76 °F cooling mode with the fan set to auto. The goal for this experiment was to force the DHP to be the primary cooling source and for the central system to act as a back-up if the DHP could not keep up.

1.6.5 Cooling Experiment – Central: Complex Schedule

The goal of this experiment was to understand the energy savings potential of focusing on conditioning locations within the home that would likely be occupied during the day versus at night. The DHP was the primary cooling source during the day, and the central system was the primary cooling source at night. For this experiment, the DHP in the Experimental Home was set to 76 °F cooling from 6am - 10pm, and 81 °F cooling from 10pm - 6am, with the fan set to auto. The central system in the experimental home was set to 90 °F cooling from 7am - 9pm and set to 76 °F cooling from 9pm - 7am, with the fan set to auto.

1.7 Cooling Experiment – Zonal

1.7.1 Cooling Experiment – Zonal: Test Condition

The zonal cooling experiments were conducted in the Summer, from August 9th to September 23rd, 2019. The temperatures during this time had lows in the 50's and 60's and highs in the 80's and 90's. In this set of experiments, window AC units were installed in each of the bedrooms, assuming that if a homeowner had either baseboard heat or central heating (but not cooling), window ACs would be the only way they would be cooling the bedrooms. The Baseline Home was configured the same for all of the zonal experiments with both the DHP and the window AC units set to 76 °F cooling and the fans set to auto.

1.7.2 Cooling Experiment – Zonal: Experiment Calibration

The goal of this experiment was to understand the way in which the homes behaved while they were setup to run exactly the same. The difference between the homes would then be assumed to be true throughout the rest of the zonal cooling experiments and be used as an adjustment factor for the subsequent experiments. In this case, both homes had both the DHP and all the window AC units set to a cooling setpoint of 76 °F. The calibration was conducted with both the bedroom doors opened and closed.

1.7.3 Cooling Experiment – Zonal: Bedroom Setback

In this experiment, the goal was to force the DHP to be the primary system and to only use the window AC units if the bedroom temperatures rose 5 °F above the DHP setpoint at night (when occupants were presumed to be in the bedrooms). The setpoint schedule for this experiment was selected by the advisory committee for this project. The Experimental Home had the DHP set to 76 °F with the fan set to auto for all hours of the day and night. The window AC units were scheduled to be off from 7am - 9pm and set to 81 °F cooling from 9pm - 7am. Bedroom doors were opened during this experiment.

1.7.4 Cooling Experiment – Zonal: Transfer Fans

The goal of this experiment was to understand the energy savings potential from using transfer fans installed above the doorways of the bedrooms to push cool air from the DHP into the bedrooms. In this case, the Experimental Home had the DHP set to 76 °F cooling with the fan set to auto all day and night, while the transfer fans were on from 9pm - 7am. In this case, window AC units were set to 81°F from 9pm – 7am. This setting was chosen by the advisory committee. Bedroom doors were closed in both homes for this experiment.

1.7.5 Cooling Experiment – Zonal: Complex Schedule

This experiment was originally conducted in August with the doors open, however the results were inconclusive. Once other experiments were completed, the team revisited this experiment again in September and had to use lower setpoints to compensate for the lower outdoor temperatures. In this experiment, the Baseline Home had the DHP and window ACs set to 65 °F at all times. The Experimental Home had the DHP set to 65 °F cooling from 6am - 10pm, and 70 °F cooling from 10pm - 6am. The window AC units were off from 6am - 10pm, and set to 65 °F cooling from 10pm - 6am. The setpoint schedule was again selected by the advisory committee. Bedroom doors were closed in both homes to provide more conclusive results for this experiment.

1.8 Summary of Test Setup

Table 1 shows a summary of the test setup for each experiment. Where applicable, the notes section describes if a difference in set-up was on purpose or on accident.

Table 1. Summary of Experimental Set-Up

Experiment	Lab A			Lab B			Notes
	DHP Set Point(s)	Central Set Point(s)	Door status	DHP Set Point(s)	Central/ Bedroom Set Point(s)	Door Status	
Central Heating: Fan Only	Off	72 °F	Open	72 °F	Fan only	Open	
Central Heating: Central Offset	Off	72 °F	Open	72 °F	67 °F	Open	
Central Heating: Complex Schedule	Off	72 °F	Open	*	*	Open	
Zonal Heating: Bedroom Setback	85 °F	85 °F	Closed	85 °F	60 °F Day 80 °F Night	Closed	Raised set point due to rising outdoor temperature
Zonal Heating: Transfer Fans	85 °F	85 °F	Closed	85 °F	Off, just transfer fans on at night	Closed	Raised set point due to rising outdoor temperature
Zonal Heating: Complex Schedule	85 °F	85 °F	Closed	*	*	Closed	Raised set point due to rising outdoor temperature
Central Cooling: Fan Only	Off	76 °F	Open	76 °F	Fan only	Open	
Central Cooling: Central Offset	Off	76 °F	Open	76 °F	80 °F	Open	
Central Cooling: Complex Schedule	Off	76 °F	Open	*	*	Open	
Zonal Cooling: Bedroom Setback	76 °F	76 °F	Open	76 °F	Off Day 81 °F Night	Open	Lesson learned from heating to open doors
Zonal Cooling: Transfer Fans	76 °F	76 °F	Closed	76 °F	Off Day 81 °F Night with Transfer fans	Closed	Lesson learned from heating to turn on backup HVAC to prioritize comfort
Zonal Cooling: Complex Schedule	65 °F	65 °F	Closed	*	*	Closed	Lowered set points due to decreasing outdoor temperatures

*See Table 2

Table 2. Complex Schedule for Each Experiment

	Central Heating	Zonal Heating	Central Cooling	Zonal Cooling
DHP Conditioning Main Living Area				
Occupied (7am – 9pm)	72 °F	85 °F	76 °F	65 °F
Unoccupied (9pm – 7am)	66 °F	80 °F	81 °F	70 °F
Central System/Zonal Electric or Window AC Conditioning the Bedrooms				
Occupied (9pm - 7am	66 °F	80 °F	76 °F	65 °F
Unoccupied (7am - 9pm	55 °F	60 °F	90 °F	Off

2.0 Results

2.1 Heating Experiment – Central

2.1.1 Heating Experiment – Central: Experiment Calibration

Research Question: What is the baseline performance of central heating equipment in both the baseline and experimental homes?

The eFAF only baseline testing occurred December 20th, 2018 through January 4th, 2019, and both homes were operated with the eFAF set to 71 °F. Across the eFAF baseline data set, the average HVAC difference between the two homes was 1,782 Wh/day or 2.4%, with the Baseline Home using more energy.

The DHP only baseline testing occurred January 19th to 21st, 2019, and both homes were operated with the eFAF turned off and the DHP set to 71 °F heating and the fan set to high. Across the DHP baseline data set, the average HVAC difference between the two homes was 1,568 Wh/day or 6.1%, with the Baseline Home using more energy.

The results from the blower door calibration test reported a 4.5% difference in the pressure profile between the homes. At a blower door setting of 50 Pascals, the Baseline Home registered approximately 835 CFM while the Experimental Home had registered 798 CFM. This is a 4.5% difference in the air leakage between the Baseline Home and the Experimental Home.

The original plan made with the advisory committee included using the dual-use baseline throughout the experimental period. The goal of this baseline was to represent what would happen if a homeowner set their older central system and their new DHP to the same setpoint. This experiment occurred February 1st through February 4th, 2019.

The findings were curious because despite using the same temperature setpoints (on both the FAF and DHP systems), the home's daily HVAC energy use varied considerably– sometimes by more than 40%. This result encouraged a closer look at the data, now at 1-minute intervals, to see how each system was responding to a call for heat. The finding was the timing of a thermostat's call for heat determined which system was activated – as expected. In some cases, the less efficient eFAF cycled on to satisfy the call for heat, in other cases the more efficient DHP cycled on to satisfy the call. While the runtime of each system showed no rational pattern and appeared somewhat random, clearly there are technical reasons why one system may receive the call for heat prior to another. These may include:

- Thermostat accuracy/sensitivity
- Mounting location/position including height, distance from wall, and/or attachment method
- Environmental conditions such as differences infiltration rates or locations.

The upshot of this calibration effort led to the necessity of focusing on only one system for calibration at a time. Furthermore, this exercise highlighted the reality experienced in other DHP studies using multiple heating systems – there may be great differences in theoretical (or modeled) energy savings and those achieved (or metered) in real homes. Due to the unpredictability of this method, a decision was made to use the eFAF only as the baseline and adjustment factor (of 2% for the rest of the central heating experiments).

2.1.2 Heating Experiment – Central: Fan Only

Research Question: Would using the DHP for heating and using the central fan for circulation would be more energy efficient than using the eFAF system by itself?

On a typical day for the period that the experiment was conducted, the Baseline Home indoor temperature readings mostly stayed higher than that of the Experimental Home. This suggests that the homes were able to maintain more comfortable temperatures when using the eFAF system by itself rather than replacing the primary heat source with the DHP. Most notable is the difference between the master bedrooms in which the Baseline Home's bedroom stayed above 70 °F the entire day while the Experimental Home's bedroom dropped below 70 °F for about 10 hours, with a low temperature of 67 °F. A summary of the experimental energy use is shown in Table 3 below.

Table 3. Heating Experiment – Central: Fan Only Summary

	Baseline Home (Wh)	Experimental Home (Wh)	Savings (%)	Adjusted Savings (%)
3/16/2019	24,113	35,692	29%	
3/17/2019	24,662	33,086	22%	
Range			22% – 29%	20% - 27%

2.1.3 Heating Experiment – Central Offset (a.k.a. Droop Control)

Research Question: What is the level of energy and comfort performance if the DHP is forced to provide most conditioned air?

This experiment was conducted from February 23rd to February 24th, 2019 with the grilles in the living room closed, and from March 1st to March 2nd, 2019 with the grilles open. The outdoor temperatures for the closed-grille experiments were between 16 °F and 37 °F. The temperatures in the living room were closer to the setpoint in the experimental home. The research team hypothesizes that this is due to the proximity of the DHP thermostat.. For the grilles open experiments, the master bedroom temperature hovered around the central system set point (except when solar gains pushed the temperature above the set point), and other locations were warmer due to the higher DHP setpoint. For the grilles closed experiment, the temperatures in the master bedroom were a few degrees less than in the living room, however, they seemed to be higher than the set point.

The outdoor temperature for the grilles-open experiment ranged from the low-20's to the low-30's. The indoor temperatures were less favorable than the experiment with the grilles closed. With the grilles open, the central system ended up blowing air almost directly onto the DHP thermostat and misleading the DHP sensor that the setpoint was met. The DHP thermostat sensor is at the intake of the DHP, just more than halfway up the west wall in the homes. The living room temperature sensor is located about 2 ft. from the ceiling in the middle of the room, so the temperatures there would likely show higher than the DHP was experiencing.

Overall, both strategies appear to be good options from a comfort standpoint, with the grilles-closed option saving slightly more energy. The summary of the experimental energy use is shown in Table 4 below.

Table 4. Heating Experiment – Central: Central Offset Summary

	Baseline Home (Wh)	Experimental Home (Wh)	Savings (%)	Adjusted Savings (%)
2/23/2019	78,886	43,647	45%	
2/24/2019	105,051	66,345	37%	
Range (Grilles Closed)			37% - 45%	35% - 43%
3/02/2019	84,157	59,084	30%	
3/03/2019	98,251	61,959	37%	
Range (Grilles Open)			30% - 37%	28% - 35%

2.1.4 Heating Experiment – Central: Complex Schedules

Research Question: Can precise scheduling during the day and night improve DHP energy and comfort performance?

On February 26th, 2019, the temperatures in the Baseline Home were higher than the Experimental Home in both the morning and night. In midday, the temperatures in all rooms in the Experimental Home exceeded those of the Baseline Home. The temperatures throughout the day were more consistent in the Baseline Home which maintained indoor temperatures closer to the setpoint.

The temperatures for both homes correlated with their energy expenditures. The Baseline Home had higher energy use than the Experimental Home in both the morning and night. In midday the Baseline Home kept using power while the Experimental Home did not. Overall, the Baseline Home maintained more consistent temperatures and generally remained closer to the 72 °F setpoint. In fact, for both the morning and night, the Baseline Home master bedroom and living room were very close to 72 °F with only a few degrees variance. The summary of the experimental energy use is shown below in Table 5.

Table 5. Heating Experiment – Central: Complex Schedules Summary

	Baseline Home (Wh)	Experimental Home (Wh)	Savings (%)	Adjusted Savings (%)
2/26/2019	93,689	60,883	35%	
2/27/2019	105,069	65,408	38%	
2/28/2019	78,771	53,686	32%	
Range			32% - 38%	30% - 36%

2.1.5 Heating Experiment – Central: Summary of Results

Table 6. Heating Experiment – Central: Summary

Experiment	Adjusted Savings	Thermal Comfort Base. Home Number of Hours 5 °F or More Off Set Point- (LR/MB)	Thermal Comfort Exp. Home Number of Hours 5 °F or More Off Set Point (LR/MB)
Heating Experiment – Central: Central Fan Only	20% - 27%	22/8	15/6
Heating Experiment – Central: Central Offset (Grilles Closed)	35% - 43%	4/3	7/3
Heating Experiment – Central: Central Offset (Grilles Open)	28% - 35%	4/0	7/8
Heating Experiment – Central: Complex Schedule	30% - 36%	5/0	16/0

The summary table shows that the central offset (grilles closed) provides the best combination of energy savings and thermal comfort for these central heating control strategies.

2.2 Heating Experiment – Zonal

2.2.1 Heating Experiment – Zonal: Experiment Calibration

Research Question: What is the baseline performance of zonal heating equipment in both the baseline and experimental homes?

For the calibration experiment, the indoor temperatures for both homes were very similar, including during the day when the solar gains in both homes brought the indoor temperatures above the setpoint. The desired comfort level was met during this experiment with the main living area staying at least 72 °F and the master bedrooms remained at least 70 °F. Energy consumption for both homes also had a similar overall shape .An interesting observation about this particular set of tests is that the DHP is doing all of the work in the living room/kitchen area in both homes. The living room and hall sensors appear to be located near the fan flow for the DHP because although they kept a consistent temperature in both homes, they are also both reading about 4 °F above the DHP setpoint. This offset appears to be the case for all subsequent tests in this section. The summary of the experimental energy use is shown below in Table 7. For the zonal experiment, the houses were able to maintain reasonably consistent energy differences throughout the calibration period. Therefore, it was decided to continue to use this dual-use baseline for the duration of the zonal heating experiments.

Table 7. Heating Experiment - Zonal: Experiment Calibration

	Baseline Home (Wh)	Experimental Home (Wh)	Savings (%)
3/9/2019 (Doors Open)	52,116	47,563	8.7%
3/10/2019 (Doors Open)	44,683	45,479	-1.8%
3/11/2019 (Doors Open)	56,414	50,867	9.8%
Range			-1.8% - 9.8%
3/13/2019 (Doors Closed)	38,407	35,724	7%
3/14/2019 (Doors Closed)	39,246	39,069	0.5%
Range			0.5% - 7%

The results of these experiments provided the baseline correction factor for the remainder of the zonal heating experiments. In this case, the correction factor used was 3.7% since the bedroom doors were closed for the remainder of this experimental set. The adjusted savings column in the sections below show the results with this adjustment made.

The difference between the baseline results with the doors open and with the doors closed shows how results might differ under those two scenarios. It appears that with the doors open, the air mixing between the two heating sources makes the overall energy use more unpredictable, again introducing more variation in the results.

2.2.2 Heating Experiment – Zonal: Bedroom Setback

The results from this experiment showed that the living room and hallway temperatures were similar in both homes. The master bedroom temperatures were both maintained at setpoint throughout the night for these experiments (with outdoor temperatures around 55 °F). During the 6am - 10pm bedroom setback to 60 °F, the wall heaters remained off because the master bedroom temperatures never fell below 76 °F. The summary of the energy use and savings is shown below in Table 8.

Table 8. Heating Experiment – Zonal: Bedroom Setback Summary

	Baseline Home (Wh)	Experimental Home (Wh)	Savings (%)	Adjusted Savings (%)
4/20/2019	31,729	21,569	32%	
4/21/2019	32,688	21,567	34%	
Range			32% - 34%	28% - 30%

2.2.3 Heating Experiment – Zonal: Transfer Fans

Outdoor temperatures for this experiment had nighttime lows around 52 °F and daytime highs around 72 °F. The Baseline Home had consistent indoor temperatures throughout the living room, hallway and master bedroom. The Experimental Home had living room and hall temperatures that were consistently meeting the setpoint, with master bedroom temperatures an average of two degrees Fahrenheit below the main living areas. The summary of the experimental energy use is shown below in Table 9

Table 9. Heating Experiment – Zonal: Transfer Fans Summary

	Baseline Home (Wh)	Experimental Home (Wh)	Savings (%)	AdjustedSavings (%)
4/2/2019	39,300	38,715	1.5[1]%	
4/3/2019	38,213	30,761	20%	
4/4/2019	41,761	31,640	24%	
Range			20% - 24%	-16% - 20%

2.2.4 Heating Experiment – Zonal: Complex Schedule

The outdoor temperature lows during this time were in the mid-50's, while the highs were in the high 70's. In this case, the temperatures in the Baseline Home were reflecting the consistent schedule, other than when the solar gains were at their peak. In the Experimental Home, it appears that the DHP was on the entire night at a low output, trying to keep up with the setpoint of 80 °F. During the day, the master bedroom temperature floated with the outdoor temperature, although it never went below about 76 °F (even with the doors closed). The summary of the experimental energy use is shown below in Table 10.

Table 10. Heating Experiment – Zonal: Complex Schedule Summary

	Baseline Home (Wh)	Experimental Home (Wh)	Savings (%)	AdjustedSavings (%)
4/23/2019	26,815	16,310	39%	
4/24/2019	30,412	20,992	31%	
Range			31% - 39%	27% - 35%

2.2.5 Heating Experiment – Zonal: Summary of Results

Table 11. Heating Experiment – Zonal: Summary

Experiment	Adjusted Savings	Thermal Comfort Base. Home Number of Hours 5 °F or More Off Set Point- (LR/MB)	Thermal Comfort Exp. Home Number of Hours 5 °F or More Off Set Point- (LR/MB)
Heating Experiment – Zonal: Zonal Bedroom Setback	28% - 30%	4/4	0/5
Heating Experiment – Zonal: Zonal Transfer Fans	16% - 20%	14/0	0/16
Heating Experiment – Zonal: Complex Schedule	27% - 35%	5/2	0/4

The summary table shows that the bedroom setback or the complex schedule both provide more energy savings and comfort compared to the transfer fans. Either of these would be a great option for a zonal heating control strategy.

[1] Anomaly and not included in range

2.3 Cooling Experiment – Central

2.3.1 Cooling Experiment – Central: Experiment Calibration

The outdoor temperatures during the central cooling calibration experiment had lows between the mid-50's and mid-60's. The highs were between 80 °F and 100 °F. For this experiment, the data was shared with another experiment, so the setpoint was set to 72 °F. There was one day (July 24th, 2019) that there was a data error and no data was recorded. On a representative day during this experiment, the indoor temperatures were similar to each other in both homes. The only exception to this was in the afternoon when the master bedroom temperature was a little colder than the rest of the house in the experimental home. Since this was the hottest part of the day, this result could be due to the central system working extra hard at that time, and perhaps the duct run to the master bedroom was not as leaky as to the living room and hallway. Like the temperatures, the energy use in both homes had a nearly identical profile shape each day. The summary of the experimental energy use is shown below in Table 12.

Table 12. Cooling Experiment – Central: Experiment Calibration Summary

	Baseline Home (Wh)	Experimental Home (Wh)	Savings (%)
7/21/2019	23,181	24,464	-6%
7/22/1919	25,147	28,871	-15%
7/23/2019	28,298	31,183	-10 %
7/24/2019	Data error, data not used		
7/25/2019	18,409	21,692	-18%
7/26/2019	26,044	29,605	-14%
7/27/2019	22,503	24,846	-10 %
Range			-18% - -6%

The central cooling adjustment factor for the duration of the central cooling experiments was set to be -12%, with the Experimental Home using more energy.

2.3.2 Cooling Experiment – Central: Central Fan Only

During this experiment, the outdoor temperatures had lows between the low 50's and the low 60's, and highs in the low to mid-80's. Therefore, the most helpful temperature information for this experiment would be collected during the day. Similar to the heating experiments, when the DHP was on the indoor temperature sensor read temperatures mostly below the setpoint, likely due to the sensor being located near the air flow stream from the DHP. During the day, when the outdoor temperatures were high, the DHP was able to maintain living room temperatures close to the setpoint. However, the hall and the master bedroom temperatures were relying on the central system to circulate the cold air, and the result was that temperatures in those spaces were as much as 5 °F above the setpoint. The summary of the experimental energy use is shown below in Table 13.

