PNNL-29531

Maximizing the Use of Ductless Mini-Splits in the PNNL Lab Homes

December 2019

Travis Ashley
Cheryn E. Metzger
Jaime T. Kolln
Greg Sullivan

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

PACIFIC NORTHWEST NATIONAL LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

Printed in the United States of America

Available to DOE and DOE contractors from the
Office of Scientific and Technical Information,
P.O. Box 62, Oak Ridge, TN 37831-0062;
ph: (865) 576-8401
fax: (865) 576-5728
email: reports@adonis.osti.gov

Available to the public from the National Technical Information Service
5301 Shawnee Rd., Alexandria, VA 22312
ph: (800) 553-NTIS (6847)
email: orders@ntis.gov <https://www.ntis.gov/about>
Online ordering: http://www.ntis.gov

PNNL-29531

Maximizing the Use of Ductless Mini-Splits in the PNNL Lab Homes

December 2019

Travis Ashley
Cheryn E. Metzger
Jaime T. Kolln
Greg Sullivan

Prepared for
the U.S. Department of Energy
under Contract DE-AC05-76RL01830

Pacific Northwest National Laboratory
Richland, Washington 99354

Abstract

In the residential retrofit application, ductless mini-split heat pumps (DHP) are often reported to hold high-energy savings potential, depending on the system they are supplementing or replacing. However, of late, there have been a number of studies and analyses indicating these energy savings are not being achieved. The primary goal of this project was to determine the most 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 an existing home with central forced air furnace. Various control strategies were tested at the Pacific Northwest National Laboratory Lab Homes to compare the energy savings between the different energy efficient control strategies. A maximum of 40% energy savings was realized by using the ductless mini-split as the primary heat source with the central air conditioning unit as the secondary source.

Acknowledgments

The authors would like to thank Silicon Valley Power, the American Public Power Association, the Northwest Energy Efficiency Alliance, the Bonneville Power Administration and the New York State Research and Development Authority for their support for this project and important topic. This project would not be possible without the hard work of Graham Parker and Subrato Chandra who developed the concept and saw through the execution of the PNNL Lab Homes, located in Richland, WA. The authors would also like to thank Tom Eckhart for his knowledge and support of the use of ductless mini-splits as a retrofit option. Lastly, the authors would like to thank Sam Rosenburg for his thorough review of this report.

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
FAF – electric Forced Air Furnace
EIA – Energy Information Administration
HVAC - Heating Ventilation and Air-Conditioning
IECC – International Energy Conservation Code
Pa – Pascals
PNNL – Pacific Northwest National Laboratory
Wh – Watt-hour

Contents

Figures

Tables

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 (FAF).

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 major DHP manufacturers claim that their systems are up to 40% more efficient than existing HVAC systems in homes. Some people hypothesize that the lack of performance could be due to backup heat sources being used unnecessarily. When DHPs are used together with the CAC, the control strategy could negatively impact the net energy savings. To test some possible control strategies, 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

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 energy use by optimizing the control of ductless mini-split heat pumps in conjunction with existing heating equipment. 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. 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, with both using a CAC unit as a backup heating system. 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.

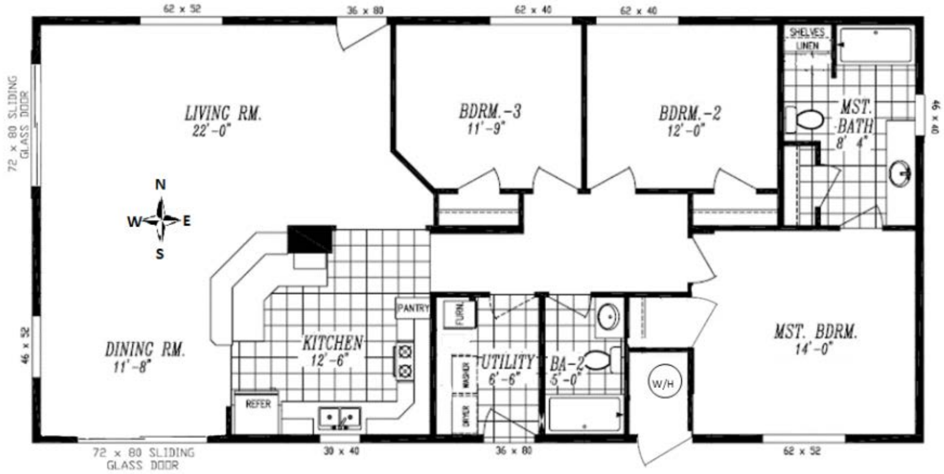

Figure 2 Lab Homes Architecture

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 an 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. This suggests that in order to produce significant savings, the furnace should be controlled so that DHP is used as the primary heat source. Further studies in the Pacific Northwest by Ecotope claim that even though the DHP provides most of the heat necessary for the home, the secondary heat provided by electric resistance heating energy use remains high because it is being delivered at about three times the energy input of the DHP system [10]. This study suggests that a significant amount of power 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 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; thus, opportunity for energy savings decreases during the night hours by having the DHP installed in the living room. Additional DHPs could be deployed to bedrooms to provide supplemental heating so that the electric resistance heating would not be required, but this is not always the case due to the added cost of installing multiple DHPs.

2.0 Methodology

2.1 Test Setup

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. The indoor unit was mounted to the wall between the dining room and living room about 1' from the ceiling. The two components connect using insulated refrigerant piping that was attached to the lower exterior walls along the home. A hole was drilled through the wall behind the DHP for the piping to be attached to the indoor unit. The 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. 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.

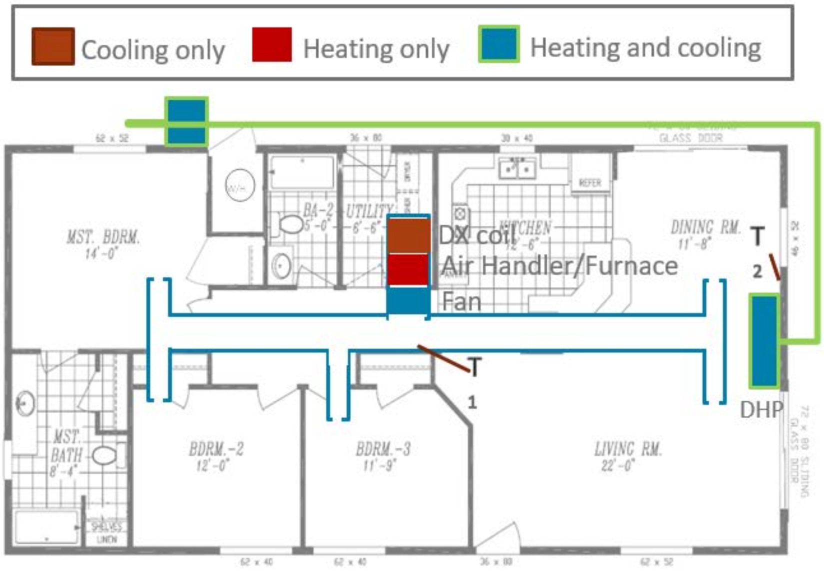

Figure 3 Central Heating/Cooling Lab Homes Setup

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.