Table 13. Cooling Experiment – Central: Central Fan Only Summary

	Baseline Home (Wh)	Experimental Home (Wh)	Savings (%)	Adjusted Savings (%)
6/22/2019	11	11,877	22,304	-88%
3/2019	6,843	20,192	-195%	
6/24/2019	9,949	21,413	-115%	
6/25/2019	10,405	22,351	-115%	
6/26/2019	8,046	20,240	-152%	
Range			-195% - -88%	-183 - -76%

This is not a recommended approach for homes with previously existing central cooling with relatively leaky ducts. Even the relatively inefficient (SEER 13) central heat pump is more efficient than running the fan all day with the DHP in weather like this. Unfortunately, we do not have data for much hotter weather.

2.3.3 Cooling Experiment – Central: Central Offset (a.k.a. Droop Control)

For this experiment, the outdoor lows were around 60 °F and the highs were in the low 90's. The living room, hall and master bedroom in the Baseline Home, tracked closely to each other and the setpoint. The temperatures in the Experimental Home showed the coolest temperatures in the living room, close to the setpoint, but floating up to 80 °F during the mid-afternoon heat (which indicates that the DHP was not able to keep up with the load). The master bedroom at one point did reach temperatures above the 80 °F setpoint of the central system, which kicked on the central system.

The Baseline Home used significantly more energy than the Experimental Home. The summary of the experimental energy use is shown below in Table 14.

Table 14. Cooling Experiment – Central: Central Offset Summary

	Baseline Home (Wh)	Experimental Home (Wh)	Savings (%)	Adjusted Savings (%)
7/30/2019	18,654	12,828	31%	
7/31/2019	20,538	13,422	35%	
8/1/2019	22,241	15,325	31%	
Range			31% - 35%	43-47%

2.3.4 Cooling Experiment – Central: Complex Schedule

For this experiment, the outdoor temperature had lows around 60 and highs in the low 90's. As expected, both homes were nearly identical when the outdoor temperatures were below the setpoint during the post-midnight hours until around 9 am. In the Baseline Home, the central system was able to keep the master bedroom cool for the rest of the day at temperatures near the setpoint. Due to the high daytime setpoint in the master bedroom, that temperature floated with the outdoor temperatures, although still remained around 84 °F while the outdoor temperature was 90 °F. At that same point in the day, when the outdoor temperatures were the highest, the living room temperatures exceeded setpoint and floated up to as high as 79 °F. So, it appears that for a short period of time the DHP was not able to keep up with the demand, although it was able to keep up for the majority of the experiment, which is reflected in the energy savings summary table below in Table 15.

Table 15. Cooling Experiment – Central: Complex Schedule Summary

	Baseline Home (Wh)	Experimental Home (Wh)	Savings (%)	Adjusted Savings (%)
7/10/2019	15,573	10,992	29%	
7/11/2019	20,164	14,035	30%	
7/12/2019	18,421	12,942	30%	
7/13/2019	19,752	14,652	26%	
7/14/2019	17,156	12,551	27%	
Range			26% - 30%	38-42%

2.3.5 Cooling Experiment – Central: Summary of Results

Table 16. Cooling Experiment – Central: Summary

		Thermal Comfort Base. Home	Thermal Comfort Exp. Home
ExpExperiment	Adjusted Savings (%)	Number of Hours 5 °F or More Off Set Point- (LR/MB)	Number of Hours 5 °F or More Off Set Point- (LR/MB)
Cooling Experiment – Central: Central Fan Only	-183 to -76%	33/23	7/13
Cooling Experiment – Central: Central Offset	43-47%	4/3	0/30
Cooling Experiment – Central: Complex Schedule	38-42%	5/1	4/0

The summary table shows that the central fan only experiment had some significant temperature deviations, including from the Baseline Home. In looking closely at the data, it is not clear why the temperature deviated so much in that experiment, but it may be a good indicator of why the energy use was more in the Experimental Home.

For central cooling, the complex schedule had the best combination of energy savings and thermal comfort.

2.4 Cooling Experiment – Zonal

2.4.1 Cooling Experiment – Zonal: Experiment Calibration

For this experiment, outdoor lows were near 60 and highs were between the mid-80’s and low-90’s. Indoor temperature profiles were very similar for both homes. With doors open, all rooms were maintaining temperatures close to the setpoint of 76 °F. For the experiment with the doors closed, the master bedroom temperatures were well maintained, while the living room and hallway temperatures floated a few degrees above the setpoint. The summary of the energy use is shown below in Table 17.

Table 17. Cooling Experiment – Zonal: Experiment Calibration, Doors Open Summary

	Baseline Home (Wh)	Experimental Home (Wh)	Savings (%)
8/10/2019	17,753	18,614	-5%
8/11/2019	14,451	15,500	-7%
8/12/2019	17,209	18,301	-6%
Range (Doors Open)			-5% - -7%
8/14/2019	20,573	19,566	5%
8/15/2019	21,554	20,061	7%
Range (Doors Closed)			5% - 7%

The adjustment factor used for the subsequent experiments was either -6% or 6%, depending on if the doors were open or closed.

2.4.2 Cooling Experiment – Zonal: Bedroom Setback

During this experiment, the outdoor temperatures had lows in the mid-60's, and highs in the high-80's and low-90's. Indoor temperatures were primarily a result of the work the DHP was doing. On a typical day during this experiment when the outdoor temperature high was about 93 °F, the temperatures throughout the home tracked the overall shape of the outdoor temperature very closely. The living room temperatures were maintained around the setpoint of 76 °F through the mid-afternoon, at which point the loads in the home were too great for the DHP to keep up. At that point, temperatures in the living room were floating to about 80 °F, while temperatures in the master bedroom were floating to about 84 °F (before the window AC's came on at 9pm). Around the time that the window AC units were allowed to turn on, the temperature would float back down to 81 °F, and the window AC units would not have to come on after all. The summary of the energy use is shown below in Table 18.

Table 18. Cooling Experiment – Zonal: Bedroom Setback Summary

Dates	Baseline Home (Wh)	Experimental Home (Wh)	Savings (%)	Adjusted Savings (%)
8/17/2019	14,378	11,085	23%	
8/18/2019	17,063	12,449	27%	
8/19/2019	18,237	13,358	27%	
Range			23% - 27%	29% - 33%

2.4.3 Cooling Experiment – Zonal: Transfer Fans

The outdoor temperatures had lows between 50 °F and 70 °F and highs between 86 °F and 91 °F. Overall, the Baseline Home tracked very closely to the 76 °F setpoint in all locations of the home. The indoor temperatures in the Experimental Home were close to the setpoint of 76 °F in the living room and a little higher in the hallway. However, temperatures reached as high as 87 °F in the master bedroom in the mid-afternoon, which was not acceptable. The summary of the energy use is shown below in Table 19.

Table 19. Cooling Experiment – Zonal: Transfer Fans Summary

	Baseline Home (Wh)	Experimental Home (Wh)	Savings (%)	Adjusted Savings (%)
8/21/2019	16,367	10,964	33%	
8/22/2019	18,157	12,702	30%	
8/23/2019	17,287	11,765	32%	
8/24/2019	19,049	13,217	31%	
8/25/2019	17,754	12,724	28%	
8/26/2019	17,595	12,591	28%	
Range			28% - 33%	22% - 27%

2.4.4 Cooling Experiment – Zonal: Complex Schedule

Outdoor temperatures during this experiment had lows between high 40's and high 50's. High temperatures were in the mid- to high-70's. The summary of the energy use is shown below in Table 20.

Table 20. Cooling Experiment – Zonal: Complex Schedule Summary

	Baseline Home (Wh)	Experimental Home (Wh)	Savings (%)	Adjusted Savings (%)
9/21/2019	21,129	13,292	37%	
9/22/2019	18,863	13,042	31%	
9/23/2019	17,580	12,465	29%	
Range			29% - 37%	23% - 31%

2.4.5 Cooling Experiment – Zonal: Summary of Results

Table 21. Cooling Experiment – Zonal: Summary

		Thermal Comfort Base. Home	Thermal Comfort Exp. Home
Experiment	Adjusted Savings	Number of Hours 5 °F or More Off Set Point- (LR/MB)	Number of Hours 5 °F or More Off Set Point- (LR/MB)
Cooling Experiment – Zonal: Bedroom Setback	29% - 33%	0/3	0/0
Cooling Experiment – Zonal: Transfer Fans	22% - 27%	8/1	4/10
Cooling Experiment – Zonal: Complex Schedule	23% - 31%	3/0	3/0

The summary table shows that both the bedroom setback and the complex schedule provide more energy savings and comfort than the transfer fans. Both of those would be good options for a control strategy. With these zonal experiments using the dual (uncontrolled) baseline as the reference point, the energy savings for just using the controls available to these zonal conditioning systems appears to be significant.

3.0 Conclusions

Energy efficiency is a key component to reducing energy use through efficient product and control strategies. DHPs are an example of one product that are highly energy efficient compared to other ways equipment can heat and cool a house. In this study, DHPs were evaluated under various conditions at the PNNL Lab Homes to estimate the energy savings of certain control strategies for both heating and cooling.

The recommended control strategies for each scenario are shown in Table 22.

Table 22. Recommended Control Strategies for Given Scenarios

Experiment	Recommended Control Strategy
Central Heating	Offset (Grilles Closed)
Zonal Heating	Bedroom Setback or Complex Schedule
Central Cooling	Complex Schedule
Zonal Cooling	Bedroom Setback or Complex Schedule

While this study is helpful in guiding the industry towards next steps, it is not conclusive about the exact amount of energy that could be saved through these strategies, due to the low number of data points for each experiment. A modeling report titled *Energy Savings Quantification of Ductless Heat Pumps (DHP) in Existing Homes* builds on these results by using the results from the lab home experiments to extrapolate savings estimates in multiple prototype buildings, in many climate zones, for an entire year. Those results are more comprehensive for a utility who is looking to understand more about the total energy savings potential for the various strategies tested here.

One important finding was the importance of the timing of a thermostat's call for heat, which determined which system was activated first and therefore dominant for the rest of that day. In some cases, the less efficient EFAF cycled on to satisfy the call for heat first, in other cases the more efficient DHP cycled on to satisfy the call first. While the runtime of each system showed no rational pattern and appeared somewhat random, clearly there are technical reasons why one system may receive the call for heat prior to another. These may include:

- Thermostat accuracy/sensitivity
- Mounting location/position including height, distance from wall, and/or attachment method
- Environmental conditions such as differences infiltration rates or locations.

If a utility would like to use the less expensive third-party controllers to control the two systems together, there are some helpful programming tips in Appendix B of this report. Some general lessons learned about the challenges of using third party controllers include:

- IR controllers only communicate one way (no feedback indicating the state of the DHP). This means that coordinating settings between two controllers is problematic. One controller will not show the homeowner or programmer changes made on another controller
- The Ecobee "hold" command defaults to hold temps and fan settings for 24 hours. Ideally, settings should be changed in "Comfort Settings" and those settings must be implemented in the schedule for the change to be permanent.

- The temporary “hold” or changed command can be viewed as a benefit for the Ecobee. If a homeowner changes a setting, by default, it will revert to the original schedule at the next schedule change.
- In the Lab Homes and potentially in other homes with multiple heat sources, the Ecobee “Heat” setting uses the heat pump and “Aux” setting uses the resistive elements.
- The IFTTT app does not provide the ability to have nested if statements. This means that two smart plugs were needed to implement complex scheduling with temperature varying based on schedule.
- The IFTTT action only occurred when temperature passed through a set point. For example, if the temperature was already lower than the “turn on” set point, the smart outlet would stay off. This was problematic when using the timer function on the plugs and it needed to be jump started manually to get it within the range that we had commands programmed for.

The next step for this project is to synthesize this information in a format that is more digestible for utilities and the general public.

4.0 References

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Appendix A – Daily Profiles for Indoor Temperatures and Energy Consumption

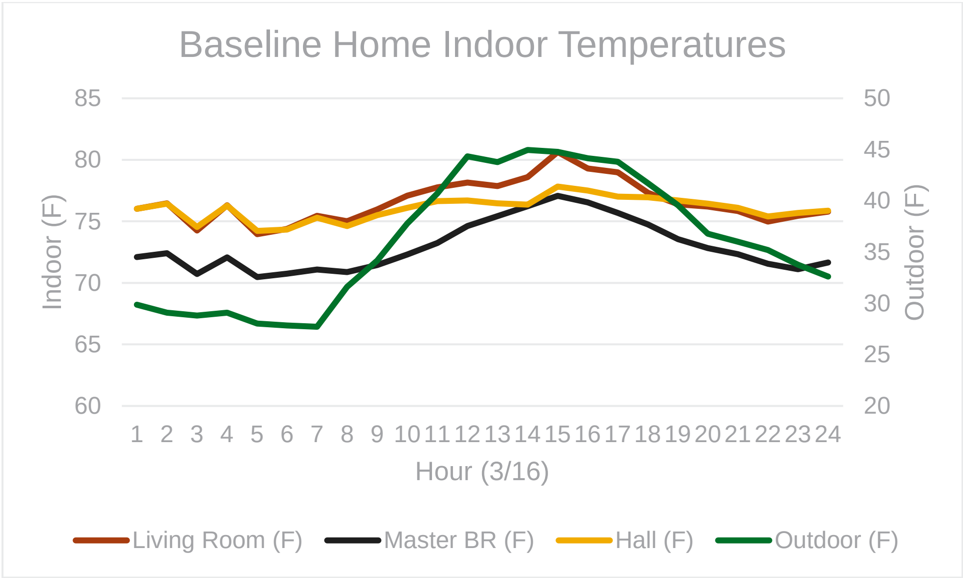

Figure A.1. Heating Experiment – Central: eFAF Only Baseline Home Indoor Temperatures

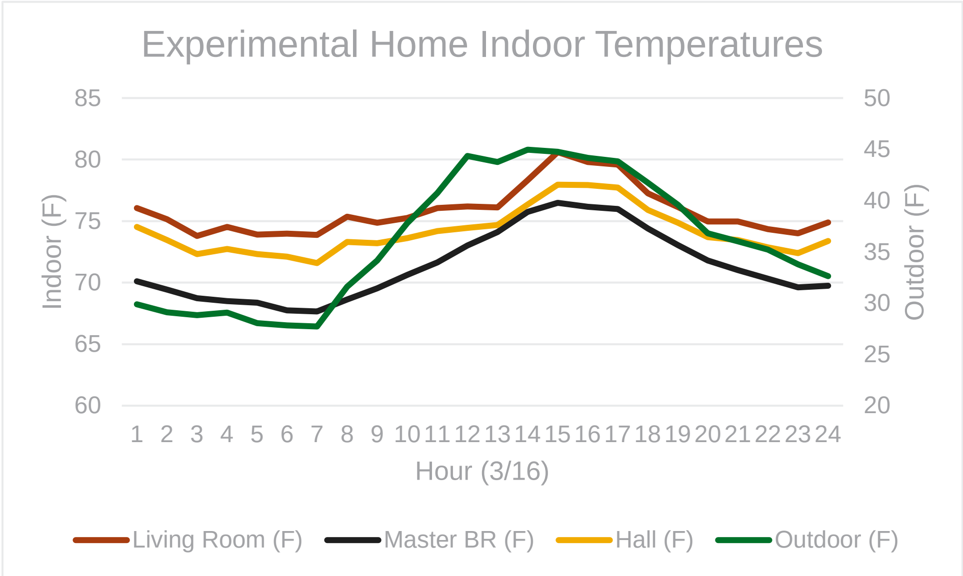

Figure A.2. Heating Experiment – Central: eFAF Only Experimental Home Indoor Temperatures

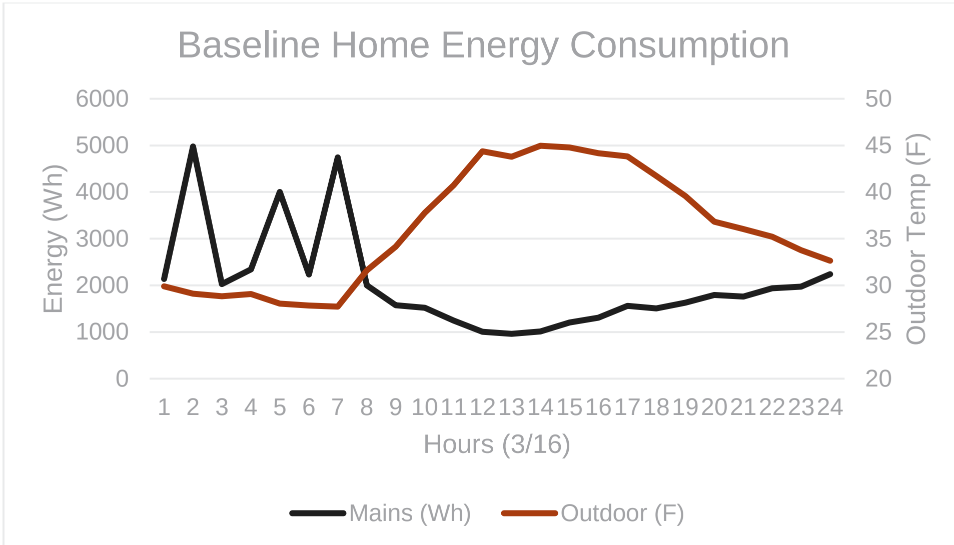

Figure A.3. Heating Experiment – Central: eFAF Only Baseline Home Energy Consumption

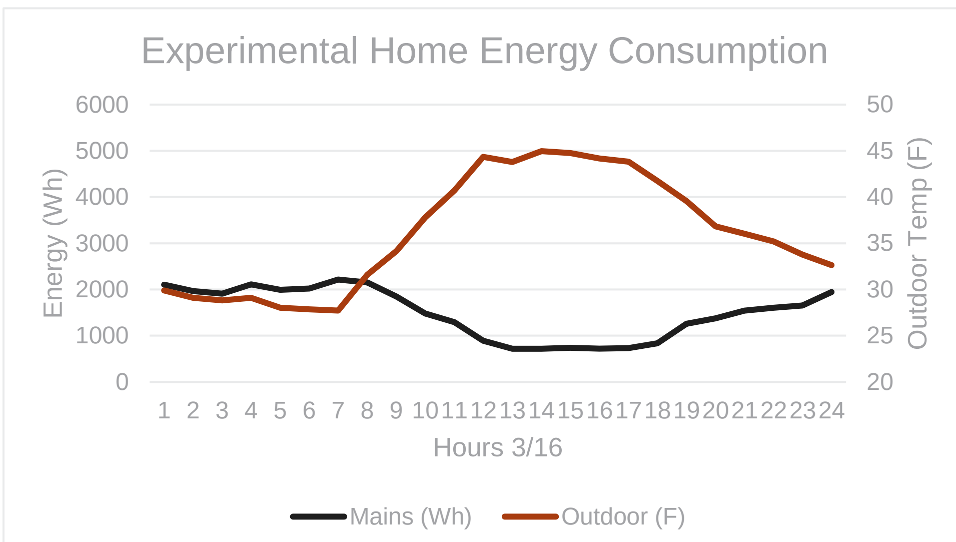

Figure A.4. Heating Experiment – Central: eFAF Only Experimental Home Energy Consumption

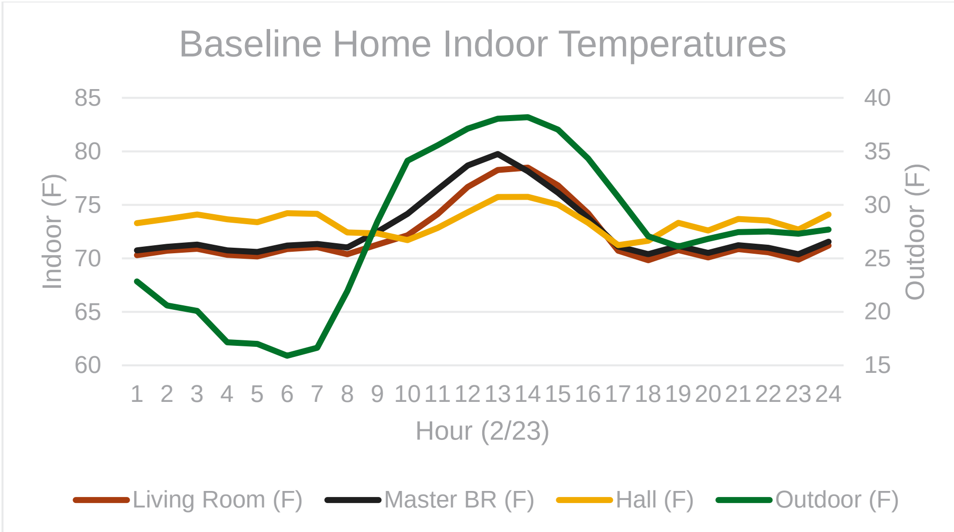

Figure A.5. Heating Experiment – Central: eFAF Offset Baseline Home Indoor Temperatures

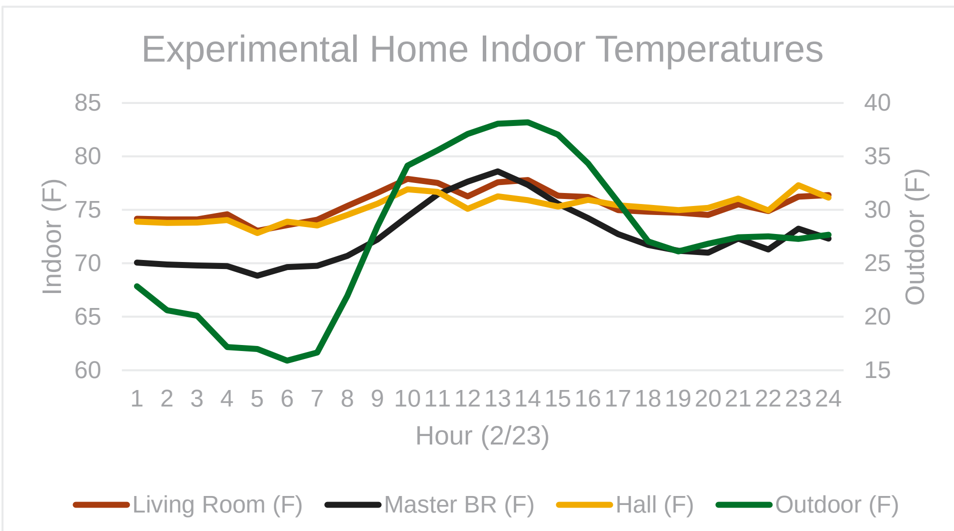

Figure A.6. Heating Experiment – Central: eFAF Offset Experimental Home Indoor Temperatures

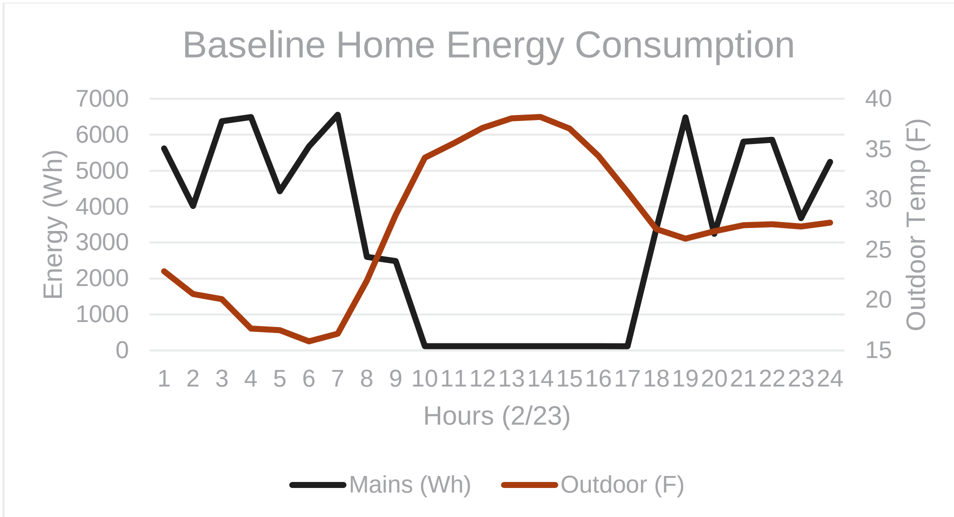

Figure A.7. Heating Experiment – Central: eFAF Offset Baseline Home Energy Consumption

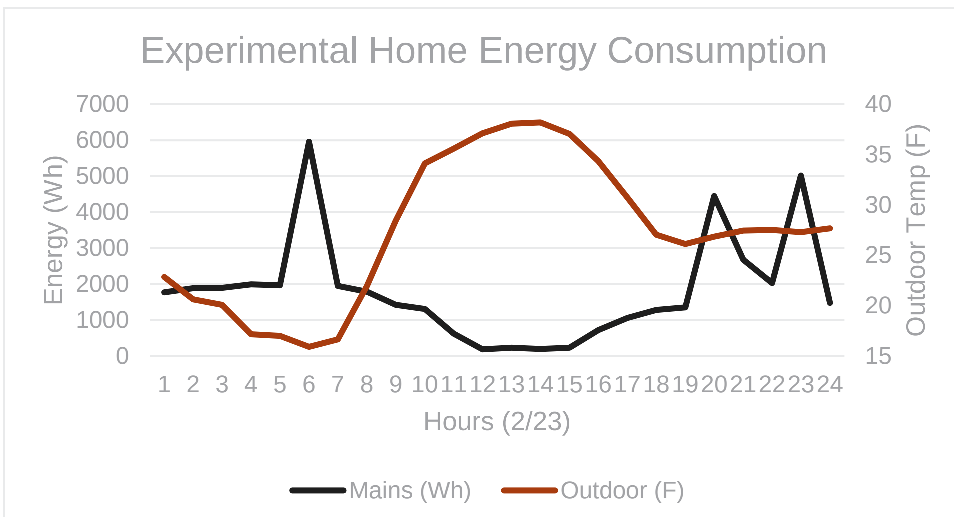

Figure A.8. Heating Experiment – Central: eFAF Offset Experimental Home Energy Consumption

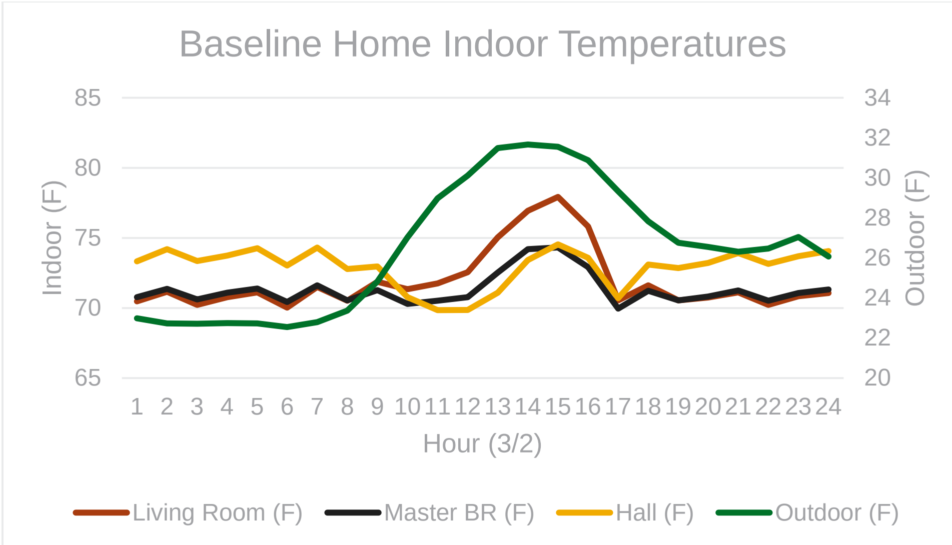

Figure A.9. Heating Experiment – Central: eFAF Offset (Grilles Open) Baseline Home Indoor Temperatures

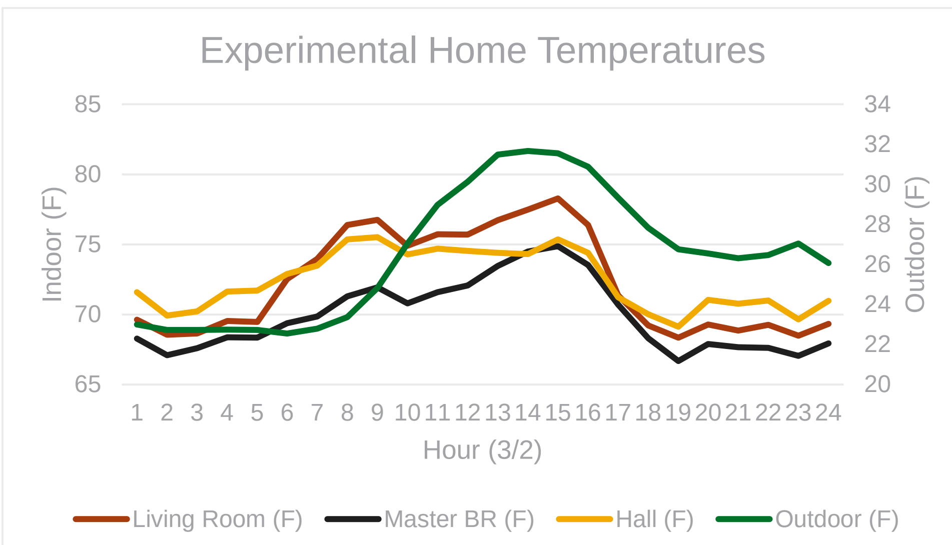

Figure A.10. Heating Experiment – Central: eFAF Offset (Grilles Open) Experimental Home Indoor Temperatures

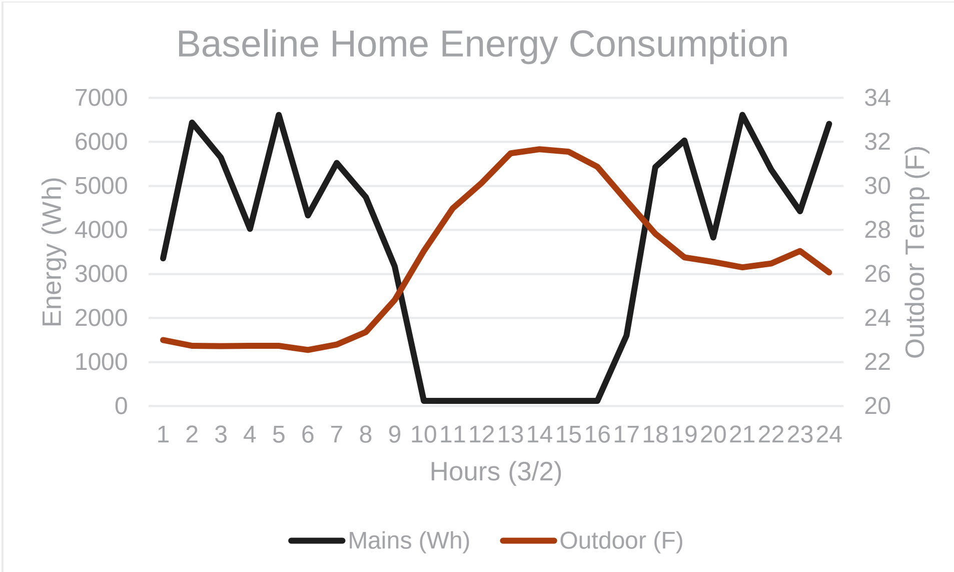

Figure A.11. Heating Experiment – Central: eFAF Offset (Grilles Open) Baseline Home Energy Consumption

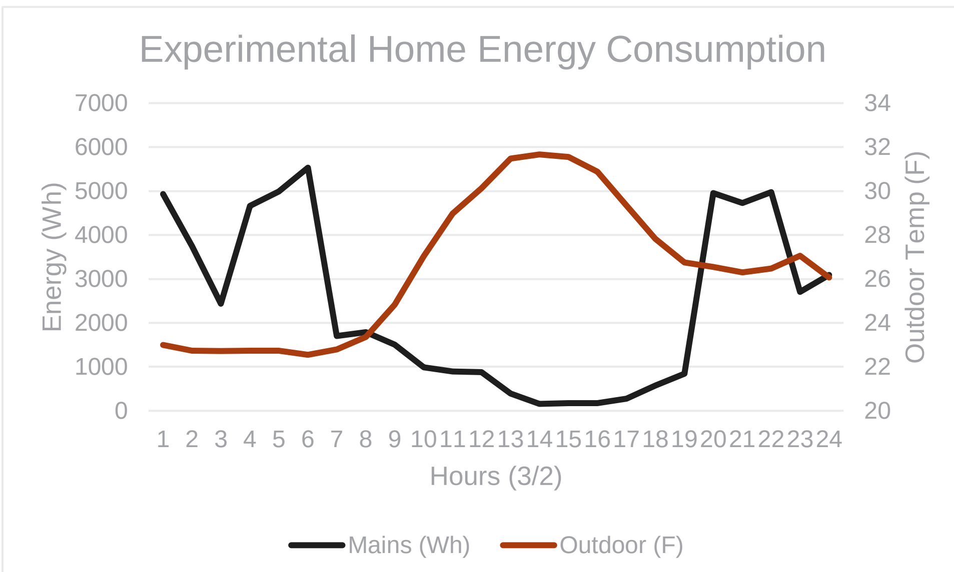

Figure A.12. Heating Experiment – Central: eFAF Offset (Grilles Open) Experimental Home Energy Consumption

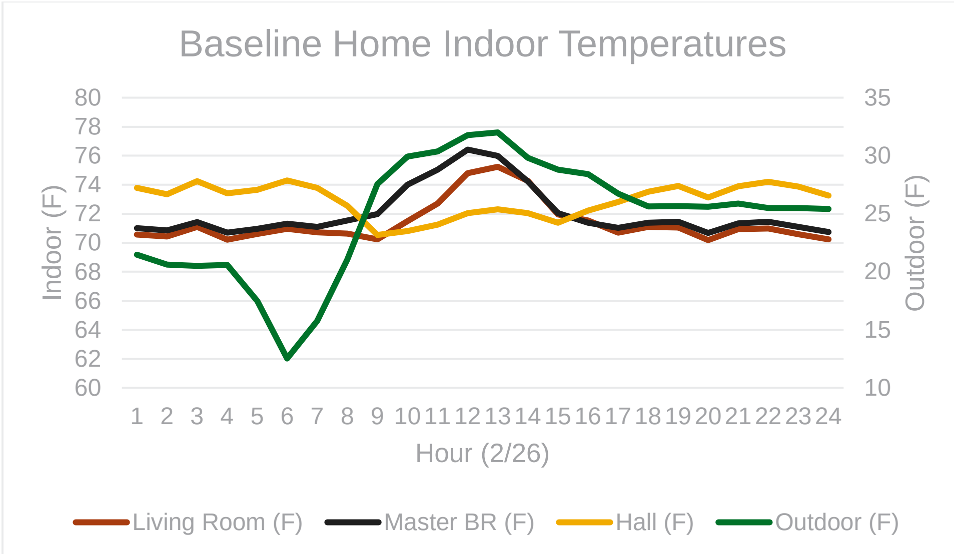

Figure A.13. Heating Experiment – Central: Complex Schedules Baseline Home Indoor Temperatures

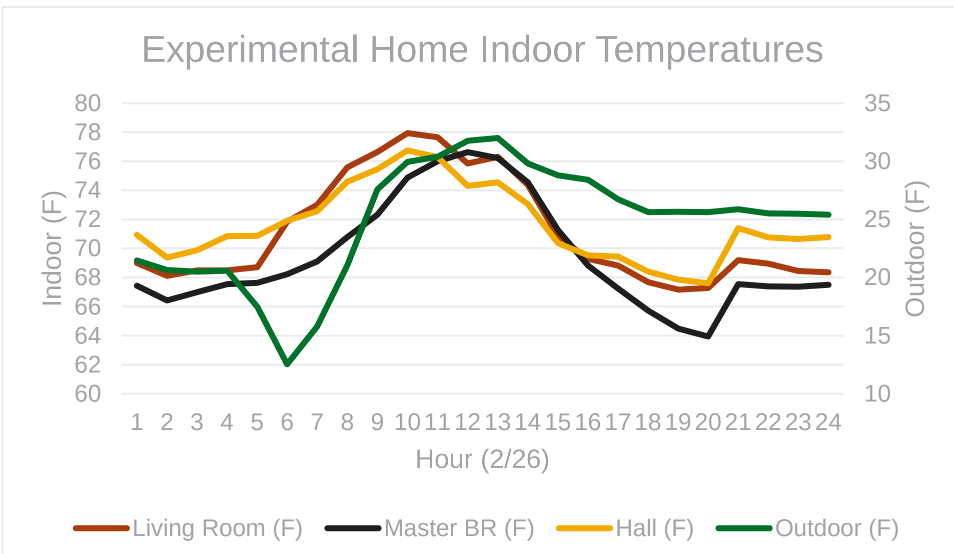

Figure A.14. Heating Experiment – Central: Complex Schedules Experimental Home Indoor Temperatures

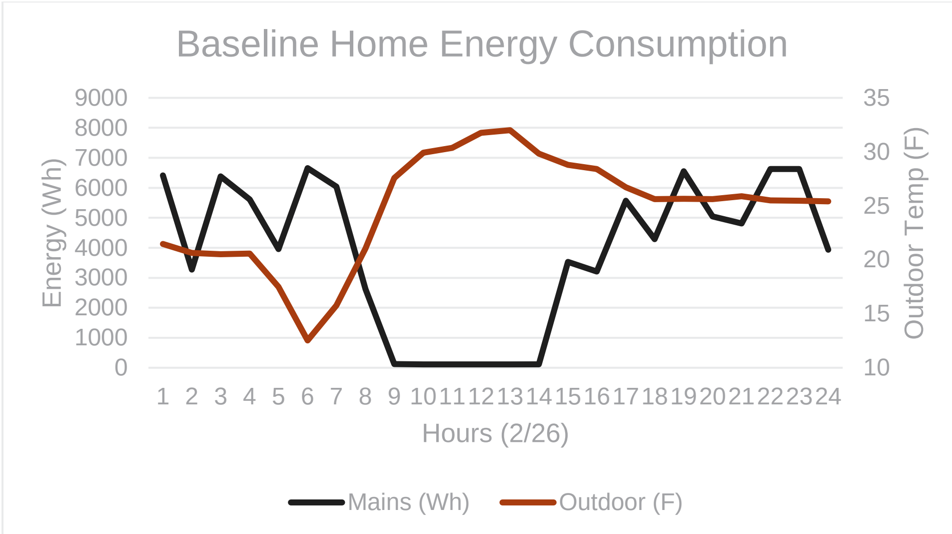

Figure A.15. Heating Experiment – Central: Complex Schedules Baseline Home Energy Consumption

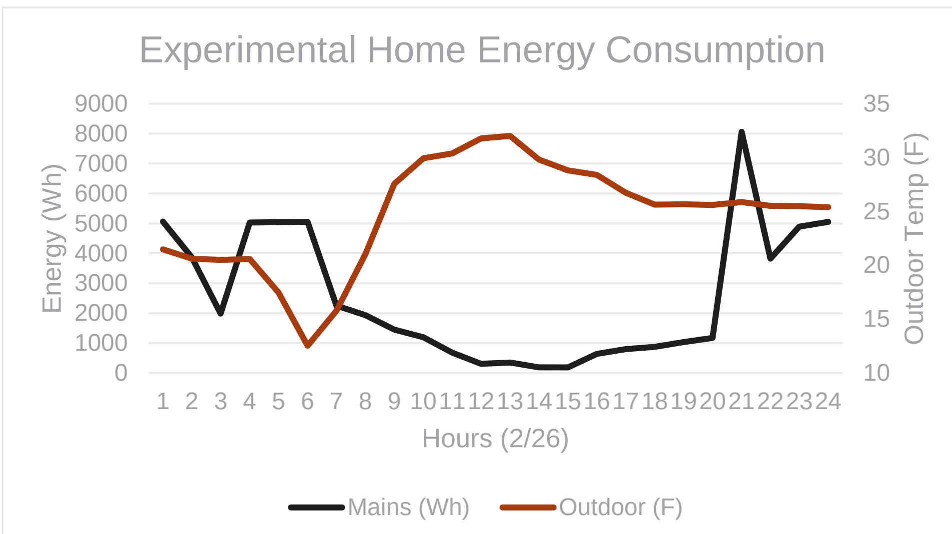

Figure A.16. Heating Experiment – Central: Complex Schedules Experimental Home Energy Consumption