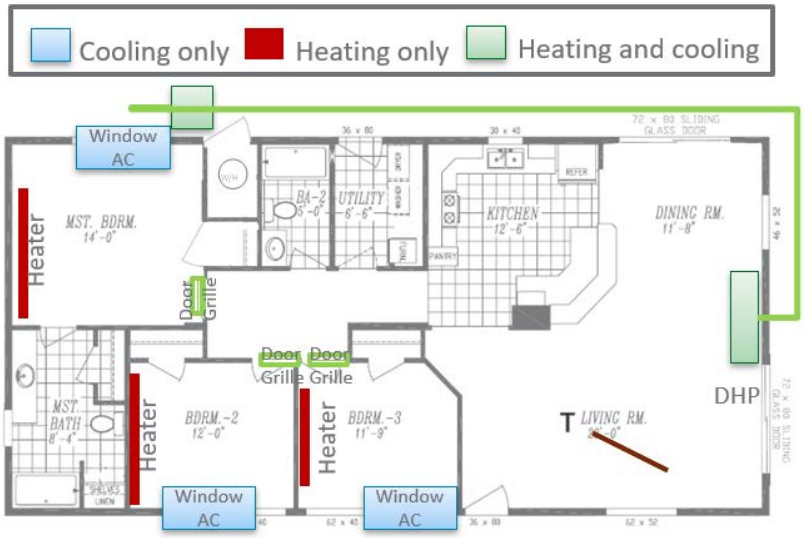

Figure 4 Zonal Heating/Cooling Lab Homes Setup

2.2 Heating Experiment – Central

2.2.1 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.

2.2.2 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. 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 71F 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.

2.2.3 Heating Experiment - Central: eFAF 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.

2.2.4 Heating Experiment - Central: Central eFAF 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 under 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 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.

2.2.5 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.

2.3 Heating Experiment – Zonal

2.3.1 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. 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, for 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. In all of these cases, the central system was turned off.

2.3.2 Heating Experiment – Zonal: Experiment Calibration

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

2.3.3 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.

2.3.4 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. Additionally, it was important to find out if this strategy saved energy or used more than the baseline. 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).

2.3.5 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.

2.4 Cooling Experiment – Central

2.4.1 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 to89 °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.

2.4.2 Cooling Experiment – Central: Experiment Calibration

The home calibration for the central cooling experiments ran from July 21st to July 27th, 2019. 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.

2.4.3 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.

2.4.4 Cooling Experiment – Central: Central System 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.

2.4.5 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.

2.5 Cooling Experiment – Zonal

2.5.1 Cooling Experiment – Zonal: Test Condition

The zonal cooling experiments from in the Summer, 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), that would be the only way they would be cooling the bedrooms. The Baseline Home was configured the same for all of the experiments in this section with both the DHP and the window AC units set to 76 °F cooling and the fans set to auto.

2.5.2 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 systems set to a cooling setpoint of 76 °F. The calibration was conducted with both the bedroom doors opened and closed.

2.5.3 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 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.

2.5.4 Cooling Experiment – Zonal: Transfer Fans

The goal of this experiment was to understand if there was any 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. Bedroom doors were closed in both homes for this experiment.

2.5.5 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.

3.0 Results

3.1 Heating Experiment – Central

3.1.1 Heating Experiment – Central: Experiment Calibration

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 2,907 kWh/day or 4.1%, 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 1,634 kWh/day or 6.3%, with the Baseline Home using more energy.

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 4% for the rest of the central heating experiments).

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 4.5% difference in the air leakage with the Baseline Home having slightly more air leakage than the Experimental Home.

3.1.2 Heating Experiment – Central: eFAF Fan Only

This experiment was conducted to determine if 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 HVAC system by itself rather than trying to replace the heat source using only 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 1 below.

Table 1 Heating Experiment – Central: eFAF Fan Only Summary

	Baseline Home (Wh)	Experimental Home (Wh)	Savings (%)	Adjusted Savings
3/16/2019	49,937	35,692	29%	
3/17/2019	42,345	33,086	22%	
Average	46,141	34,389	25%	21%

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

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, due to the DHP thermostat being located in there. The master bedroom temperatures hovered around 70 °F in both homes, except during the mid-day solar gains when it floated above setpoint.

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 2 below.

Table 2 Heating Experiment – Central: eFAF Offset Summary

	Baseline Home (Wh)	**Experimental Home (Wh)**	**Savings (%)**	**Savings Adjustment (%)**
2/23/2019	78,886	43,647	45%	
2/24/2019	105,051	66,345	37%	
Average (Grilles Closed)	91,969	54,996	40%	36%
3/02/2019	84,157	59,084	30%	
3/03/2019	98,251	61,959	37%	
Average (Grilles Open)	91,204	60,521	34%	30%

3.1.4 Heating Experiment – Central: Complex Schedules

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 on this day correlated with their power expenditures. The Baseline Home had higher energy use than the Experimental Home in both the morning and night, which caused higher temperatures. In midday the Experimental Home kept using power while the Baseline Home did not. The temperatures in the Experimental Home exceeded those of the Baseline Home during this time. 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 3.

Table 3 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%	

Average	92,510	59,992	35%	31%

3.1.5 Heating Experiment – Central: Summary of Results

Table 4 Heating Experiment – Central: Summary

Experiment	Adjusted Savings
Heating Experiment – Central: eFAF Fan Only	21%
Heating Experiment – Central: Offset (Grilles Closed)	36%
Heating Experiment – Central: Offset (Grilles Open)	30%
Heating Experiment – Central: Complex Schedule	31%

3.2 Heating Experiment – Zonal

3.2.1 Heating Experiment – Zonal: Experiment Calibration

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, and mostly stayed within the 2-4 kWh range each hour. 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. The living room and hall sensors appear to be located near the fan flow for the DHP because although they keep 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 5. For the zonal experiment, the houses were able to maintain more reasonable (and typical compared to previous experiments in the Lab Homes) calibration differences. Therefore, it was decided to continue to use this baseline for the duration of the zonal heating experiments.

Table 5 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%
Average	51,071	47,970	6.1%
3/13/2019 (Doors Closed)	38,407	35,724	7%
3/14/2019 (Doors Closed)	39,246	39,069	0.5%
Average	38,826	37,396	3.7%

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% (rounded up to 4%) 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 provides the industry with some information about 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.

3.2.2 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 6.

Table 6 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	22,567	34%	
Average	32,209	21,568	33%	29%

3.2.3 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 7**.**

Table 7 Heating Experiment – Zonal: Transfer Fans Summary

	Baseline Home (Wh)	**Experimental Home (Wh)**	**Savings (%)**	**Adjusted Savings (%)**
4/2/2019	39,300	38,715	1.5%	
4/3/2019	38,213	30,761	20%	
4/4/2019	41,761	31,640	24%	
Average	33,706	39,758	15%	11%

3.2.4 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 8.

Table 8 Heating Experiment – Zonal: Complex Schedule Summary

	Baseline Home (Wh)	**Experimental Home (Wh)**	**Savings (%)**	**Adjusted Savings (%)**
4/23/2019	26815	16310	39%	
4/24/2019	30412	20992	31%	
Average	28614	18651	35%	31%

3.2.5 Heating Experiment – Zonal: Summary of Results

Table 9 Heating Experiment – Zonal: Summary

Experiment	Adjusted Savings
Heating Experiment – Zonal: Zonal Bedroom Setback	29%
Heating Experiment – Zonal: Zonal Transfer Fans	11%
Heating Experiment – Zonal: Complex Schedule	31%

3.3 Cooling Experiment – Central

3.3.1 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 10.