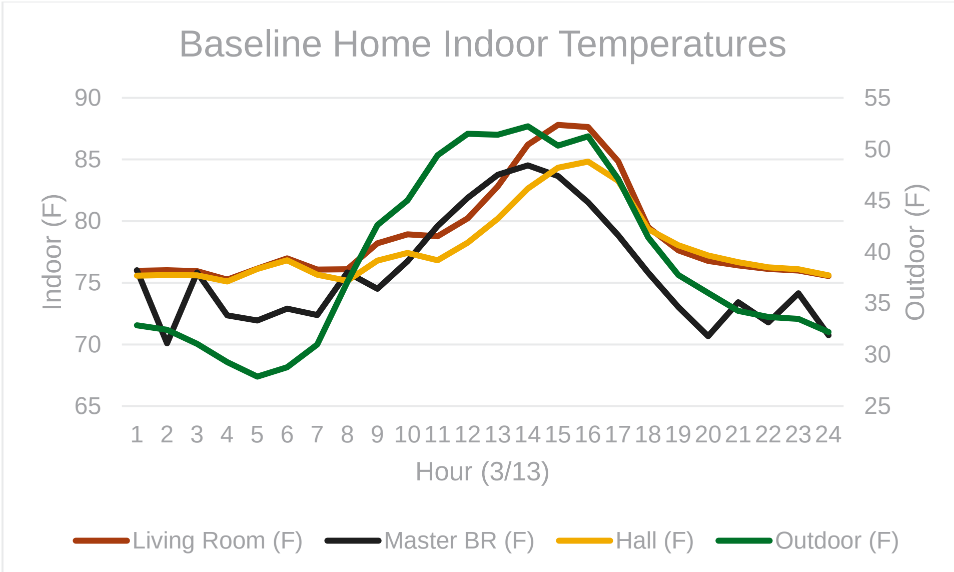

Figure A.17. Heating Experiment – Zonal: Home Calibration, Doors Closed Baseline Home Indoor Temperatures

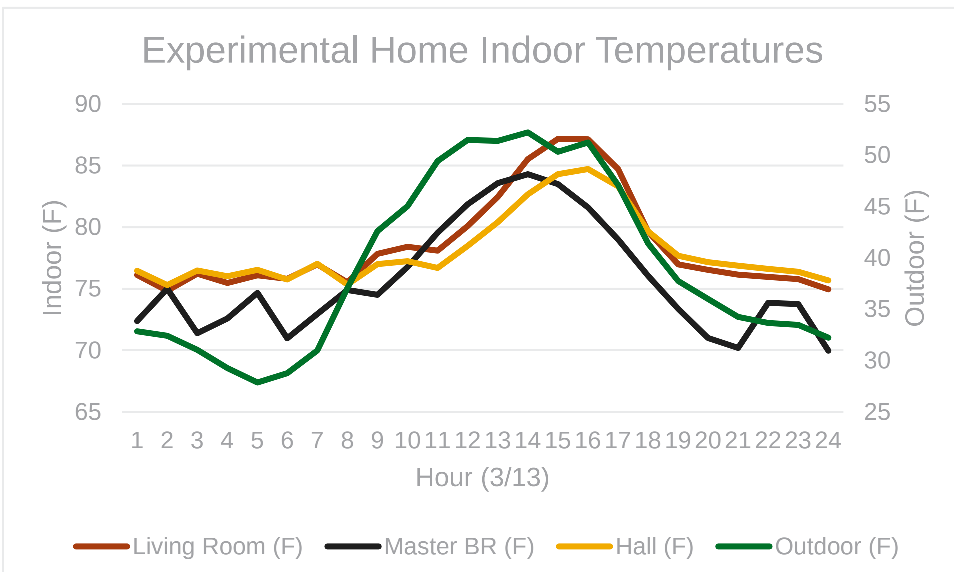

Figure A.18. Heating Experiment – Zonal: Home Calibration, Doors Closed Experimental Home Indoor Temperatures

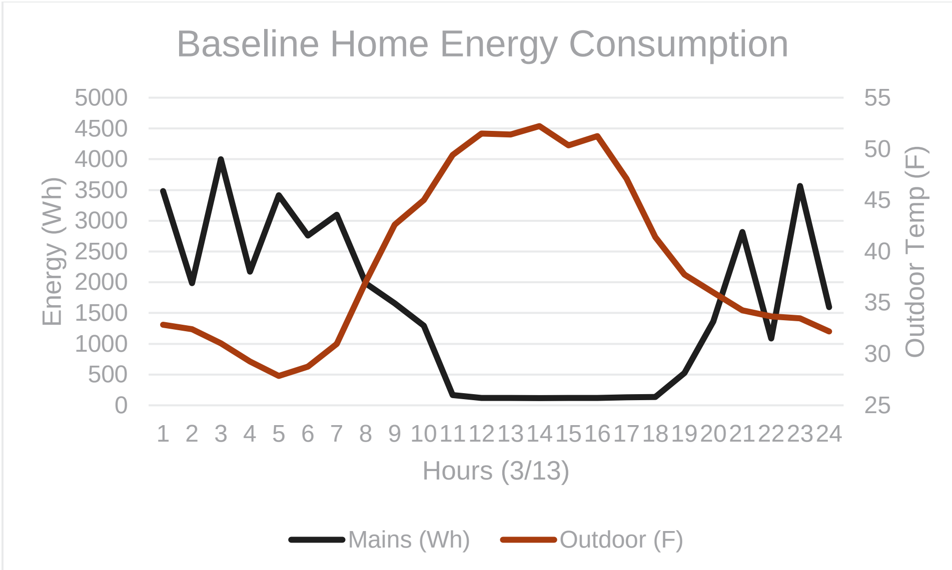

Figure A.19. Heating Experiment – Zonal: Home Calibration, Doors Closed Baseline Home Energy Consumption

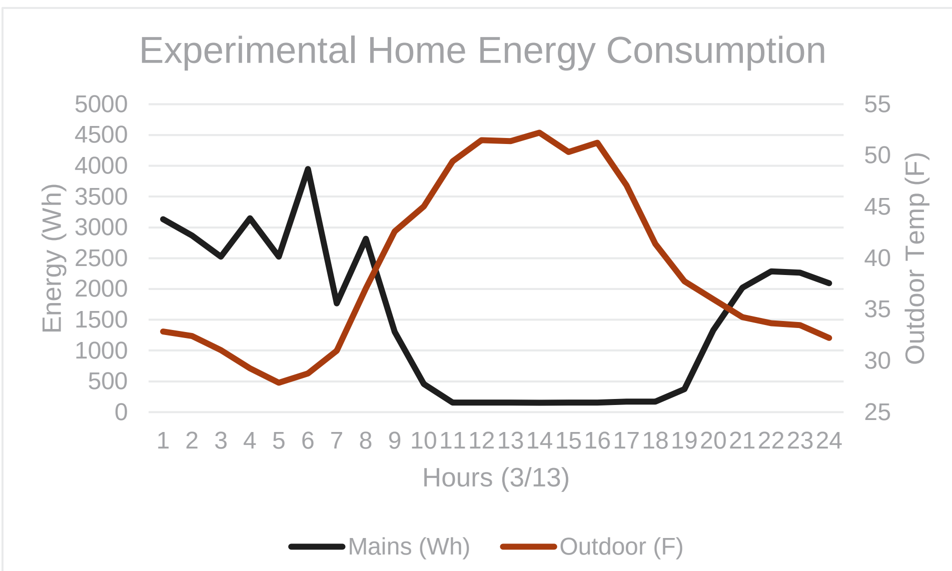

Figure A.20. Heating Experiment – Zonal: Home Calibration, Doors Closed Experimental Home Energy Consumption

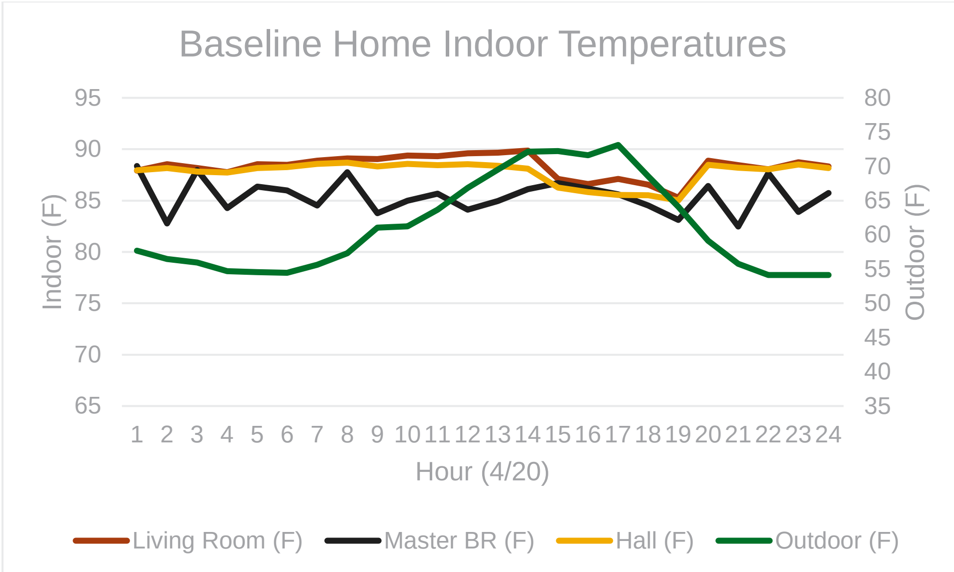

Figure A.21. Heating Experiment – Zonal: Bedroom Setback Baseline Home Indoor Temperatures

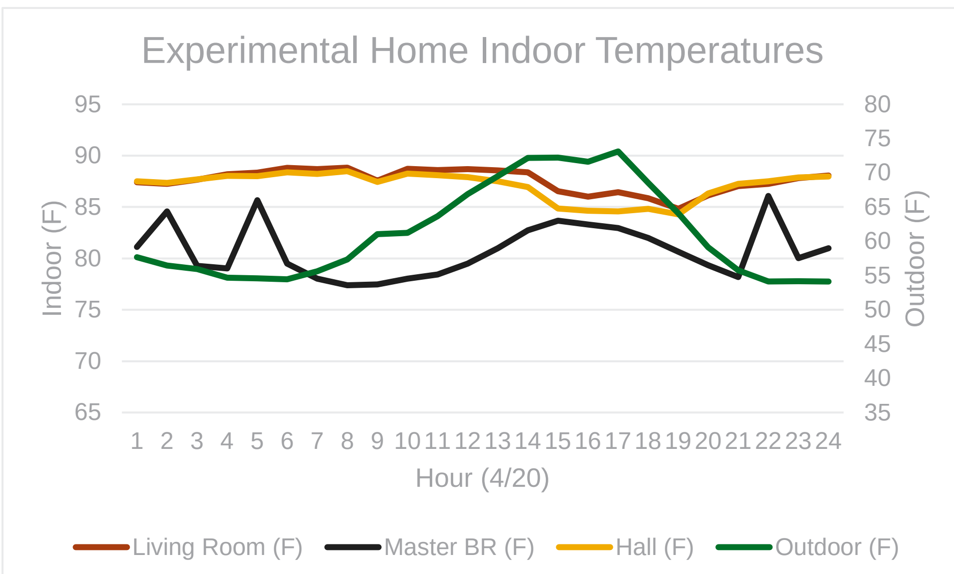

Figure A.22. Heating Experiment – Zonal: Bedroom Setback Experimental Home Indoor Temperatures

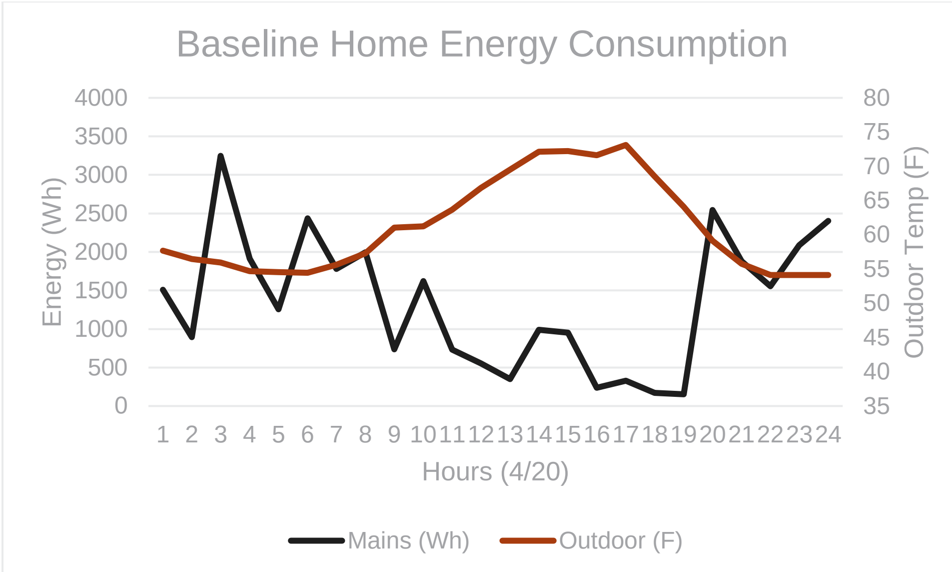

Figure A.23. Heating Experiment – Zonal: Bedroom Setback Baseline Home Energy Consumption

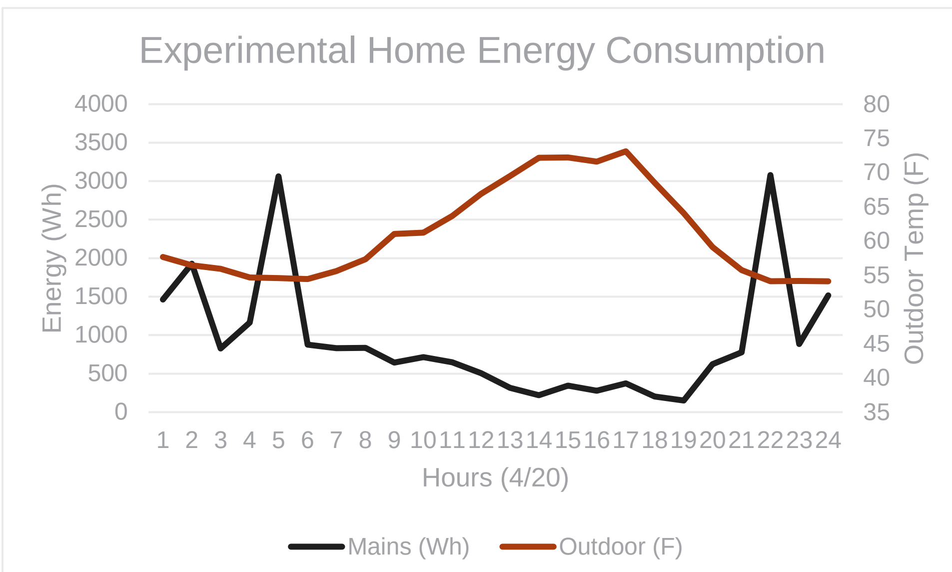

Figure A.24. Heating Experiment – Zonal: Bedroom Setback Experimental Home Energy Consumption

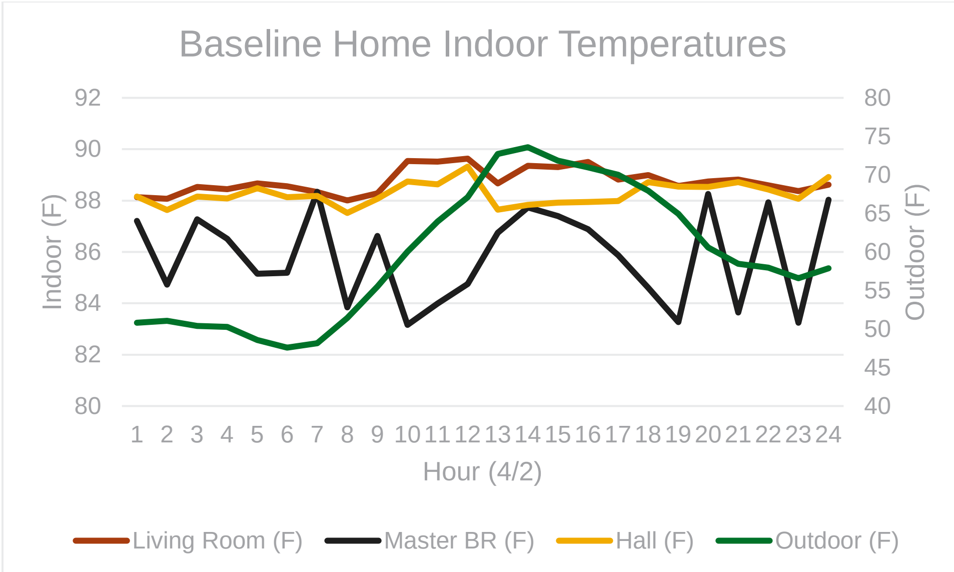

Figure A.25. Heating Experiment – Zonal: Transfer Fans Baseline Home Indoor Temperatures

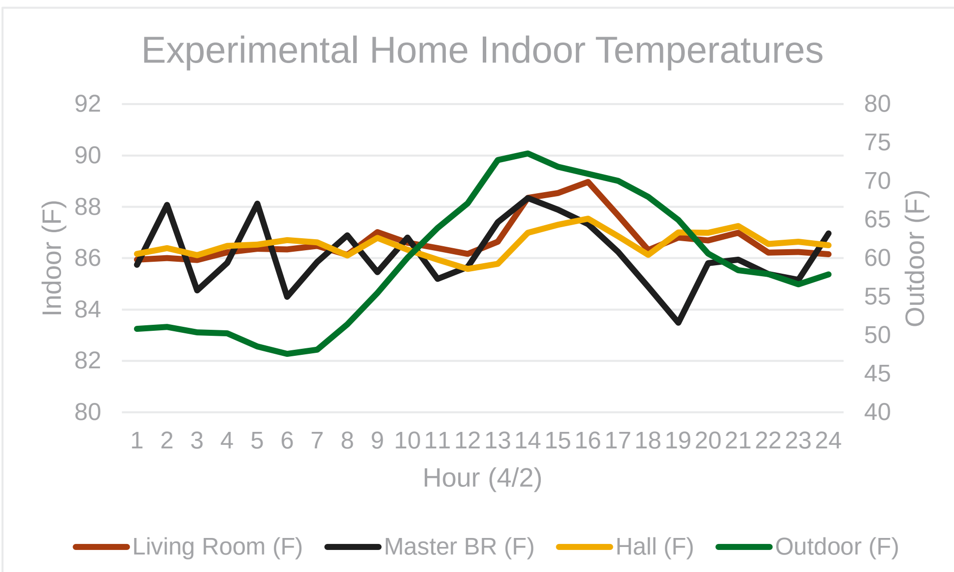

Figure A.26. Heating Experiment – Zonal: Transfer Fans Experimental Home Indoor Temperatures

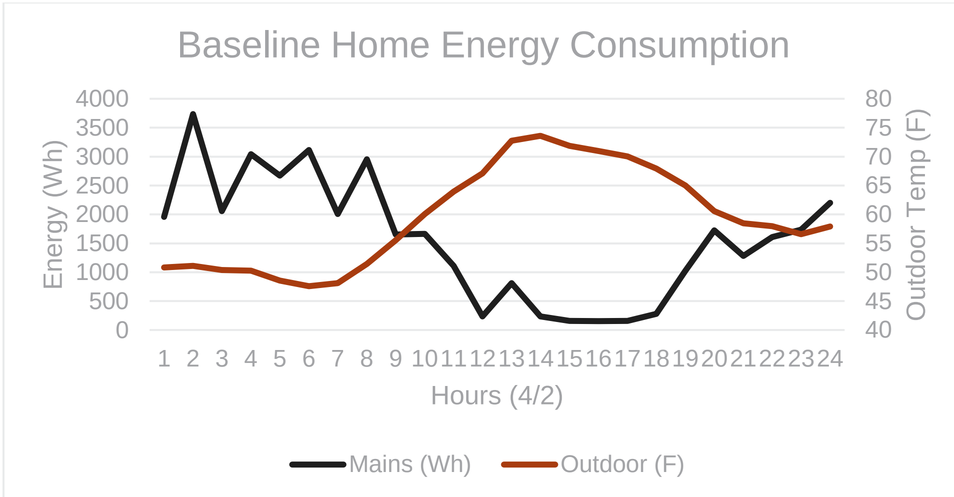

Figure A.27. Heating Experiment – Zonal: Transfer Fans Baseline Home Energy Consumption

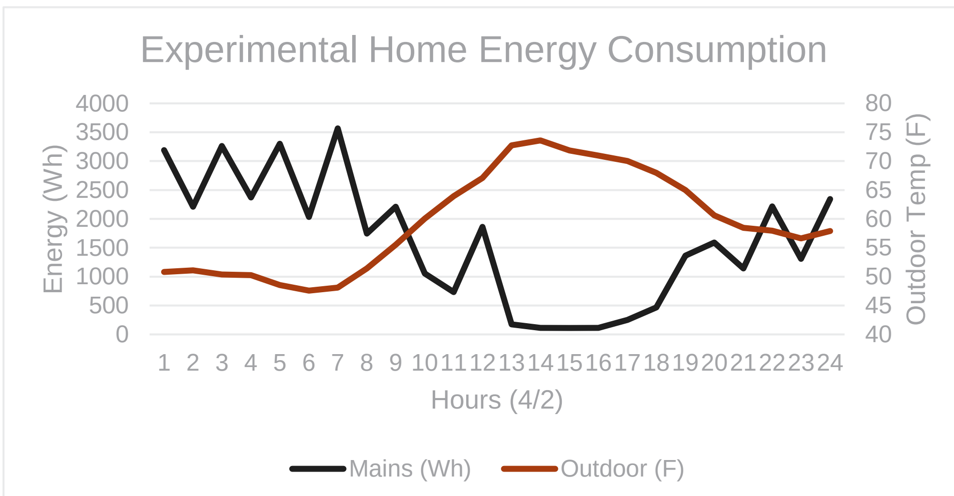

Figure A.28. Heating Experiment – Zonal: Transfer Fans Experimental Home Energy Consumption

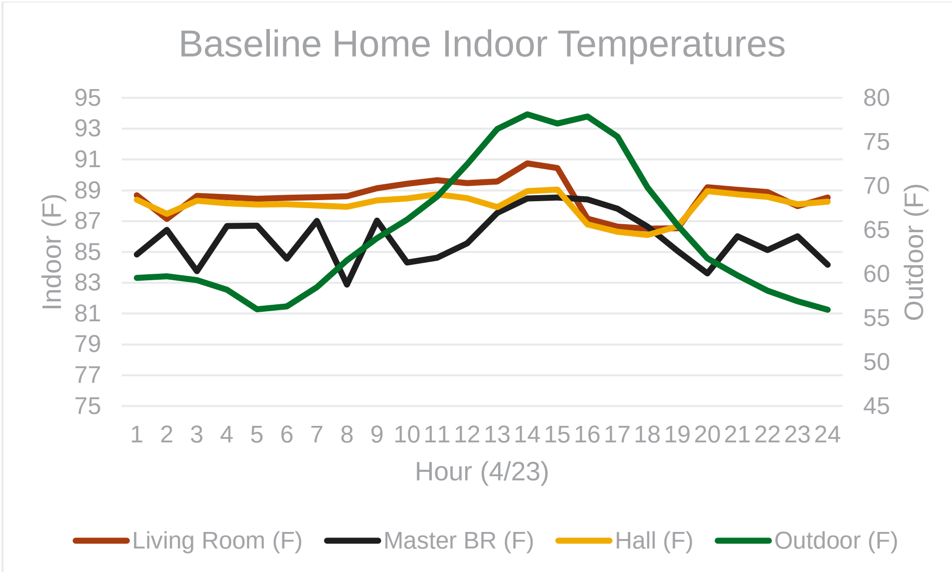

Figure A.29. Heating Experiment – Zonal: Complex Schedule Baseline Home Indoor Temperatures

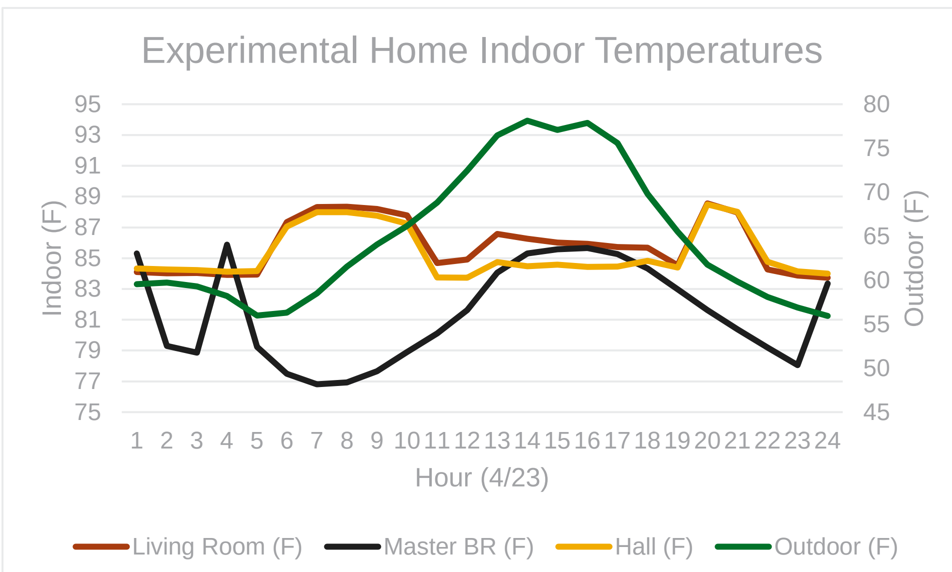

Figure A.30. Heating Experiment – Zonal: Complex Schedule Experimental Home Indoor Temperatures

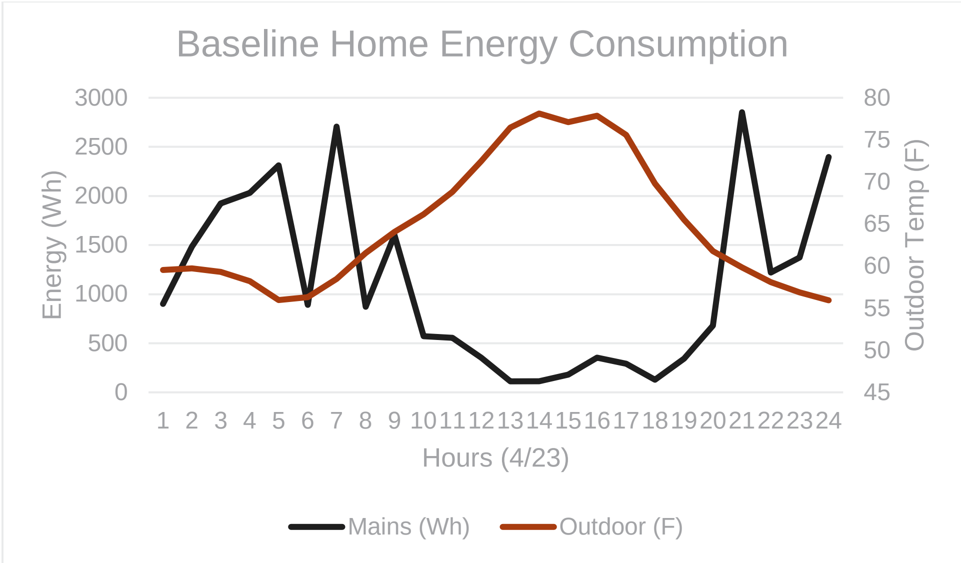

Figure A.31. Heating Experiment – Zonal: Complex Schedule Baseline Home Energy Consumption

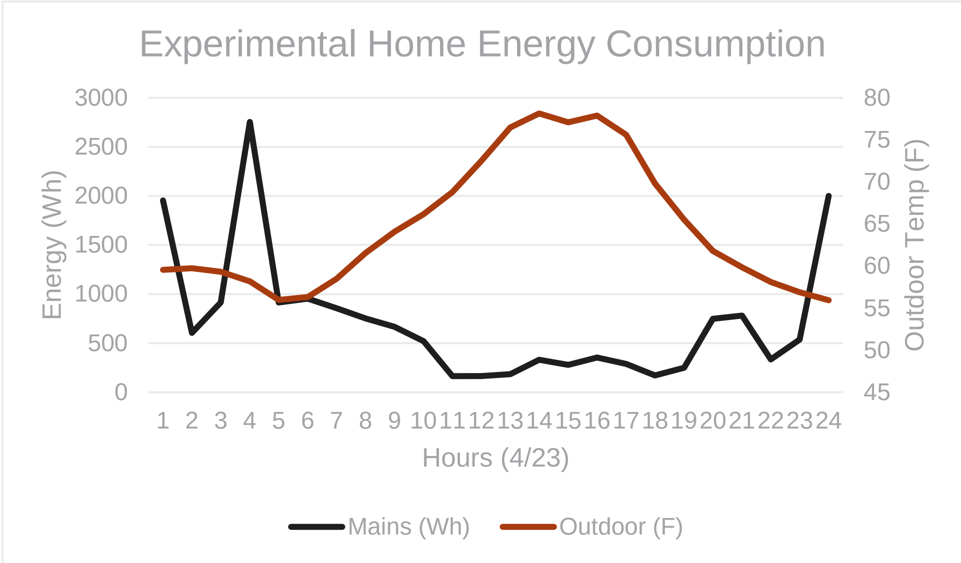

Figure A.32. Heating Experiment – Zonal: Complex Schedule Experimental Home Energy Consumption

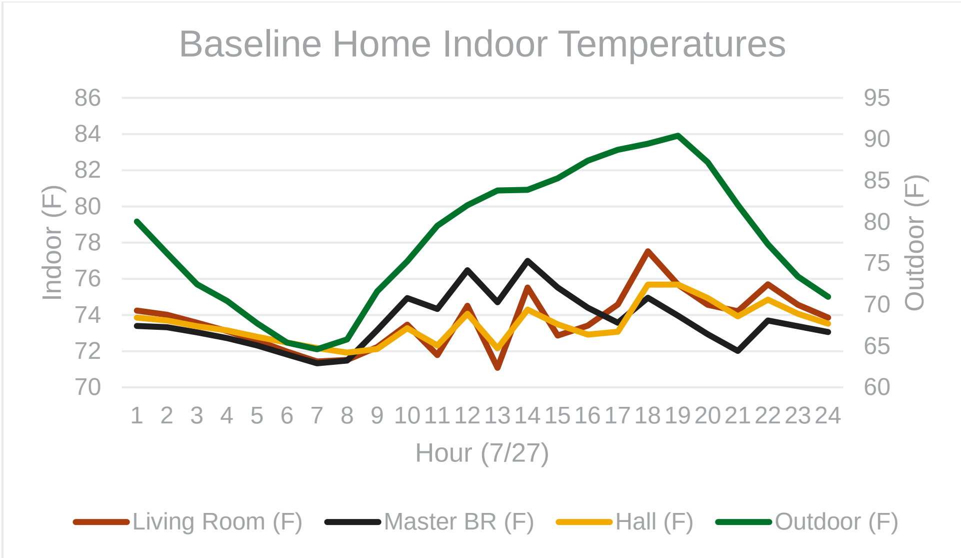

Figure A.33. Cooling Experiment – Central: Experiment Calibration Baseline Home Indoor Temperatures

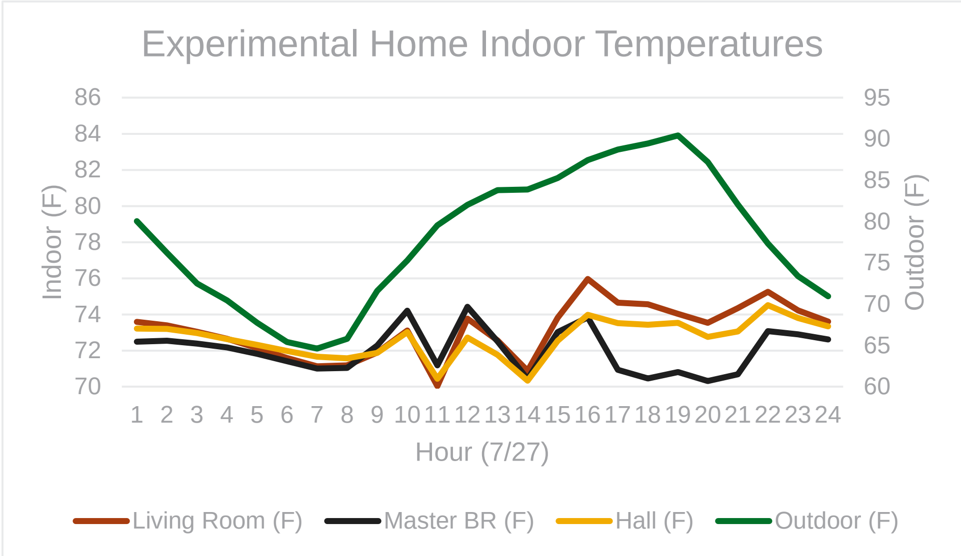

Figure A.34. Cooling Experiment – Central: Experiment Calibration Experimental Home Indoor Temperatures

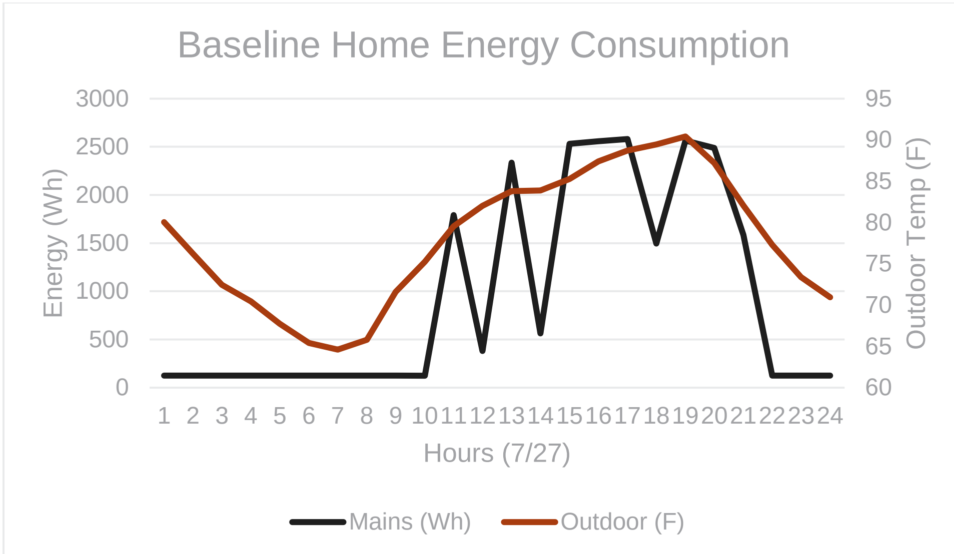

Figure A.35. Cooling Experiment – Central: Experiment Calibration Baseline Home Energy Consumption

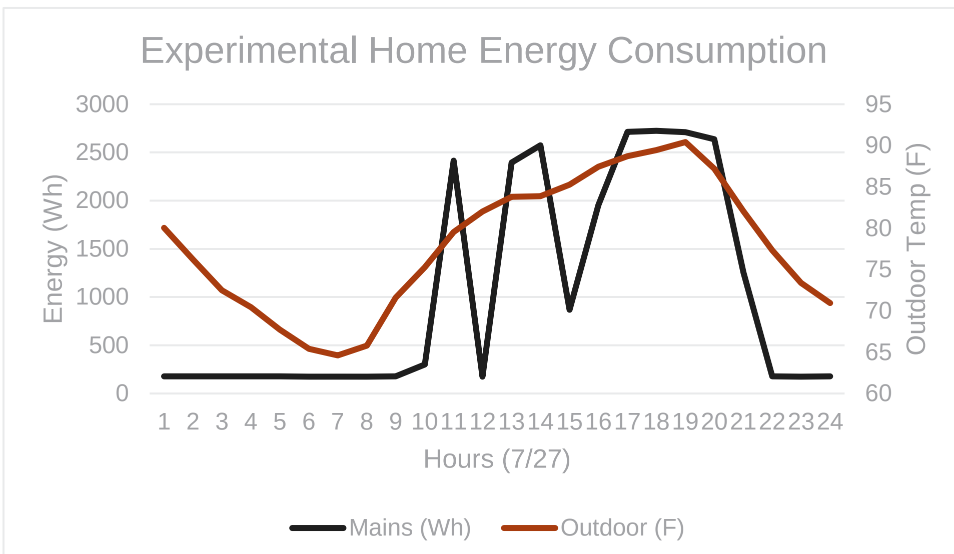

Figure A.36. Cooling Experiment – Central: Experiment Calibration Experimental Home Energy Consumption

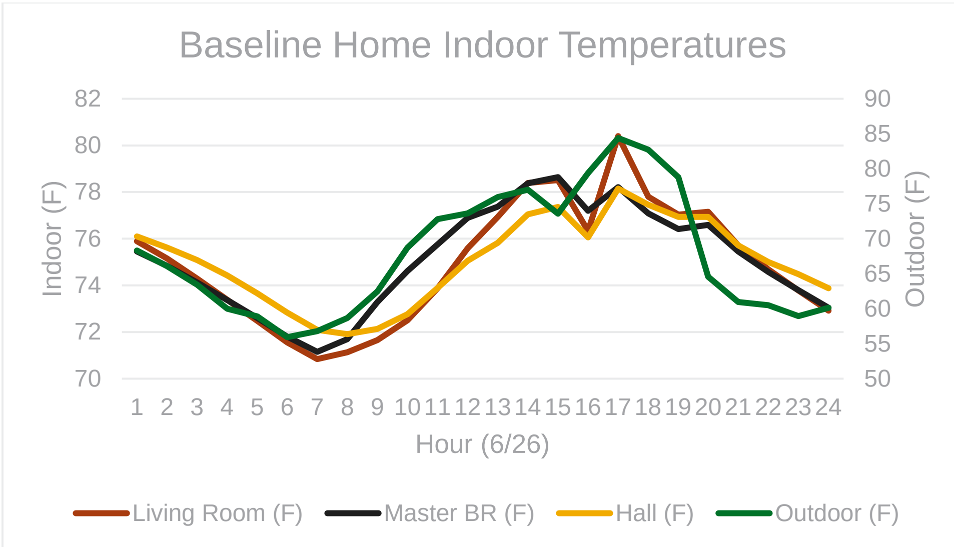

Figure A.37. Cooling Experiment – Central: Central Fan Only Baseline Home Indoor Temperatures

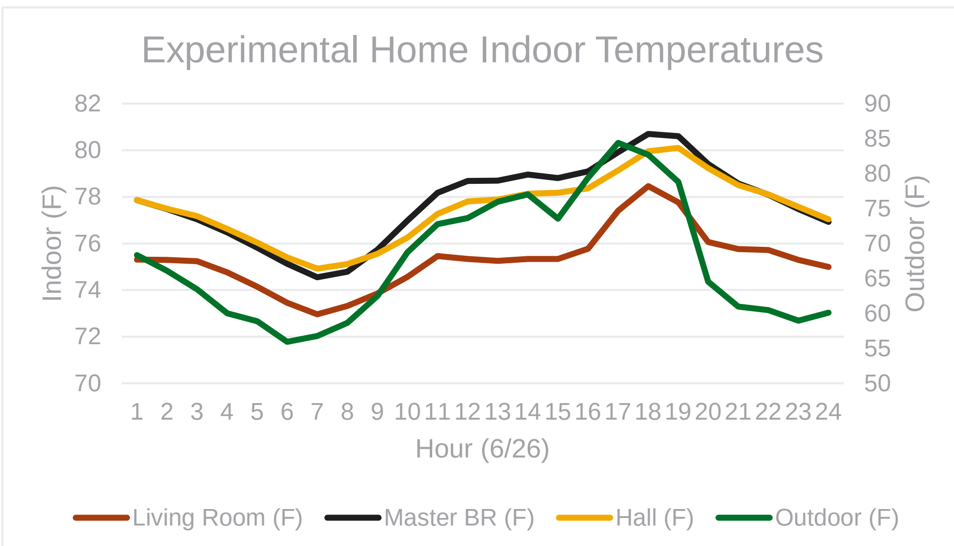

Figure A.38. Cooling Experiment – Central: Central Fan Only Experimental Home Indoor Temperatures

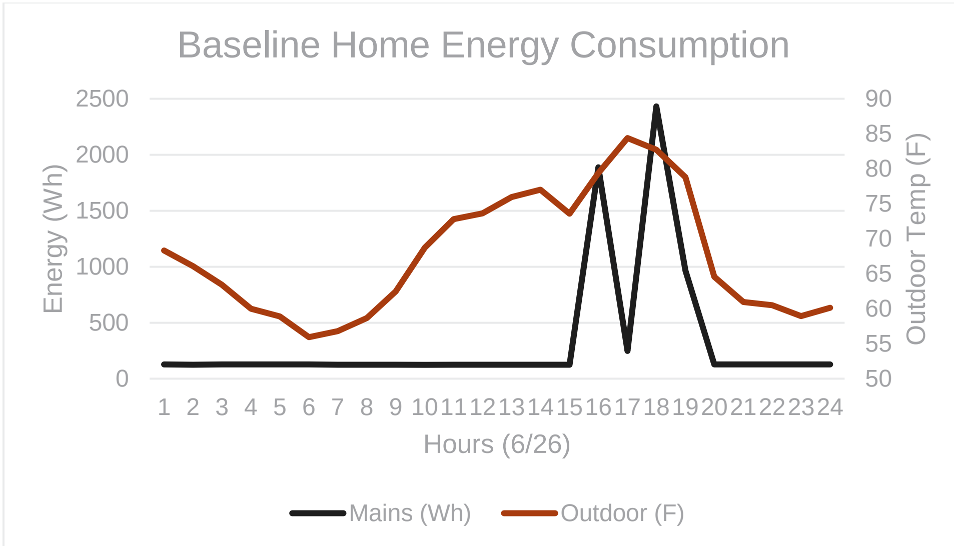

Figure A.39. Cooling Experiment – Central: Central Fan Only Baseline Home Energy Consumption