Table 10 Cooling Experiment – Central: Experiment Calibration Summary

	Baseline Home (Wh)	Experimental Home (Wh)	Savings (%)
7/21/2019	23,181	24,464	-5.5%
7/22/1919	25,147	28,871	-14.8%
7/23/2019	28,298	31,183	-10.2%
7/24/2019	Data error, data not used		
7/25/1919	18,409	21,692	-17.8%
7/26/2019	26,044	29,605	-13.7%
7/27/2019	22,503	24,846	-10.4%
Average	23,930	26,777	-12%

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.

3.3.2 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 temperature measured by 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 11.

Table 11 Cooling Experiment – Central: Central Fan Only Summary

	Baseline Home (Wh)	Experimental Home (Wh)	Savings (%)	Adjusted Savings (%)
6/22/19	11,877	22,304	-88%	
6/23/19	6,843	20,192	-195%	
6/24/19	9,949	21,413	-115%	
6/25/19	10,405	22,351	-115%	
6/26/19	8,046	20,240	-152%	
Average	9,424	21,300	-133%	-121%

This is not a recommended approach for homes with previously existing central cooling. 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.

3.3.3 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. Both homes had about the same variance of degrees away from the setpoint at about 3 °F below and about 4 °F above in the living room.

The Baseline Home used significantly more energy than the Experimental Home. The summary of the experimental energy use is shown below in Table 12.

Table 12 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%	
Average	20,478	13,858	32%	44%

3.3.4 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 13.

Table 13 Cooling Experiment – Central: Complex Schedule Summary

	Baseline Home (Wh)	Experimental Home (Wh)	Savings (%)	Adjusted Savings (%)
7/9/2019	15,573	10,992	29%	
7/10/2019	20,164	14,035	30%	
7/11/2019	18,421	12,942	30%	
7/12/2019	19,752	14,652	26%	
7/13/2019	17,156	12,551	27%	
Average	18,213	13,034	28%	40%

3.3.5 Cooling Experiment – Central: Summary of Results

Table 14 Cooling Experiment – Central: Summary

Experiment	Adjusted Savings (%)
Cooling Experiment – Central: Central Fan Only	-121%
Cooling Experiment – Central: Central Offset	44%
Cooling Experiment – Central: Complex Schedule	40%

3.4 Cooling Experiment – Zonal

3.4.1 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 15.

Table 15 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%
Average (Doors Open)	16,471	17,472	-6%
8/14/2019	20,573	19,566	5%
8/15/2019	21,554	20,061	7%
Average (Doors Closed)	21,064	19,813	6%

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

3.4.2 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 16.

Table 16 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%	
Average	16,559	12,297	26%	32%

3.4.3 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 17.

Table 17 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%	
Average	17,701	12,327	30%	24%

3.4.4 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 18.

Table 18 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%	
Average	19,191	12,933	32%	26%

3.4.5 Cooling Experiment – Zonal: Summary of Results

Table 19 Cooling Experiment – Zonal: Summary

Experiment	Adjusted Savings
Cooling Experiment – Zonal: Bedroom Setback	32%
Cooling Experiment – Zonal: Transfer Fans	24%
Cooling Experiment – Zonal: Complex Schedule	26%

4.0 Conclusion

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 20.

Table 20 Recommended Control Strategies for Given Scenarios

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

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.

5.0 References

1. Energy Information Administration. Table 1.1 Primary Energy Overview, pg. 3. “August 2019 Monthly Energy Review”. Department of Energy. https://www.eia.gov/totalenergy/data/monthly/archive/00351908.pdf.

2. Energy Information Administration. Table 2.1 Energy Consumption by Sector, pg. 35. “August 2019 Monthly Energy Review”. Department of Energy. https://www.eia.gov/totalenergy/data/monthly/archive/00351908.pdf.

3. Energy Information Administration: https://www.eia.gov/consumption/residential/

4. Metzger, et al. “Are ducted minisplits worth it?”. https://www.osti.gov/pages/servlets/purl/1424577

5. Sutherland, et al. “Evaluation of Mini-Split Heat Pumps as Supplemental and Full System Retrofits in a Hot Humid Climate”. https://aceee.org/files/proceedings/2016/data/papers/1_162.pdf.

6. Geraghty et al. 2009 “Residential Ductless Mini-Split Heat Pump Retrofit Monitoring: 2008-2010 Analysis”. https://pdfs.semanticscholar.org/891a/69bcf42aefddc51e81a99b0af64831839723.pdf.

7. Geraghty et al. 2010 “Residential Ductless Mini-Split Heat Pump Retrofit Monitoring: 2008-2010 Analysis”. https://www.bpa.gov/EE/Technology/EE-emerging-technologies/Projects-Reports-Archives/Documents/BPA-Report_DHP-Retrofit-Monitor-Y2-Sept2010.pdf

8. Korn et al. “Ductless Mini-Split Heat Pump Impact Evaluation”. http://ma-eeac.org/wordpress/wp-content/uploads/Ductless-Mini-Split-Heat-Pump-Impact-Evaluation.pdf

9. Baylon. https://www.bpa.gov/ee/technology/ee-emerging-technologies/projects-reports-archives/documents/dhp_faf_dec_12.pdf

10. Baylon, 2012. https://neea.org/img/uploads/ductless-heat-pump-impact-process-evaluation-field-metering-report.pdf

Appendix A – Daily Profiles for Indoor Temperatures and Energy Consumption

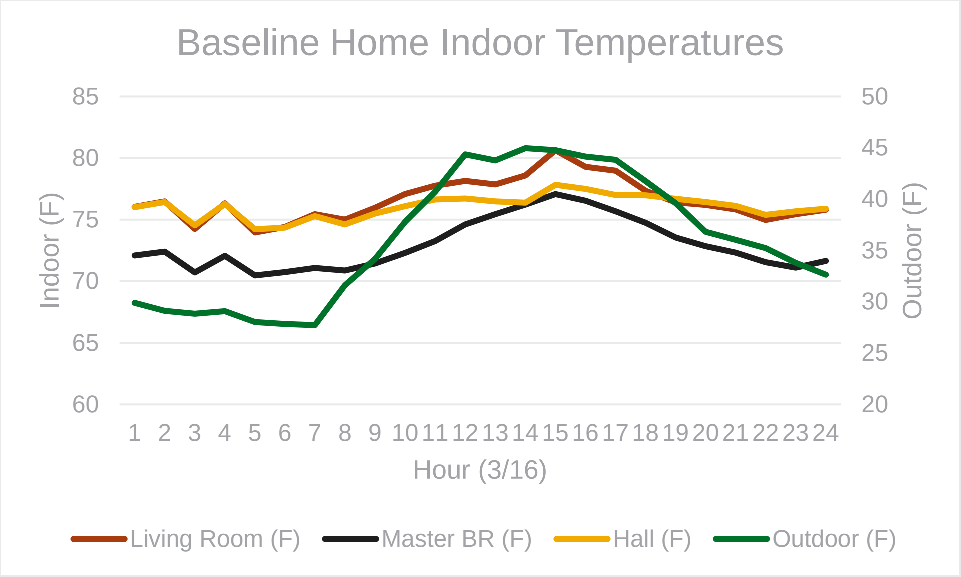

Figure 5 Heating Experiment – Central: eFAF Only Baseline Home Indoor Temperatures