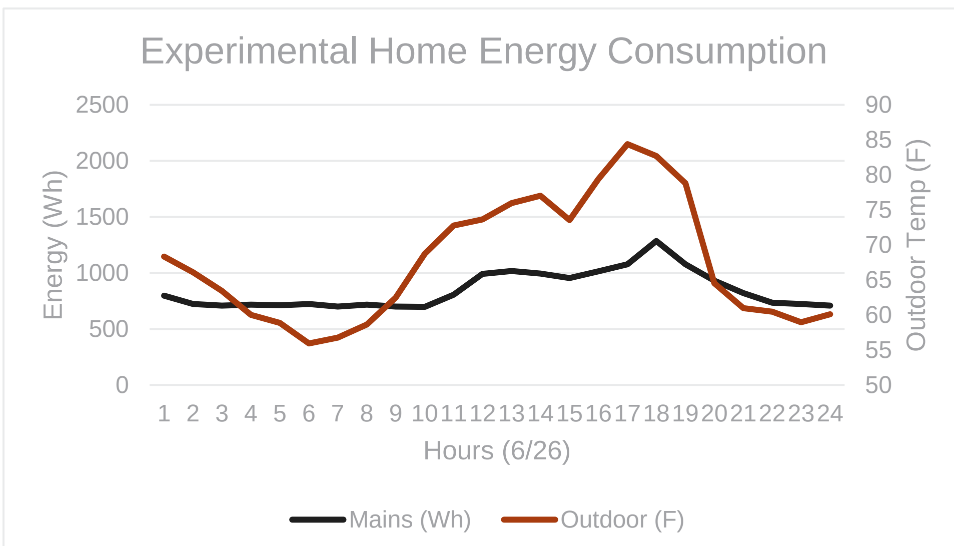

Figure A.40. Cooling Experiment – Central: Central Fan Only Experimental Home Energy Consumption

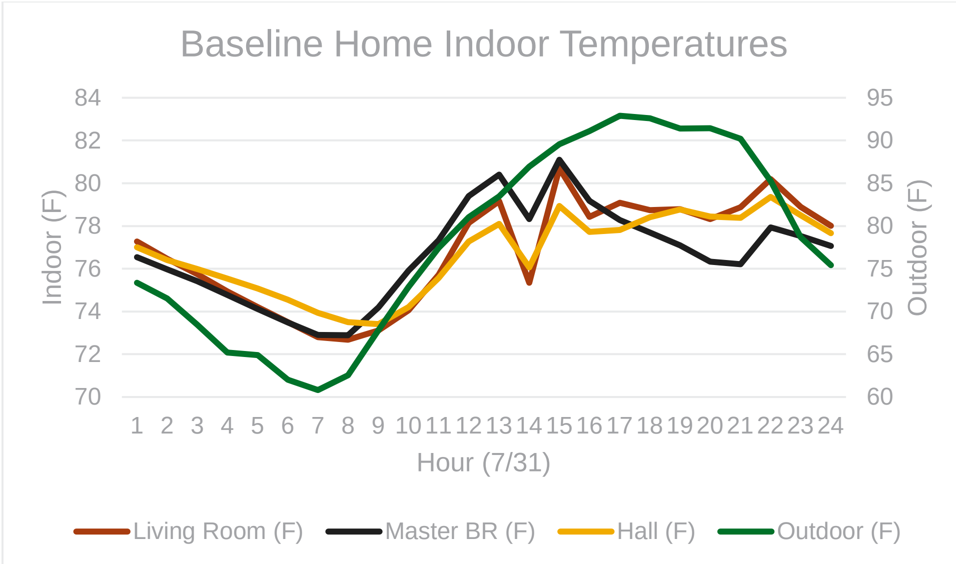

Figure A.41. Cooling Experiment – Central: Central Offset Baseline Home Indoor Temperatures

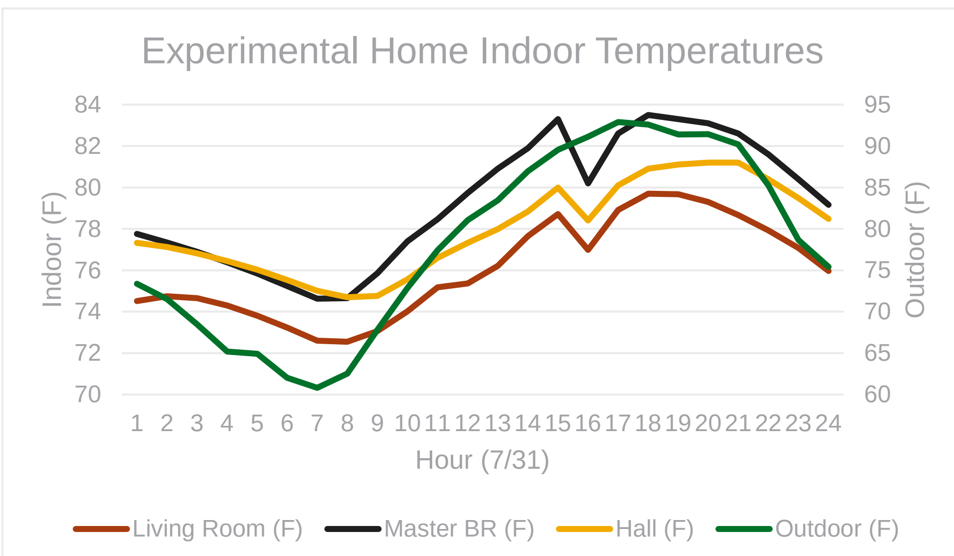

Figure A.42. Cooling Experiment – Central: CAC Offset Experimental Home Indoor Temperatures

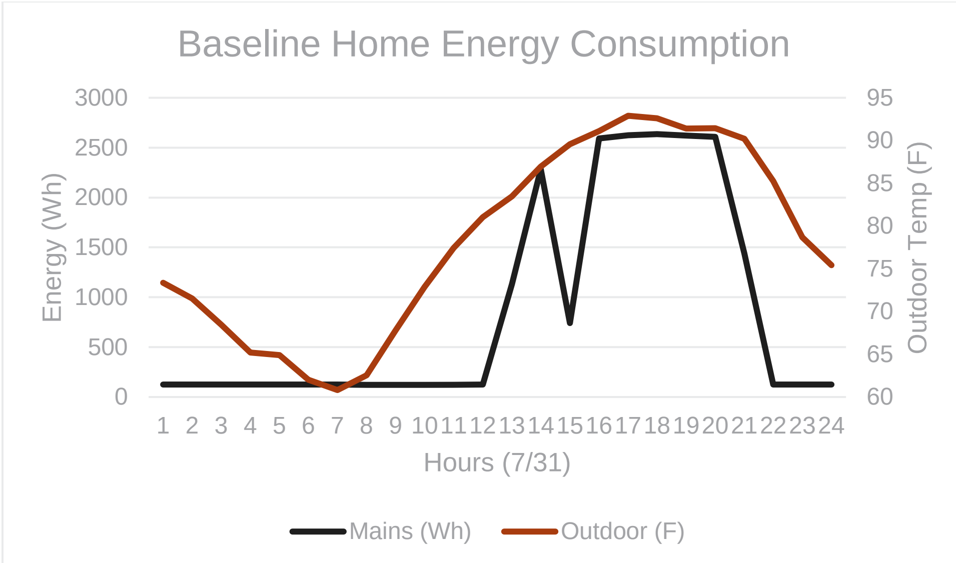

Figure A.43. Cooling Experiment – Central: CAC Offset Baseline Home Energy Consumption

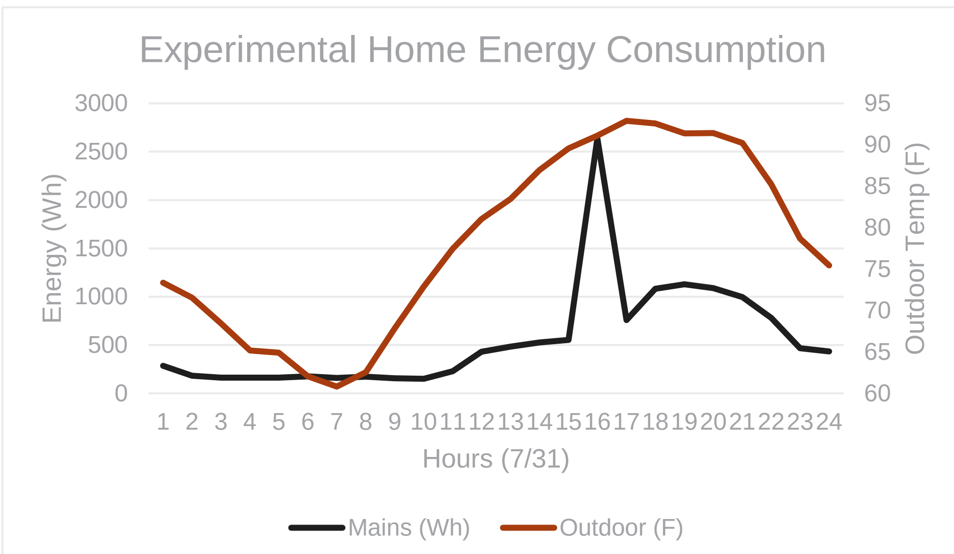

Figure A.44. Cooling Experiment – Central: CAC Offset Experimental Home Energy Consumption

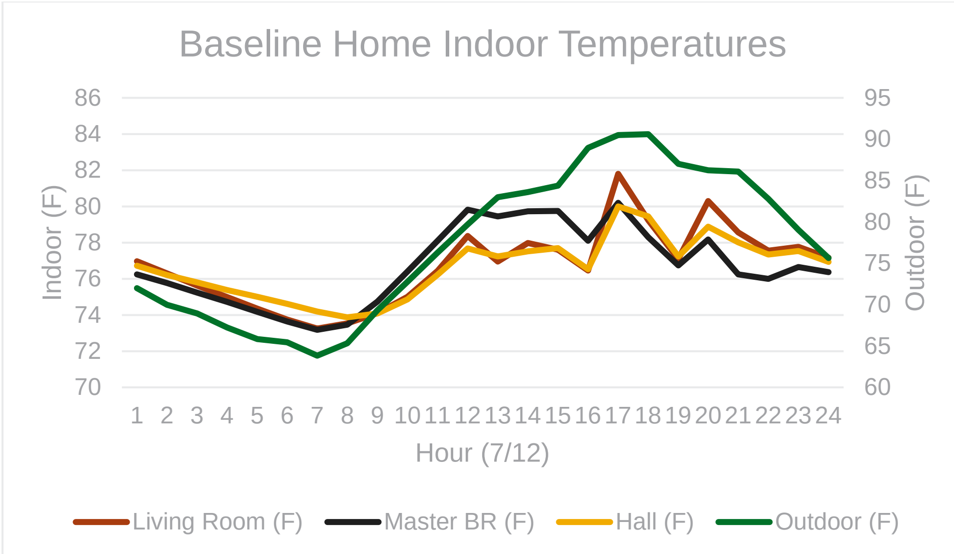

Figure A.45. Cooling Experiment – Central: Complex Schedule Baseline Home Indoor Temperatures

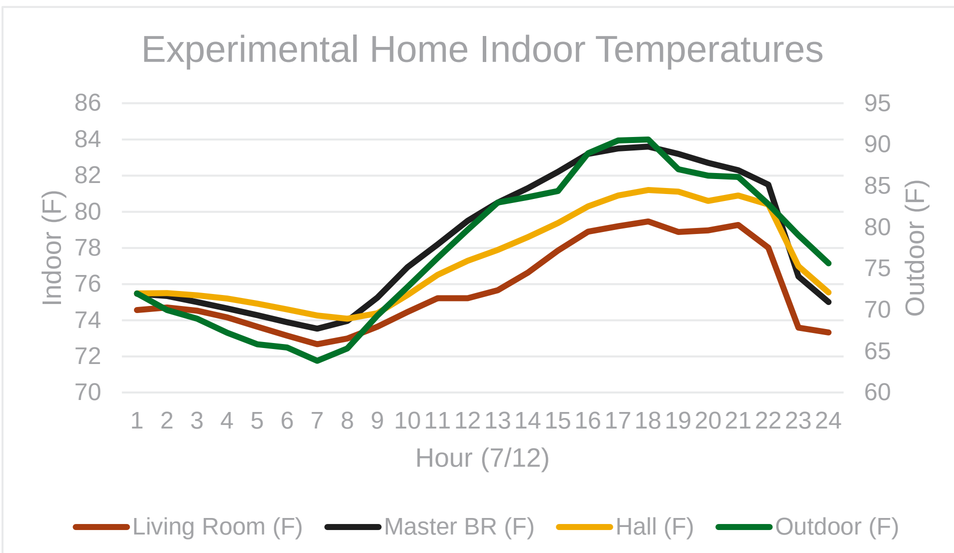

Figure A.46. Cooling Experiment – Central: Complex Schedule Experimental Home Indoor Temperatures

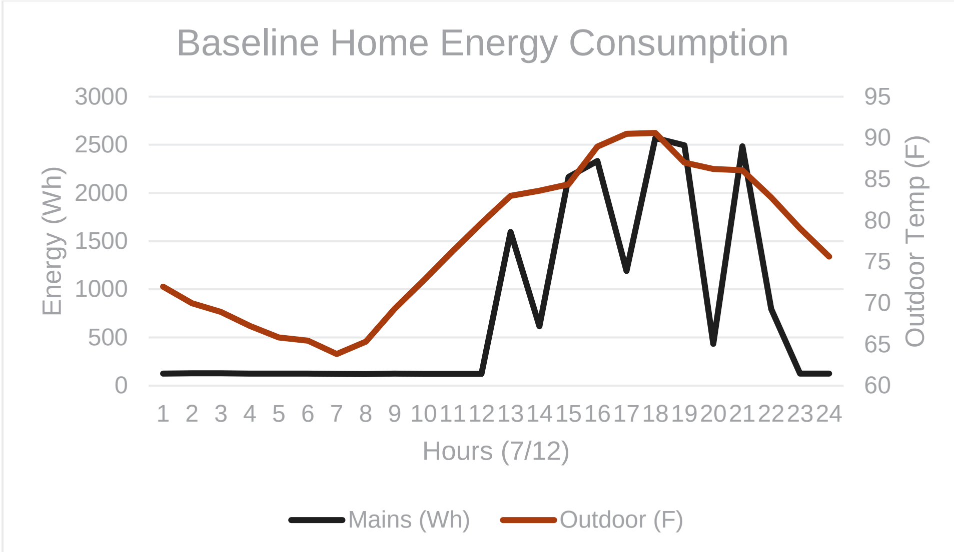

Figure A.47. Cooling Experiment – Central: Complex Schedule Baseline Home Energy Consumption

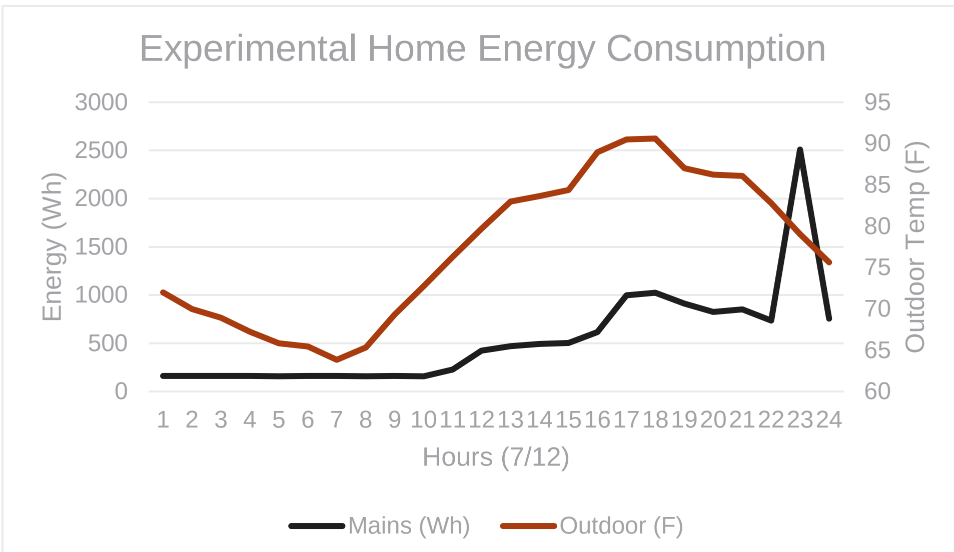

Figure A.48. Cooling Experiment – Central: Complex Schedule Experimental Home Energy Consumption

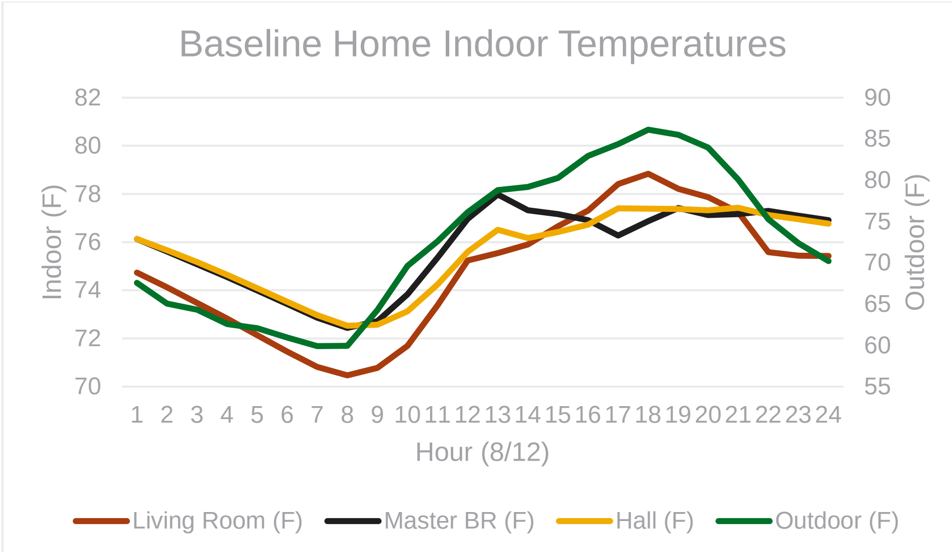

Figure A.49. Cooling Experiment – Zonal: Experiment Calibration, Doors Open Baseline Home Indoor Temperatures

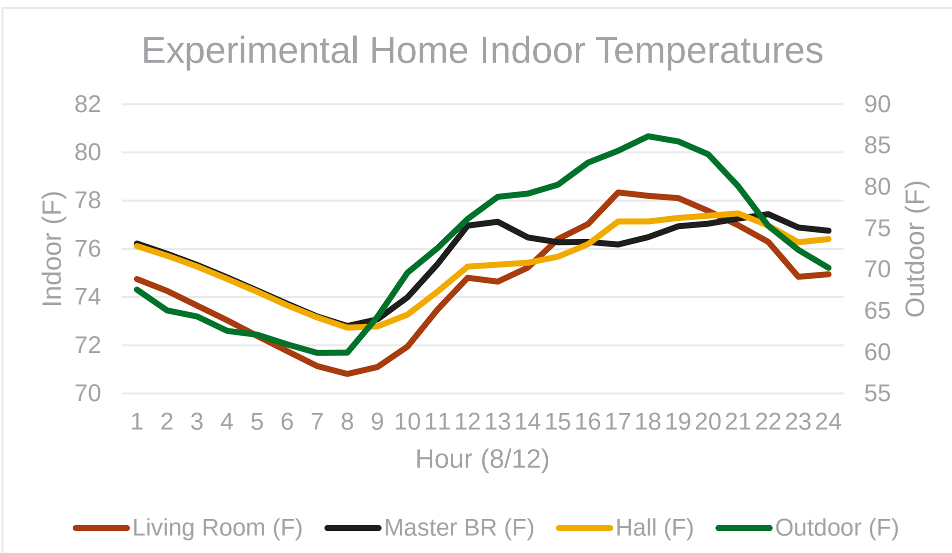

Figure A.50. Cooling Experiment – Zonal: Experiment Calibration, Doors Open Experimental Home Indoor Temperatures

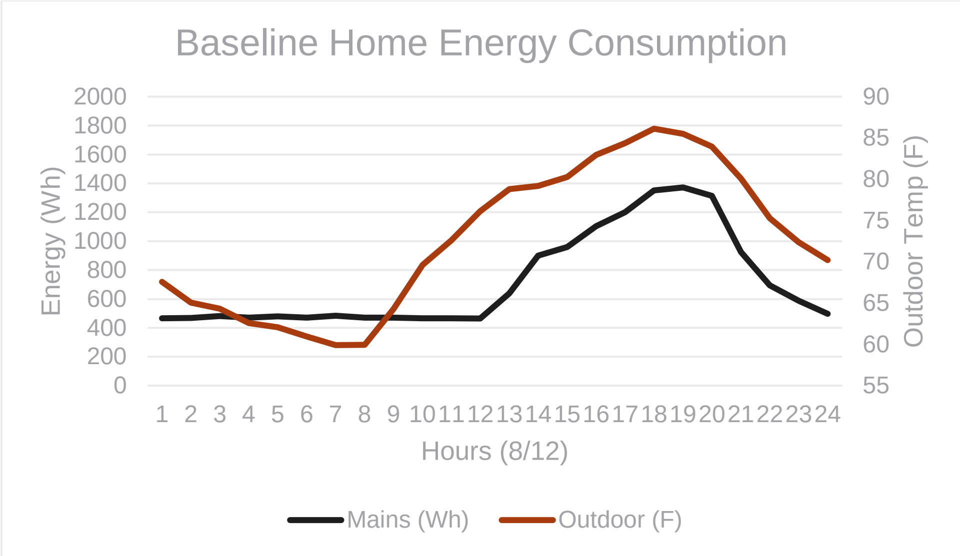

Figure A.51. Cooling Experiment – Zonal: Experiment Calibration, Doors Open Baseline Home Energy Consumption

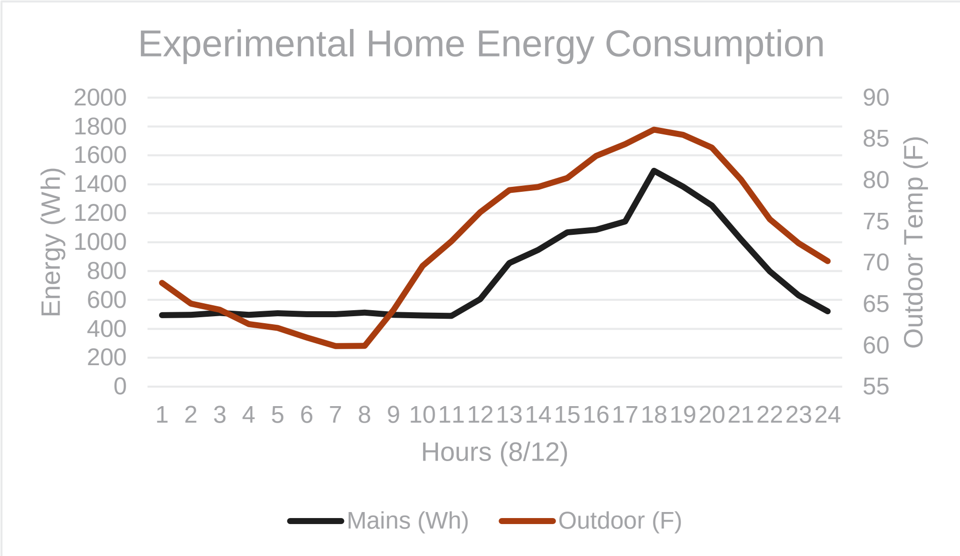

Figure A.52. Cooling Experiment – Zonal: Experiment Calibration, Doors Open Experimental Home Energy Consumption

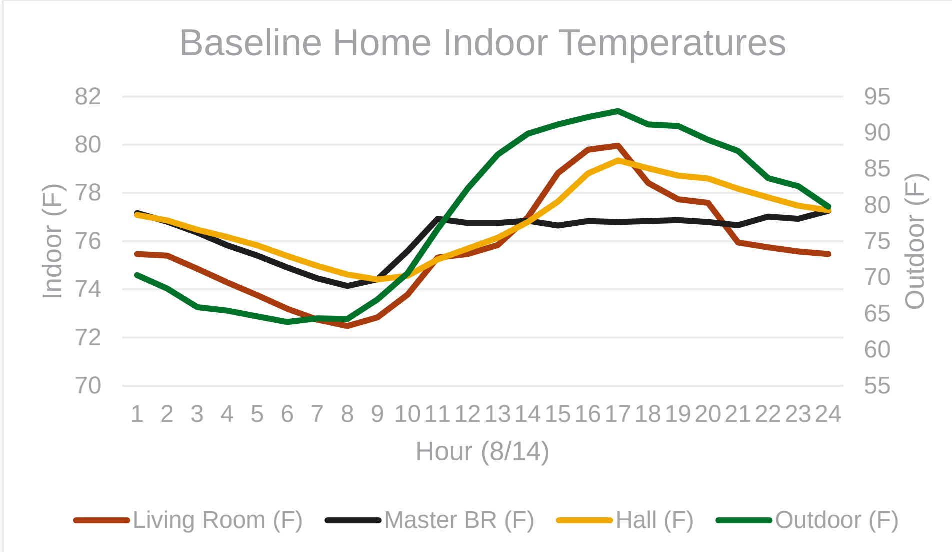

Figure A.53. Cooling Experiment – Zonal: Home Calibration, Doors Closed Baseline Home Indoor Temperatures

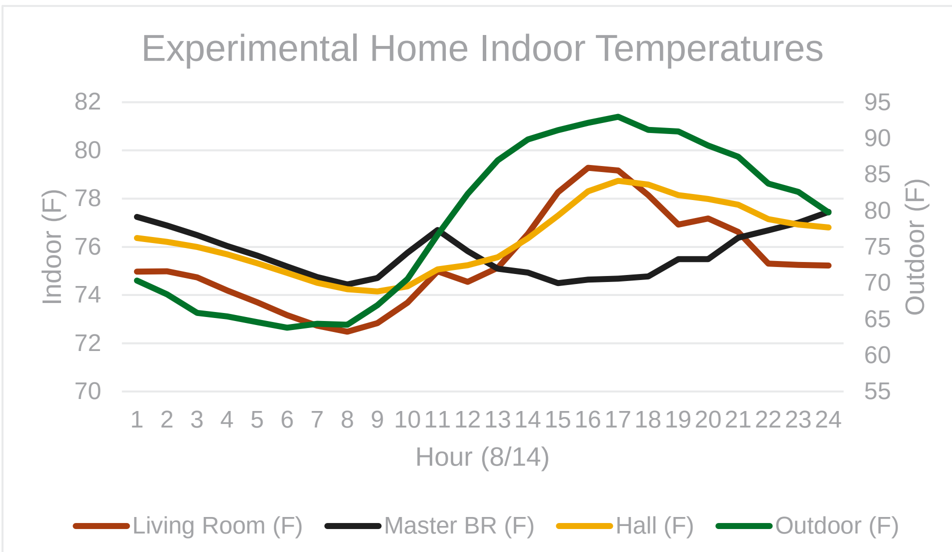

Figure A.54. Cooling Experiment – Zonal: Home Calibration, Doors Closed Experimental Home Indoor Temperatures

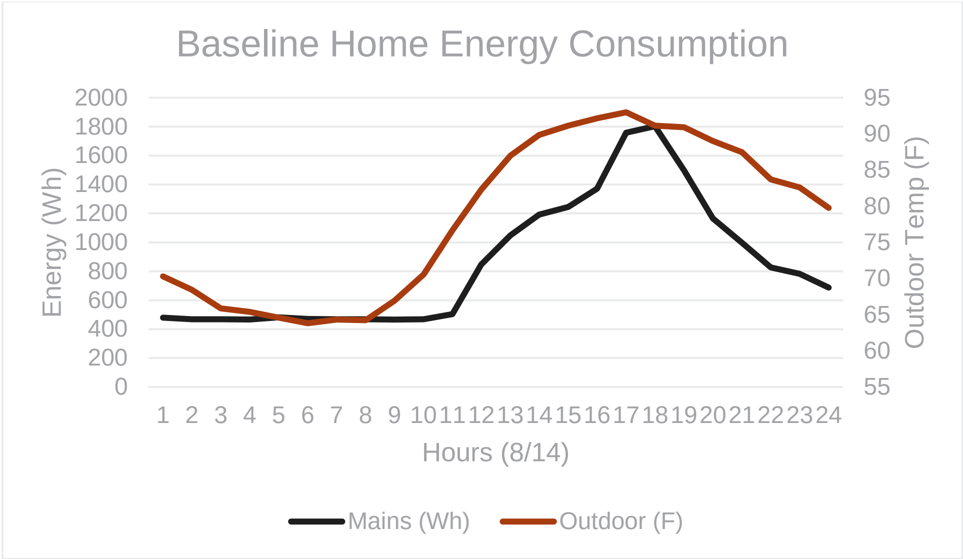

Figure A.55. Cooling Experiment – Zonal: Home Calibration, Doors Closed Baseline Home Energy Consumption

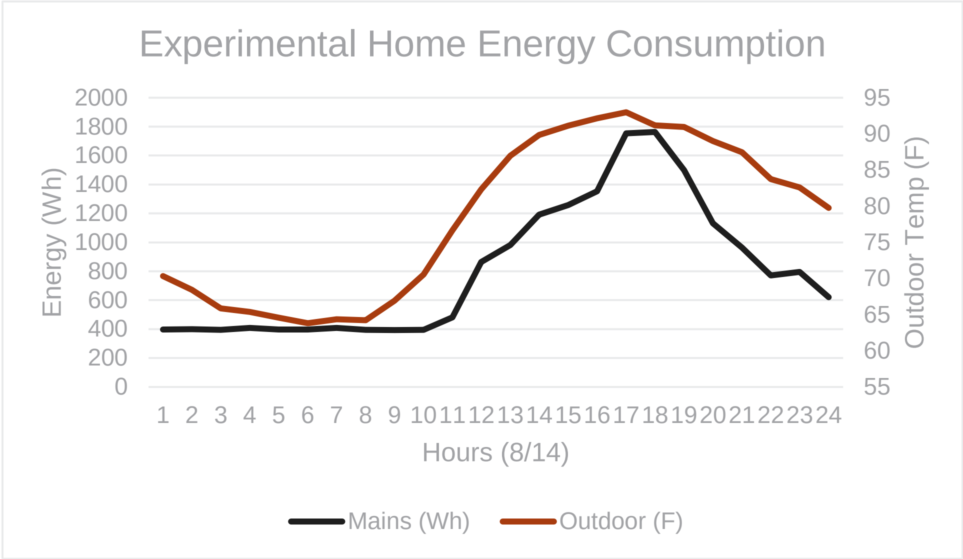

Figure A.56. Cooling Experiment – Zonal: Home Calibration, Doors Closed Experimental Home Energy Consumption

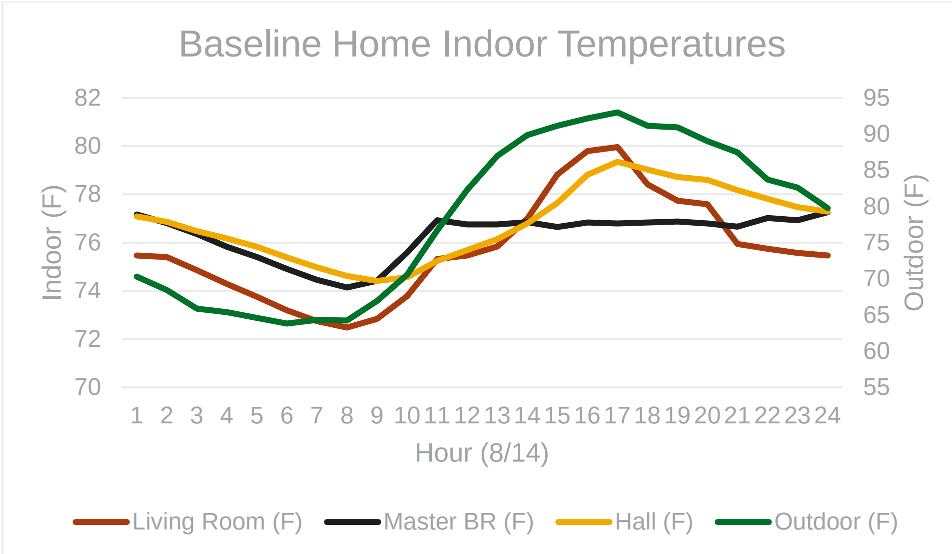

Figure A.57. Cooling Experiment – Zonal: Home Calibration, Doors Closed Baseline Home Indoor Temperatures

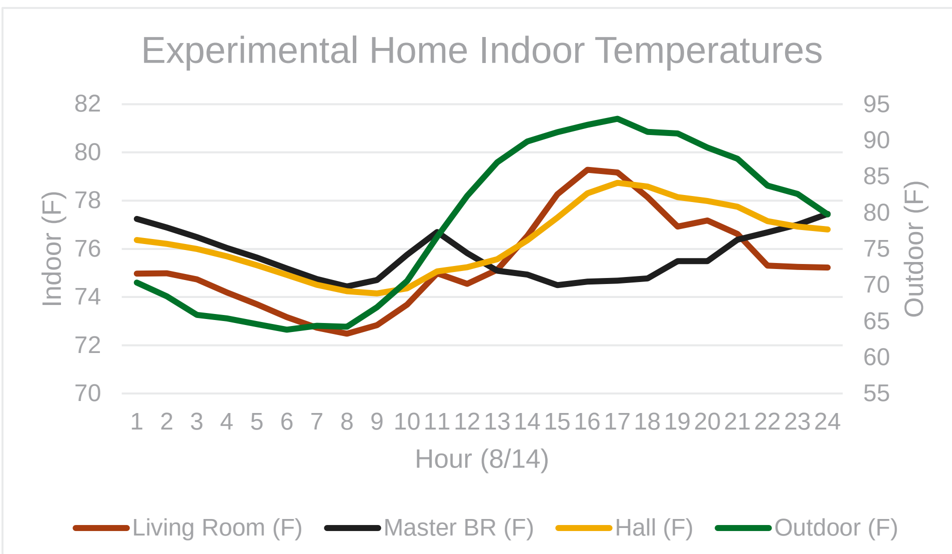

Figure A.58. Cooling Experiment – Zonal: Home Calibration, Doors Closed Experimental Home Indoor Temperatures

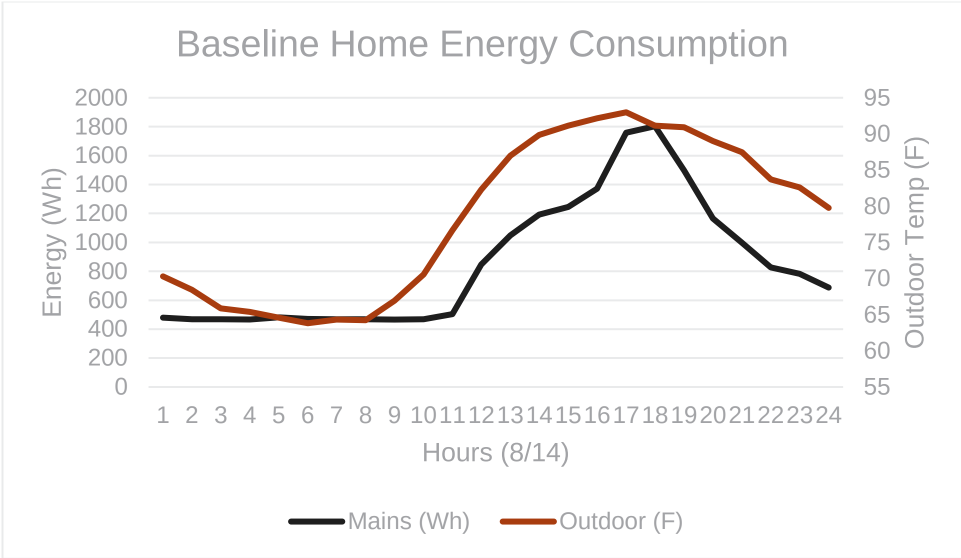

Figure A.59. Cooling Experiment – Zonal: Home Calibration, Doors Closed Baseline Home Energy Consumption

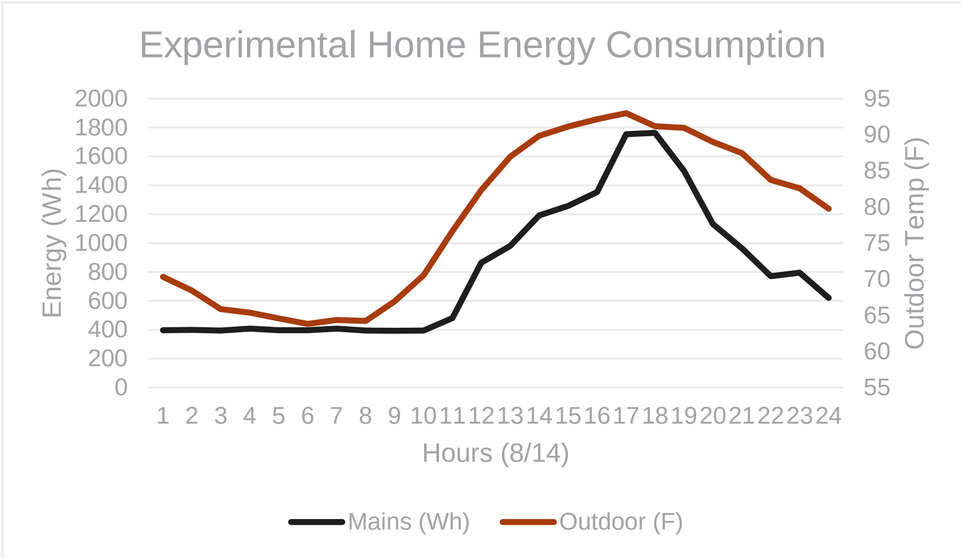

Figure A.60. Cooling Experiment – Zonal: Home Calibration, Doors Closed Experimental Home Energy Consumption

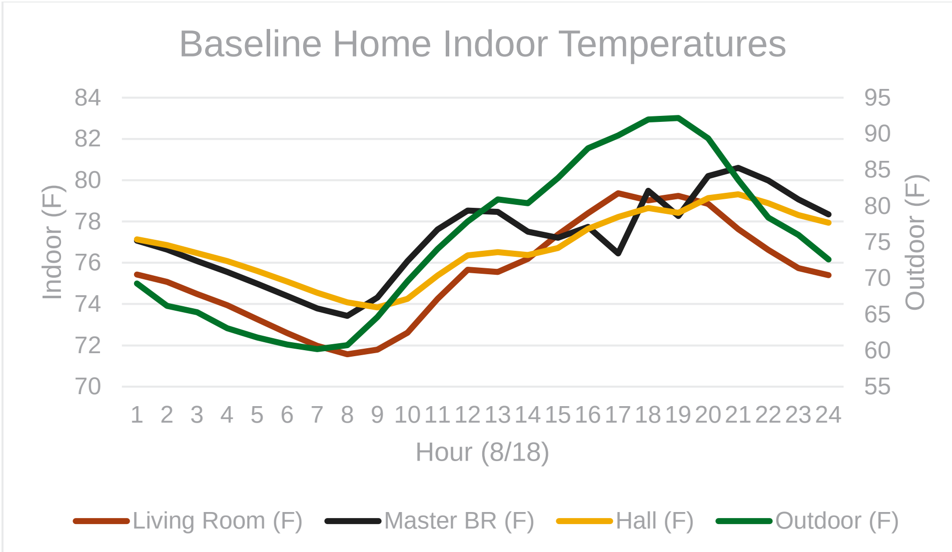

Figure A.61. Cooling Experiment – Zonal: Bedroom Setback Baseline Home Indoor Temperatures

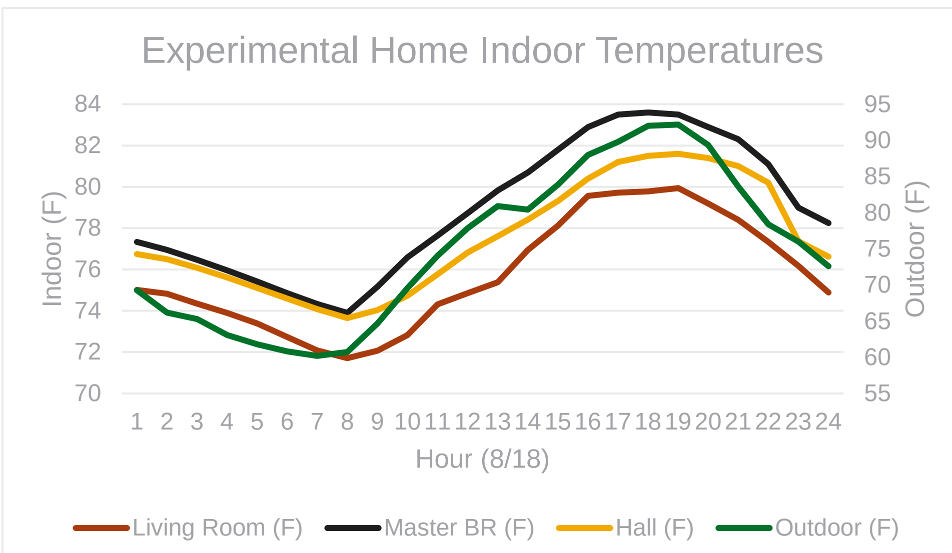

Figure A.62. Cooling Experiment – Zonal: Bedroom Setback Experimental Home Indoor Temperatures