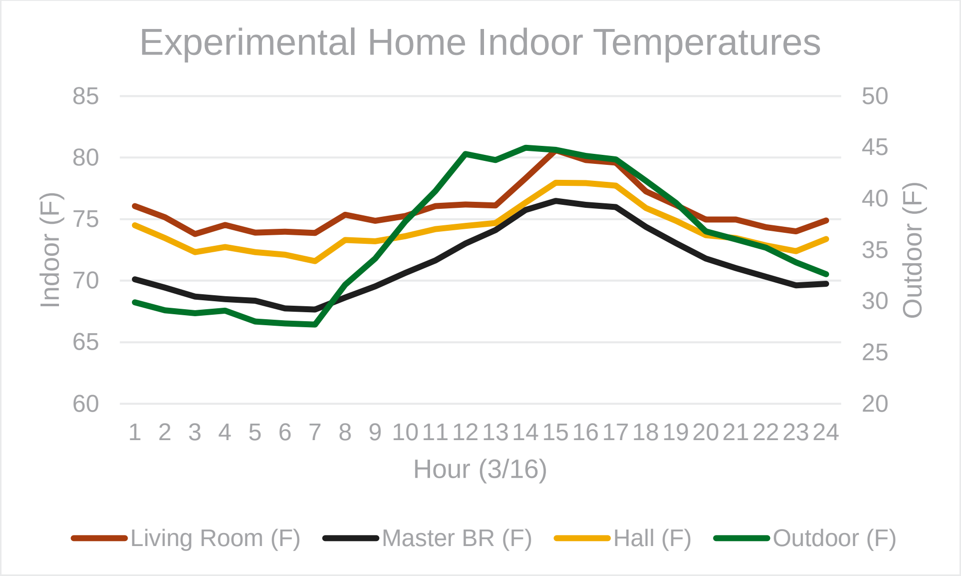

Figure 6 Heating Experiment – Central: eFAF Only Experimental Home Indoor Temperatures

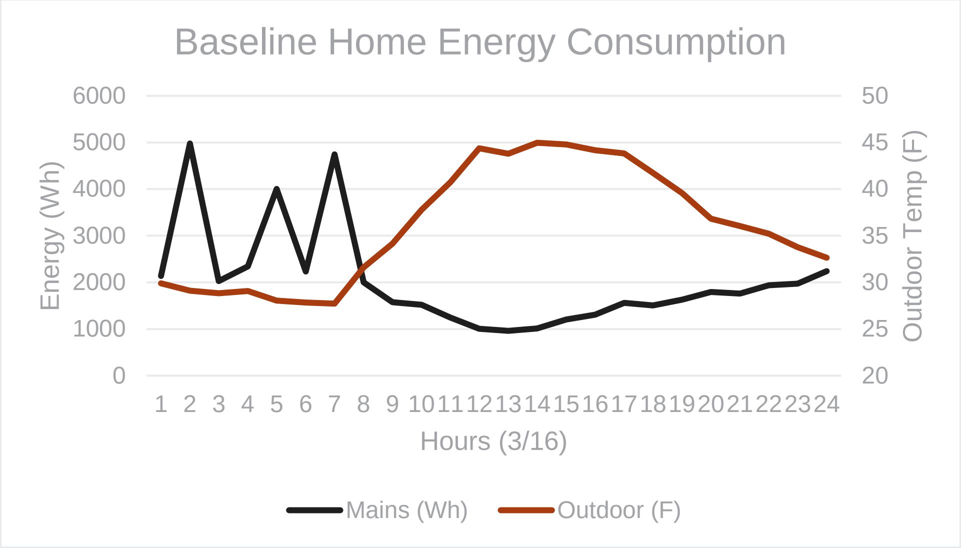

Figure 7 Heating Experiment – Central: eFAF Only Baseline Home Energy Consumption

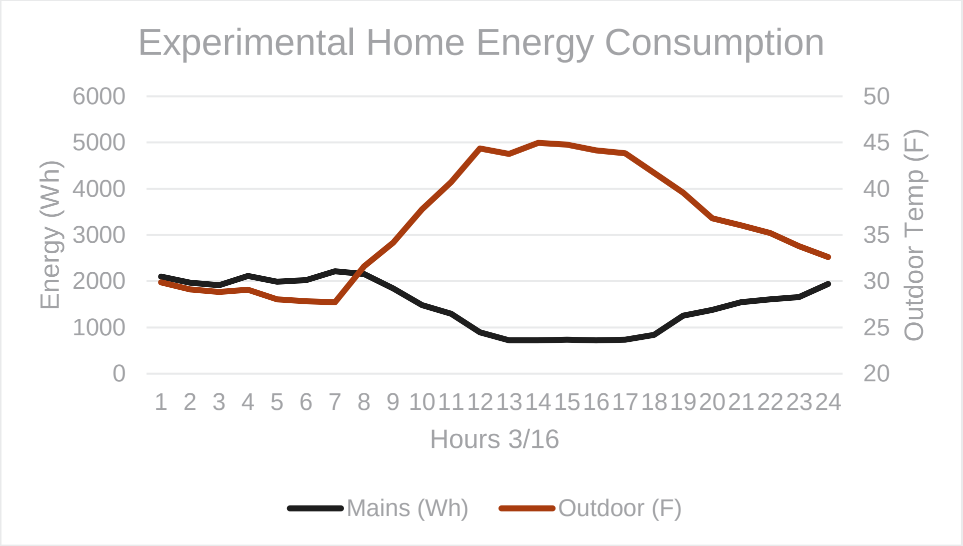

Figure 8 Heating Experiment – Central: eFAF Only Experimental Home Energy Consumption

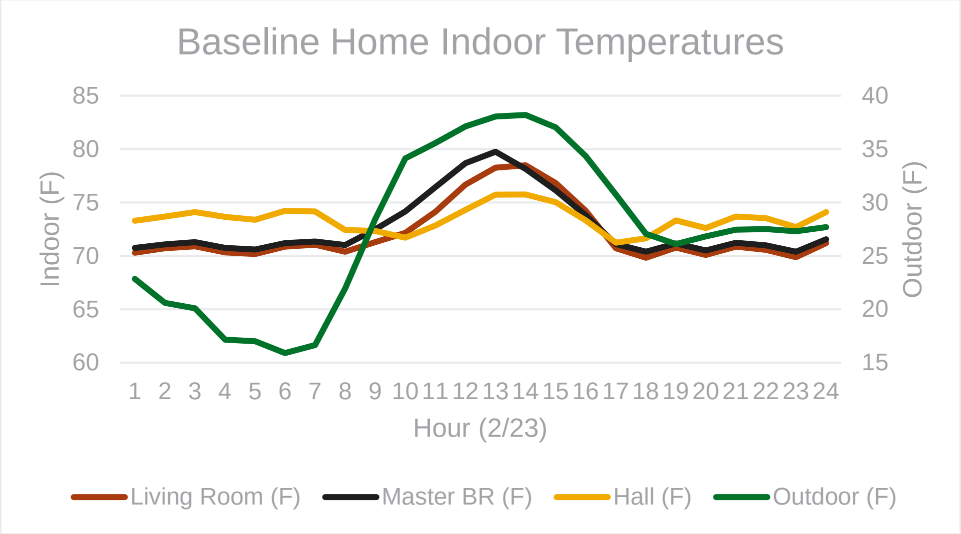

Figure 9 Heating Experiment – Central: eFAF Offset Baseline Home Indoor Temperatures