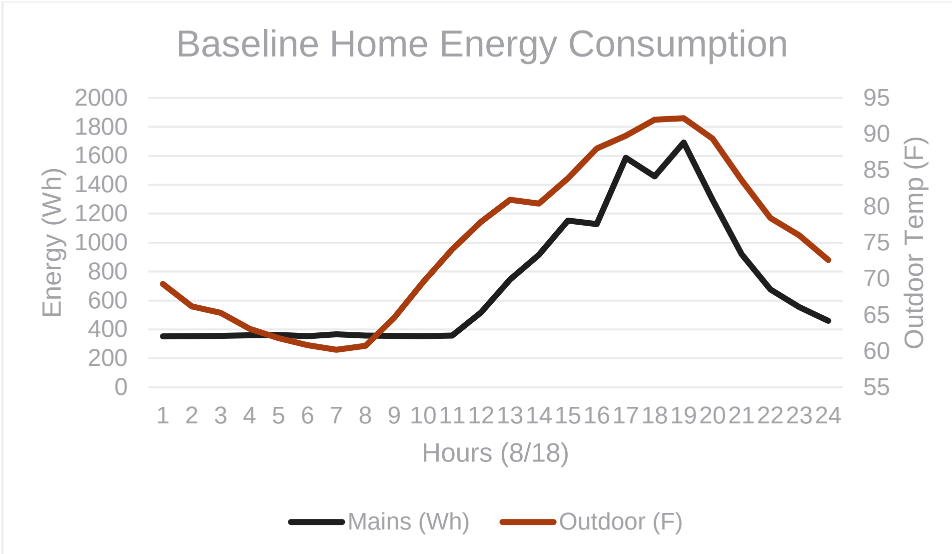

Figure A.63. Cooling Experiment – Zonal: Bedroom Setback Baseline Home Energy Consumption

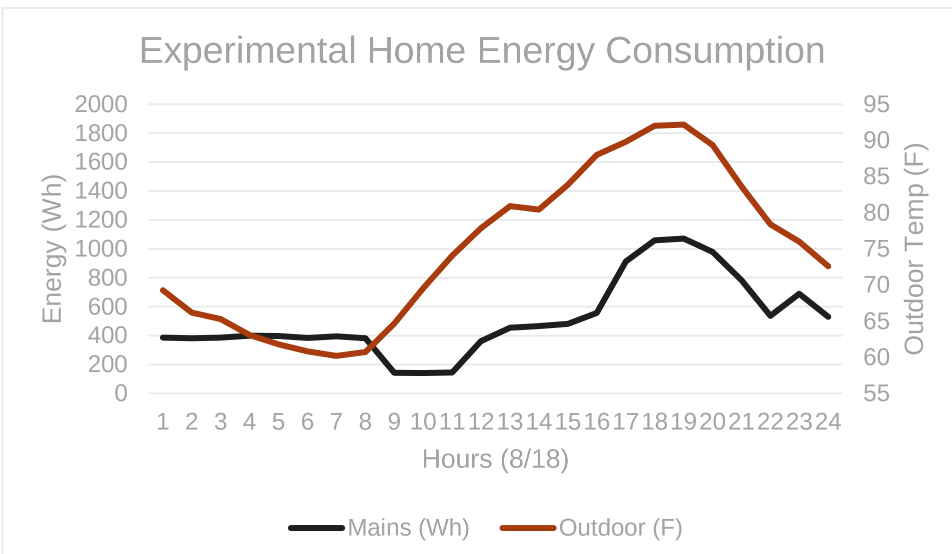

Figure A.64. Cooling Experiment – Zonal: Bedroom Setback Experimental Home Energy Consumption

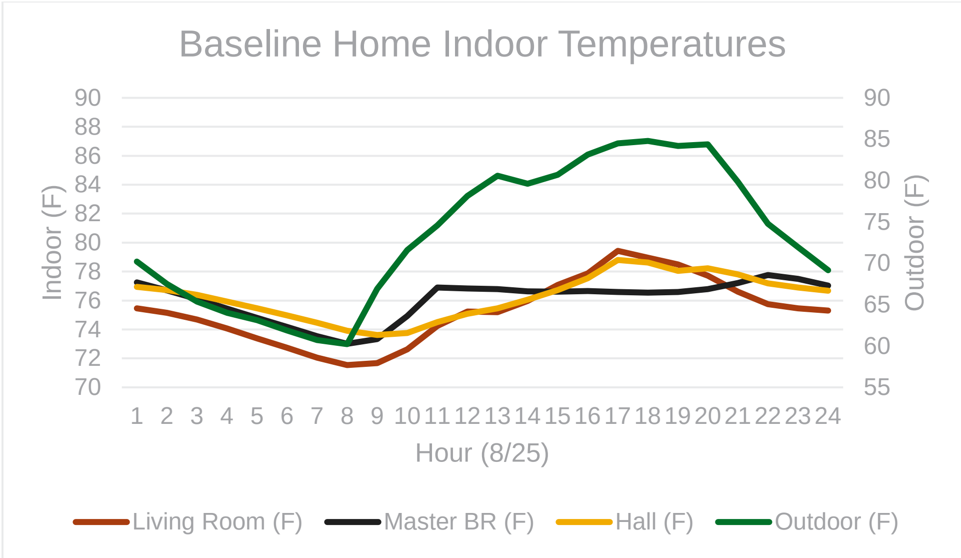

Figure A.65. Cooling Experiment – Zonal: Transfer Fans Baseline Home Indoor Temperatures

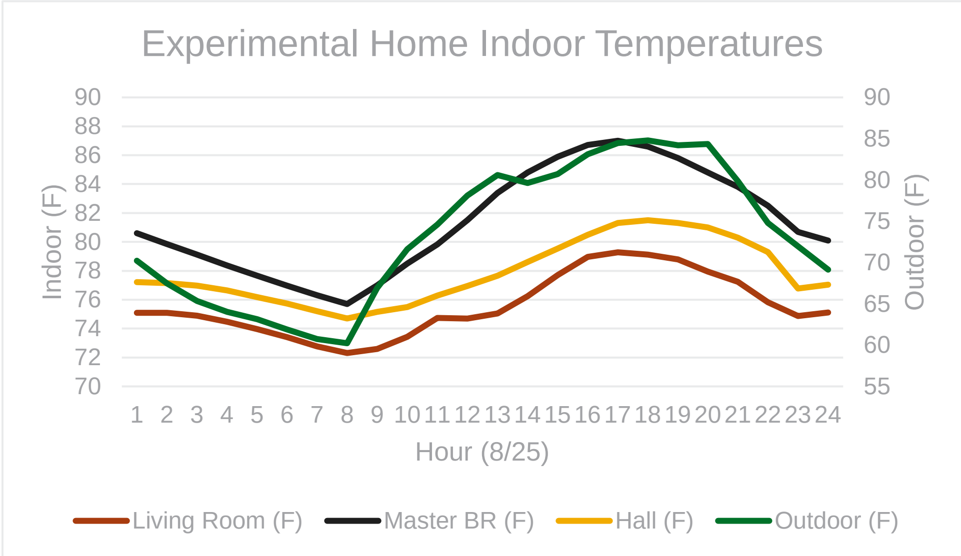

Figure A.66. Cooling Experiment – Zonal: Transfer Fans Experimental Home Indoor Temperatures

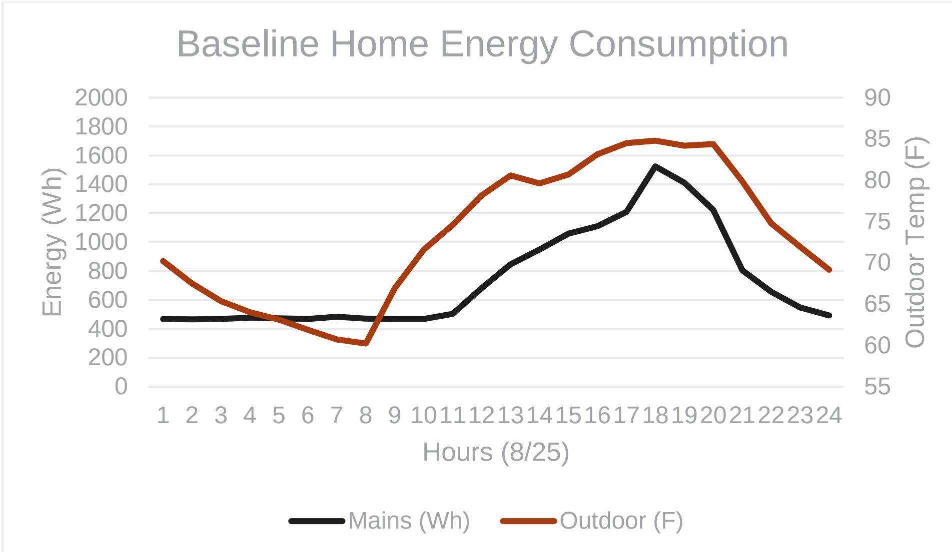

Figure A.67. Cooling Experiment – Zonal: Transfer Fans Baseline Home Energy Consumption

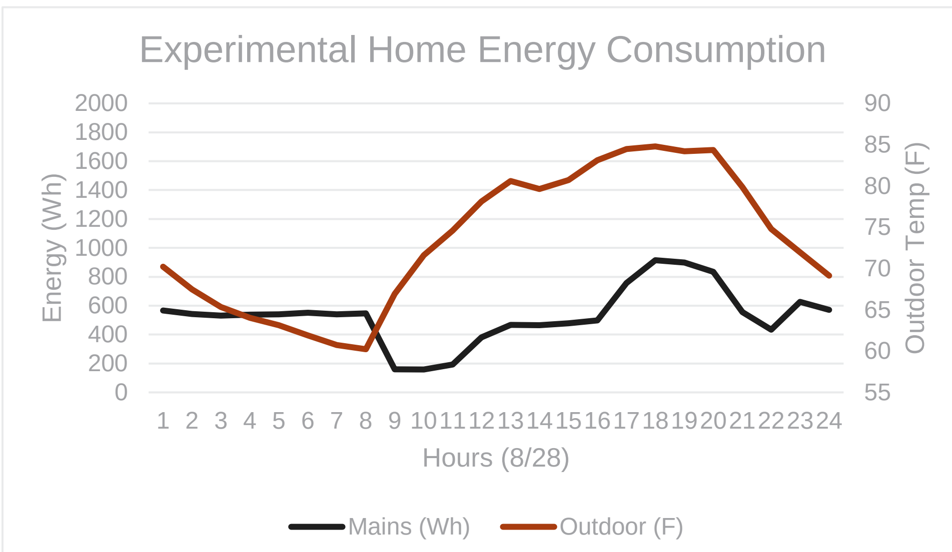

Figure A.68. Cooling Experiment – Zonal: Transfer Fans Experimental Home Energy Consumption

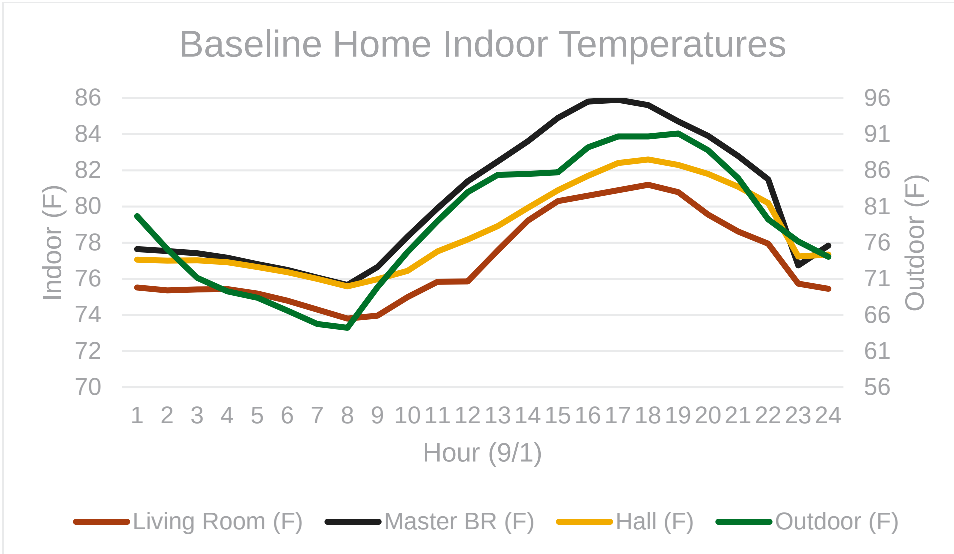

Figure A.69. Cooling Experiment – Zonal: Complex Schedule Baseline Home Indoor Temperatures

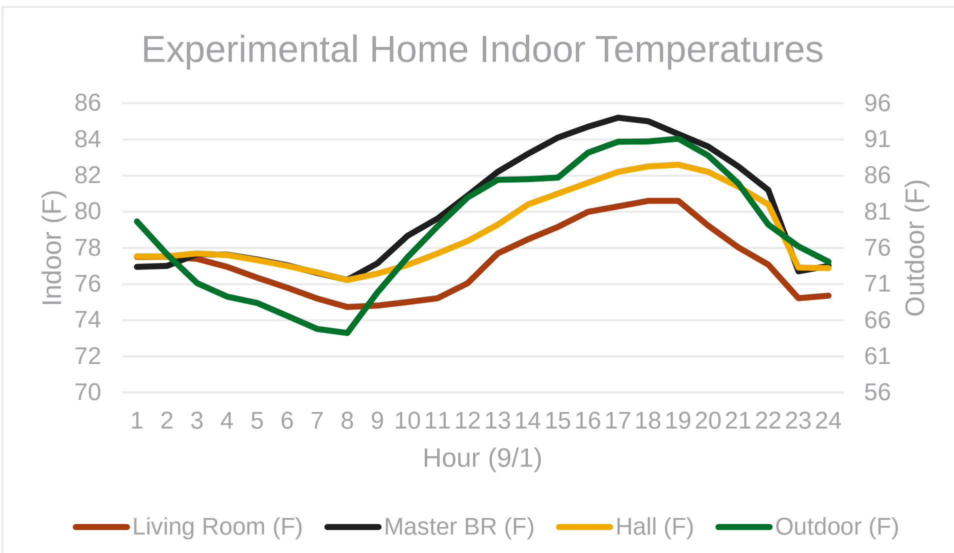

Figure A.70. Cooling Experiment – Zonal: Complex Schedule Experimental Home Indoor Temperatures

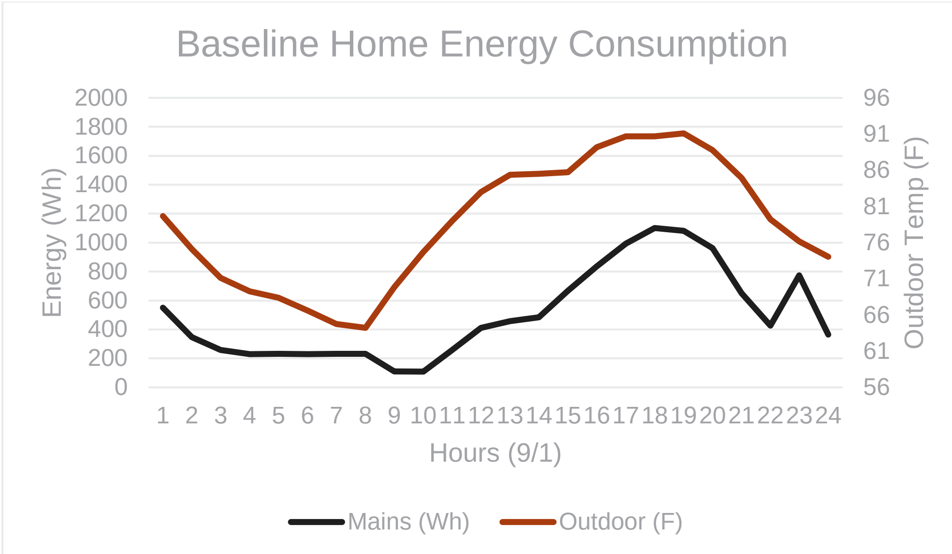

Figure A.71. Cooling Experiment – Zonal: Complex Schedule Baseline Home Energy Consumption

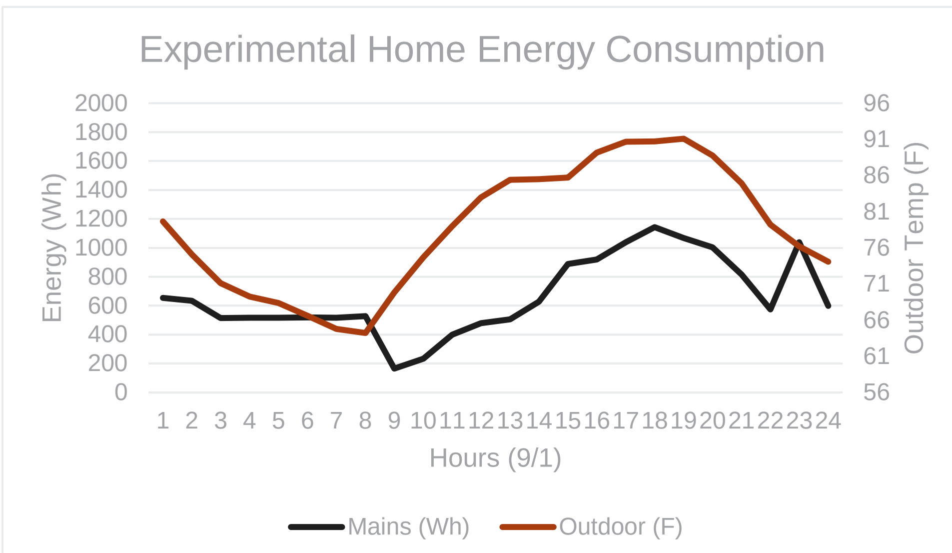

Figure A.72. Cooling Experiment – Zonal: Complex Schedule Experimental Home Energy Consumption

Appendix B – Lessons Learned from Third Party DHP Control Methods

STRATEGY A (Setpoint Reset): Reset thermostat settings to original configuration after manual change in setpoint:

Option 1: Chane default setting for hold time from “Until you change it” to “2 hours”.
Setting 1: Located on the ecobee thermostat (not available via the app) – Main Menu > Settings > Hold Action > “2 hours”
Option 1 Results: The setpoint will be returned to the temperature designated by the schedule.
Option 1 Challenges: If the user changes the “Comfort Settings” or “Schedule” the default temperature is also changed.

Option 2: Use IFTTT (“Date and Time” and “Ecobee”) to set the temperature every hour.
Option 2 Results: This is a very effective method as the setpoint is defined by the “Date and Time” IFTTT applet
Option 2 Challenges: This method overwrites any schedule configured in the Ecobee thermostat. The length of time can be set longer than every hour but is fixed. Also, this cannot be a nested statement meaning the temperature will be set to this defined value day and night.

STRATEGY B (Outdoor Reset): Prevent forced air furnace from running when outdoor temperatures are high enough that it is assumed that the ductless mini splits can support the heating load.

Option 1: Use IFTTT (“Weather Underground” and “Ecobee”) to resume the schedule of the thermostat (with a low setpoint) but when the outdoor temperature is low, adjust the thermostat setpoint to a higher value.
Option 1 Results/Challenges: This setting operates but with a delay. This delay was observed to be as long as twenty minutes which may be acceptable based on the chosen temperature settings.

Option 2: Use IFTTT (“Netatmo Weather Station” and “Ecobee”) to resume the schedule of the thermostat (with a low setpoint) but when the outdoor temperature is low, adjust the thermostat setpoint to a higher value.
Option 2 Results/Challenges: This setting operates with less delay than if Weather Underground is used as the trigger. This delay was observed to be only a few minutes.

Option 3: Use IFTTT (“Ecobee” and “Ecobee”) to resume the schedule of the thermostat (with a low setpoint) but when the outdoor temperature is low, adjust the thermostat setpoint to a higher value.
Option 2 Results/Challenges: This setting operates well, however, may not operate perfectly since outdoor temperature is updated by Ecobee cloud service approximately every five minutes rather than depending on local sensors.

STRATEGY C (Droop Control): Trying to force the Ecobee to always be 3-5 degrees lower than the DHP in heating mode (or vice versa in cooling mode):

Option 1: Use different setpoint on thermostat and the DHP.

Option 1 Challenges: if the user changes the setpoint on one device, the difference between the setpoints is also change. The other device would need to be set manually and this may require the comfort setting or schedule to be altered.

Option 2: No “affordable” automated method found.
Option 2 Challenges: Without complex third-party control algorithms, reading one device, performing a calculation based on the number read, and writing that calculated value to another device is problematic. This task can be accomplished but would take coding and equipment not currently available to the typical consumer at a low price. Complex custom applications are possible using device API but would have to be developed and are outside of the skill level of a typical consumer.

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