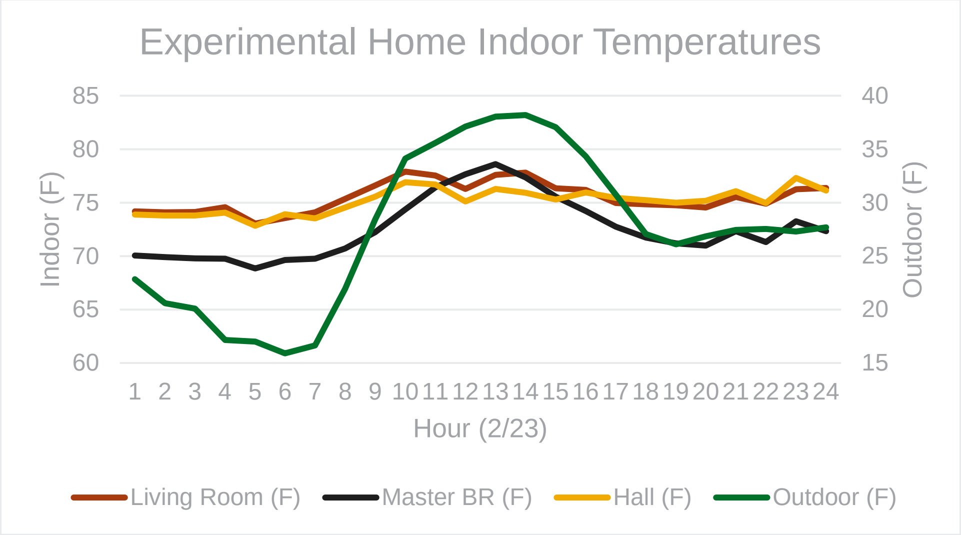

Figure 10 Heating Experiment – Central: eFAF Offset Experimental Home Indoor Temperatures

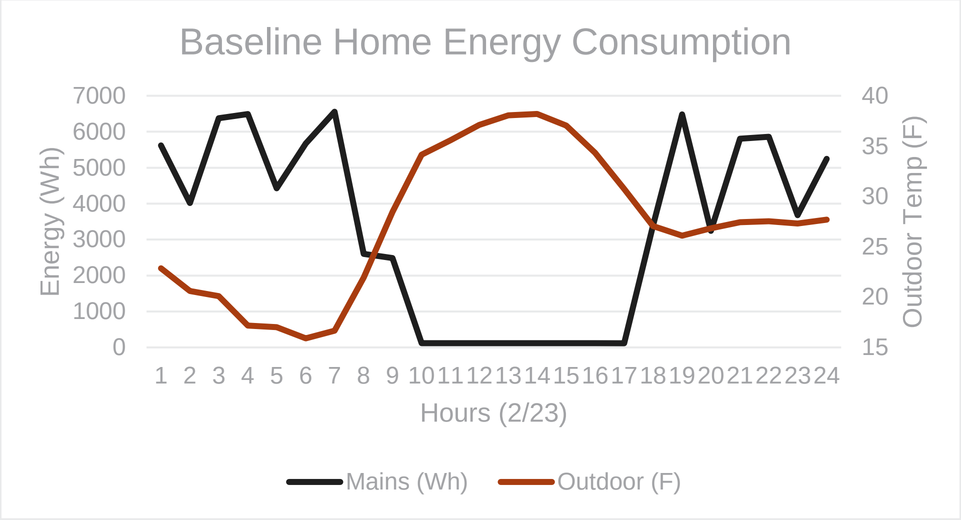

Figure 11 Heating Experiment – Central: eFAF Offset Baseline Home Energy Consumption

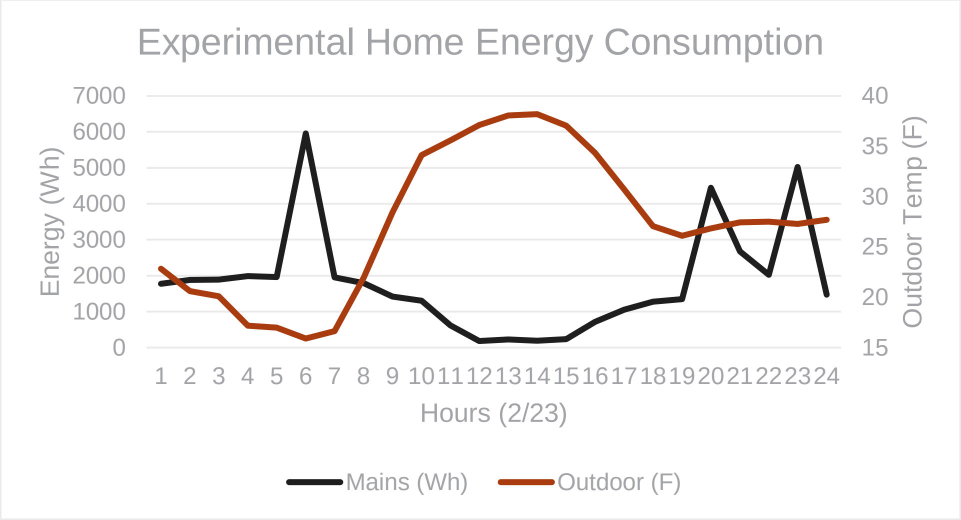

Figure 12 Heating Experiment – Central: eFAF Offset Experimental Home Energy Consumption

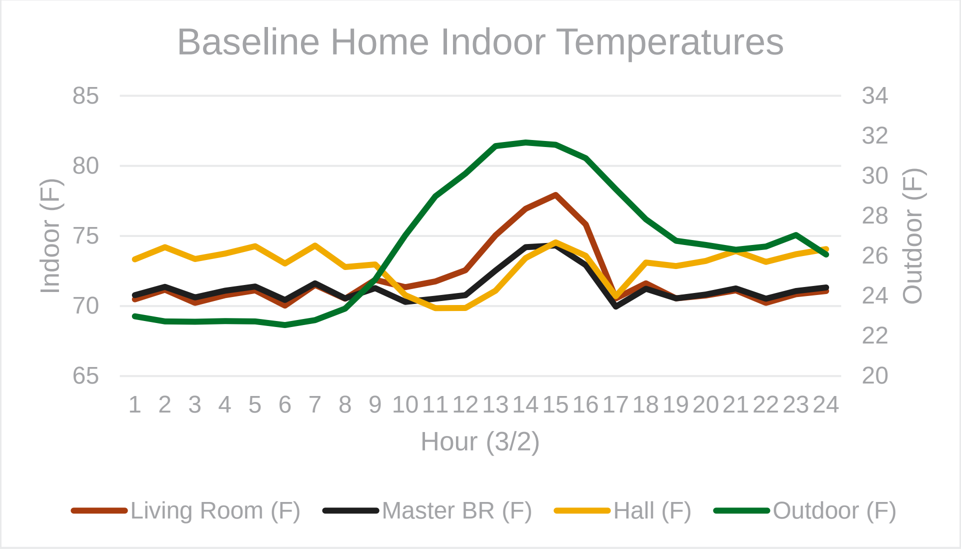

Figure 13 Heating Experiment – Central: eFAF Offset 2 Baseline Home Indoor Temperatures

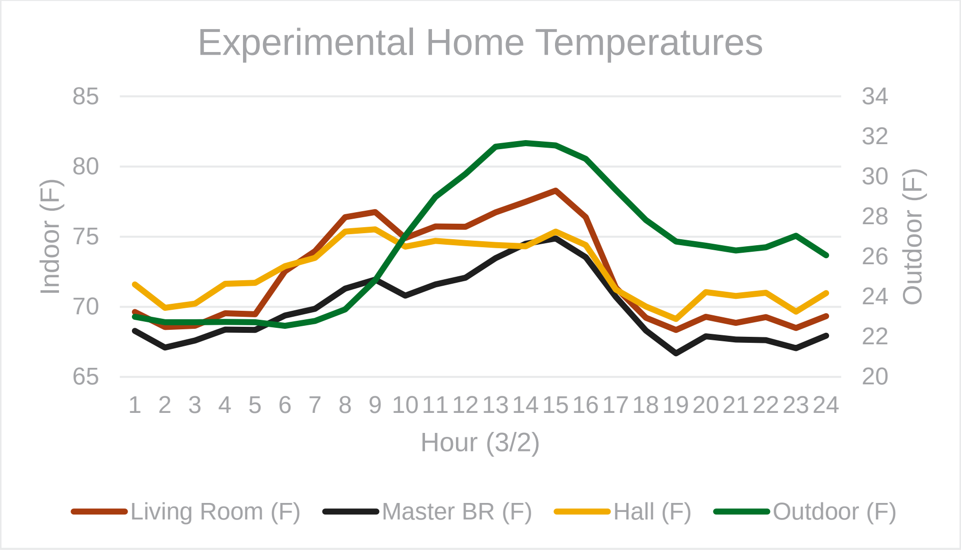

Figure 14 Heating Experiment – Central: eFAF Offset 2 Experimental Home Indoor Temperatures

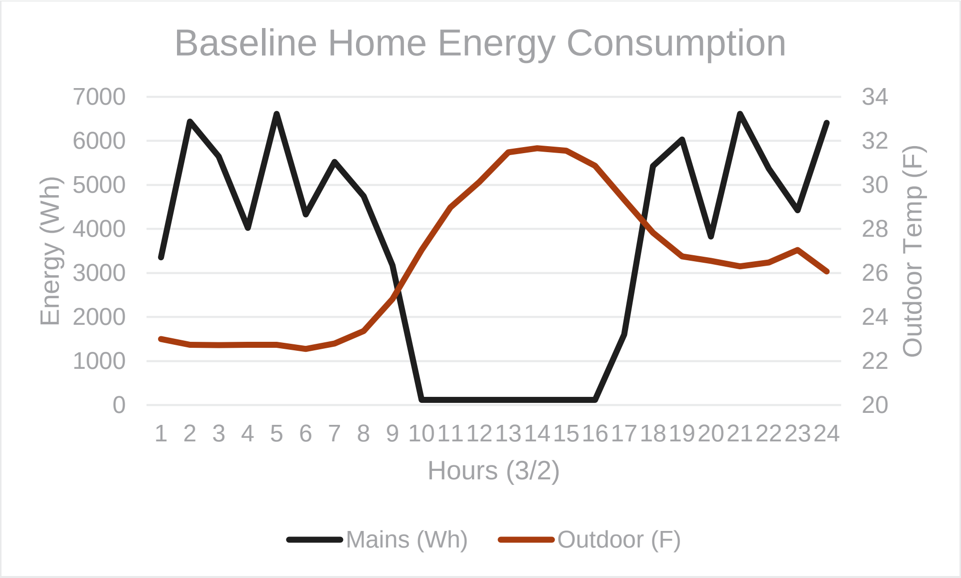

Figure 15 Heating Experiment – Central: eFAF Offset 2 Baseline Home Energy Consumption

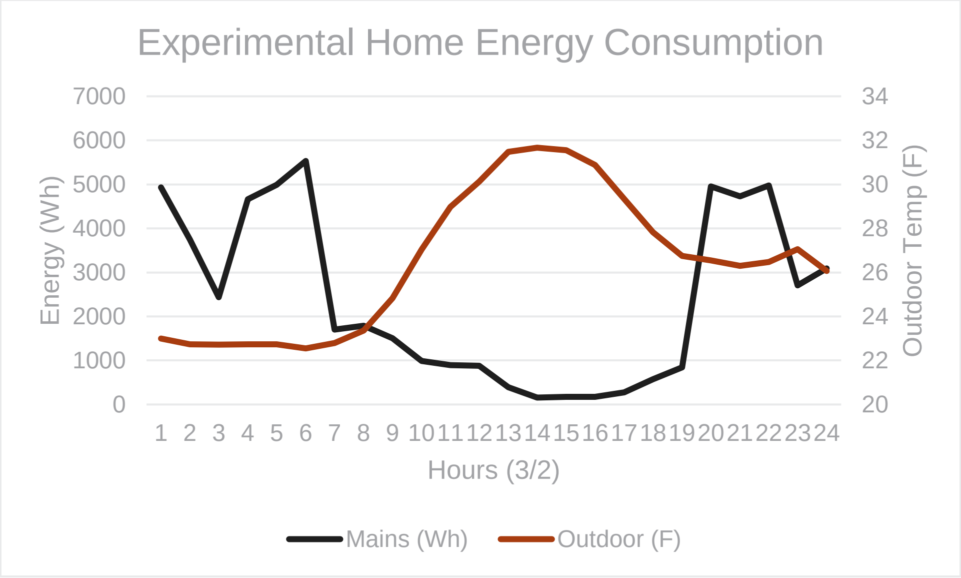

Figure 16 Heating Experiment – Central: eFAF Offset 2 Experimental Home Energy Consumption

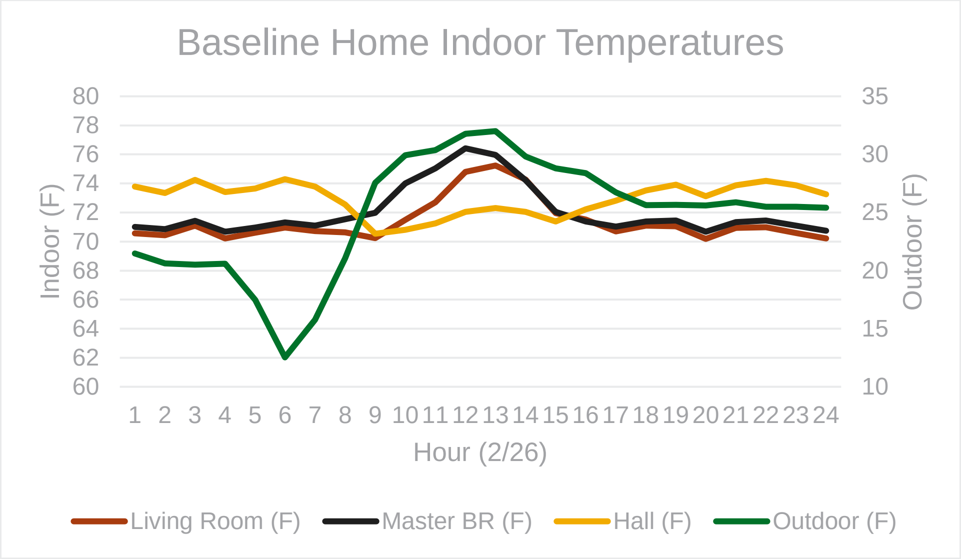

Figure 17 Heating Experiment – Central: Complex Schedules Baseline Home Indoor Temperatures

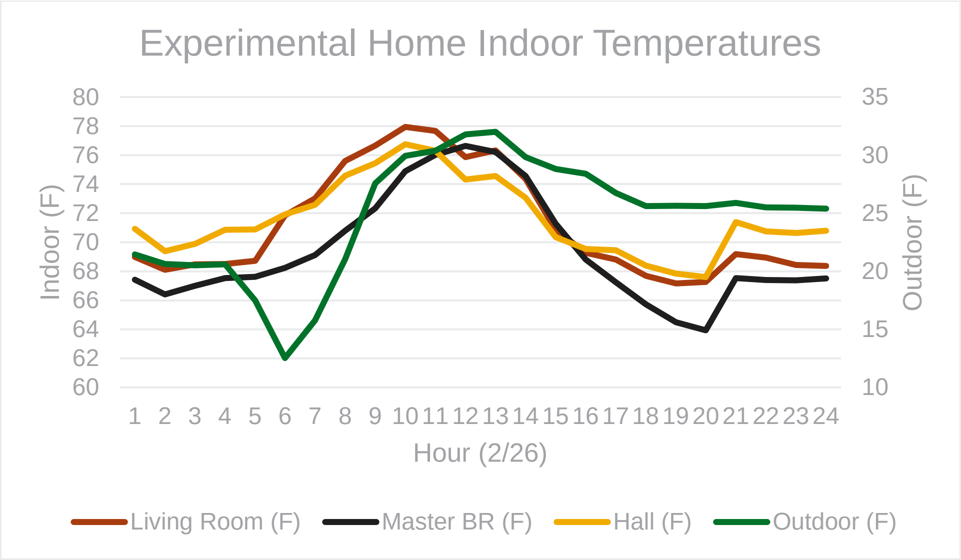

Figure 18 Heating Experiment – Central: Complex Schedules Experimental Home Indoor Temperatures

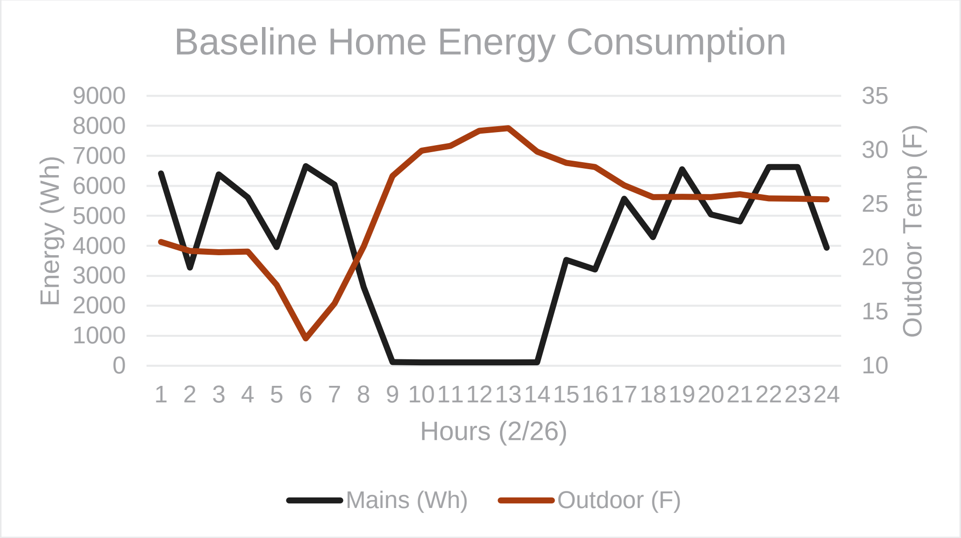

Figure 19 Heating Experiment – Central: Complex Schedules Baseline Home Energy Consumption

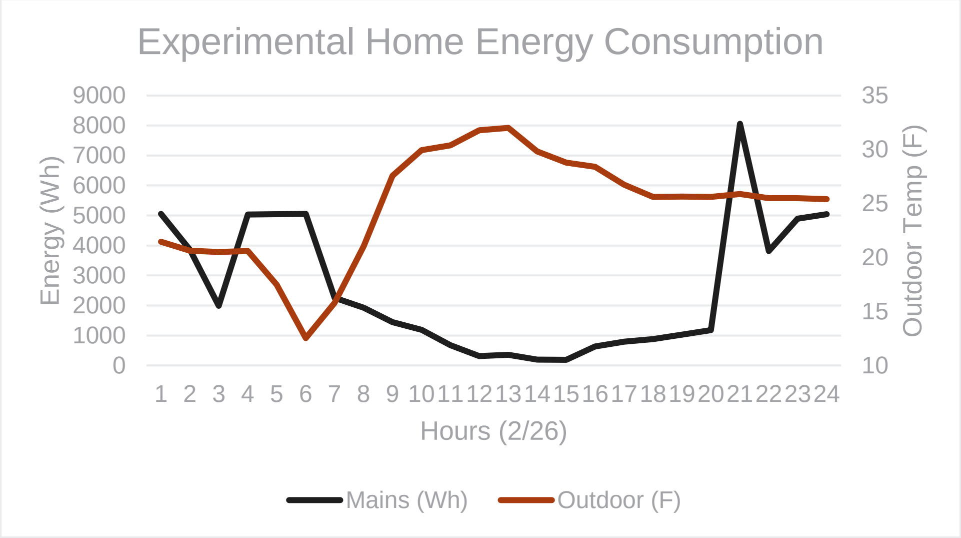

Figure 20 Heating Experiment – Central: Complex Schedules Experimental Home Energy Consumption

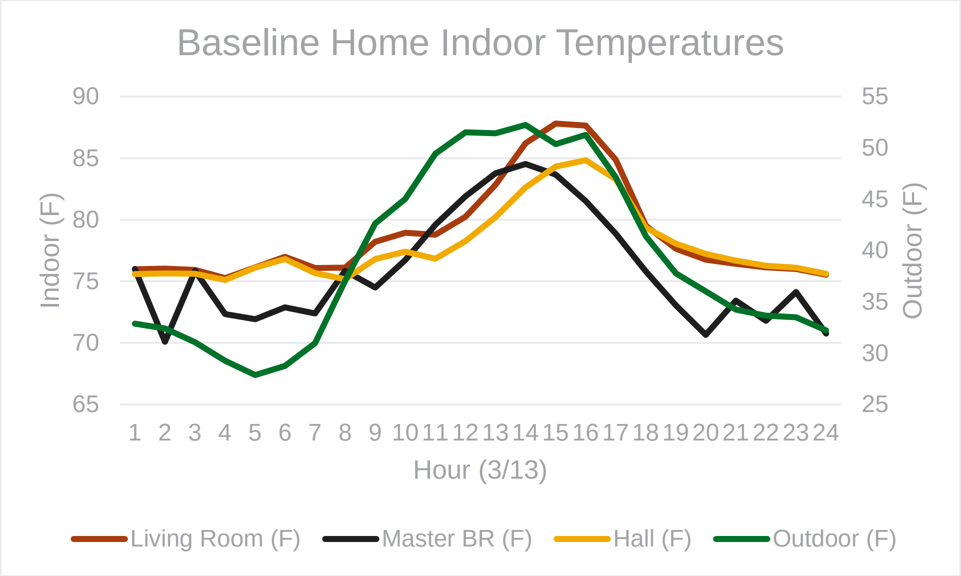

Figure 21 Heating Experiment – Zonal: Home Calibration, Doors Closed Baseline Home Indoor Temperatures

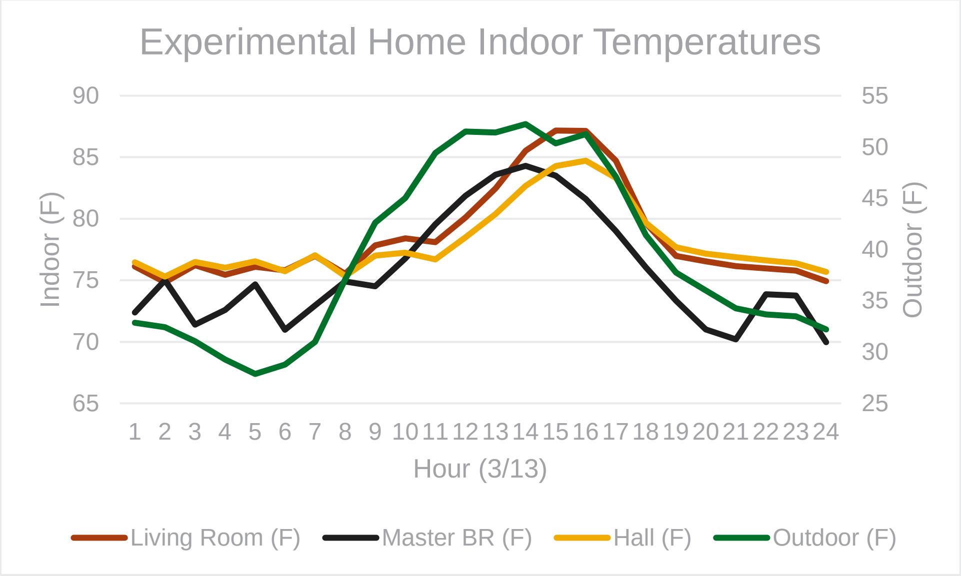

Figure 22 Heating Experiment – Zonal: Home Calibration, Doors Closed Experimental Home Indoor Temperatures

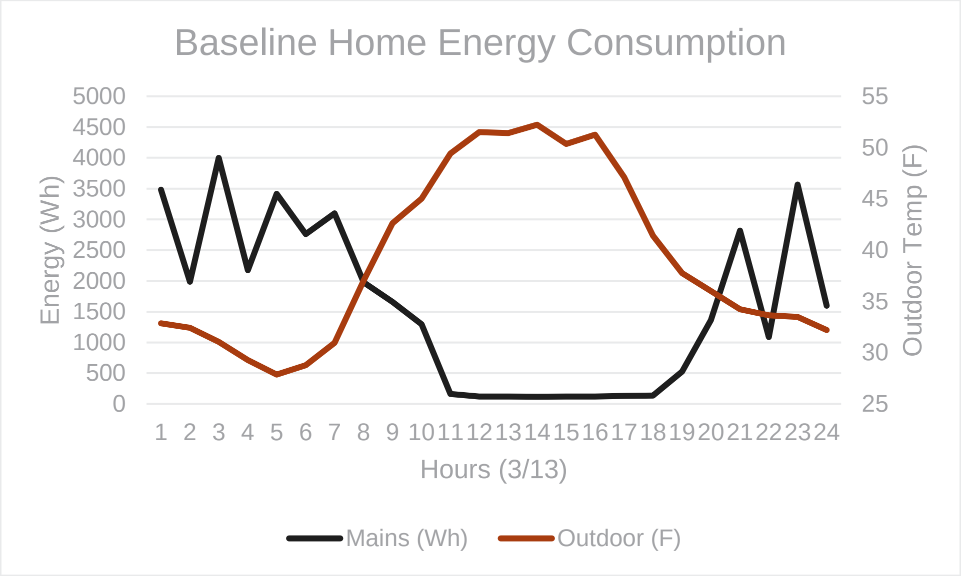

Figure 23 Heating Experiment – Zonal: Home Calibration, Doors Closed Baseline Home Energy Consumption

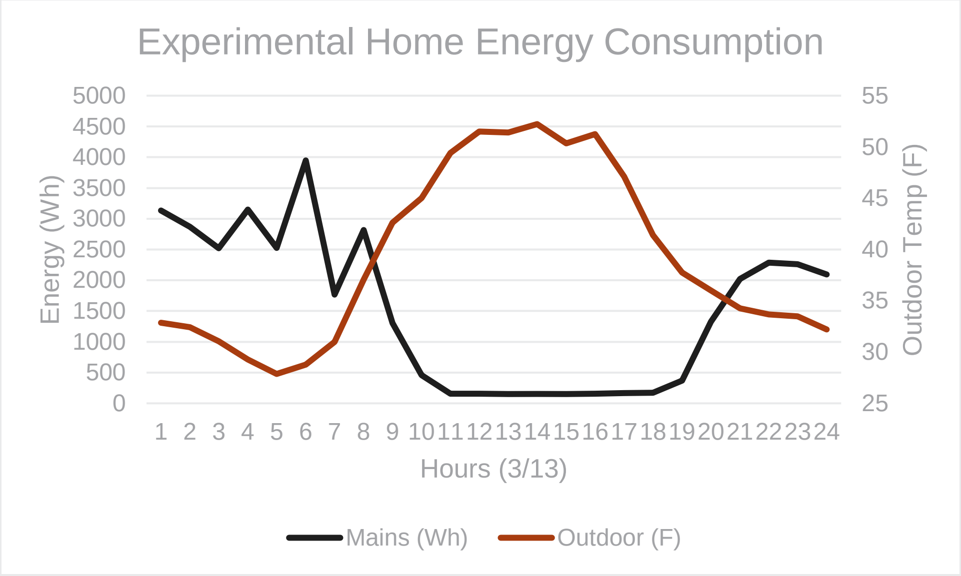

Figure 24 Heating Experiment – Zonal: Home Calibration, Doors Closed Experimental Home Energy Consumption

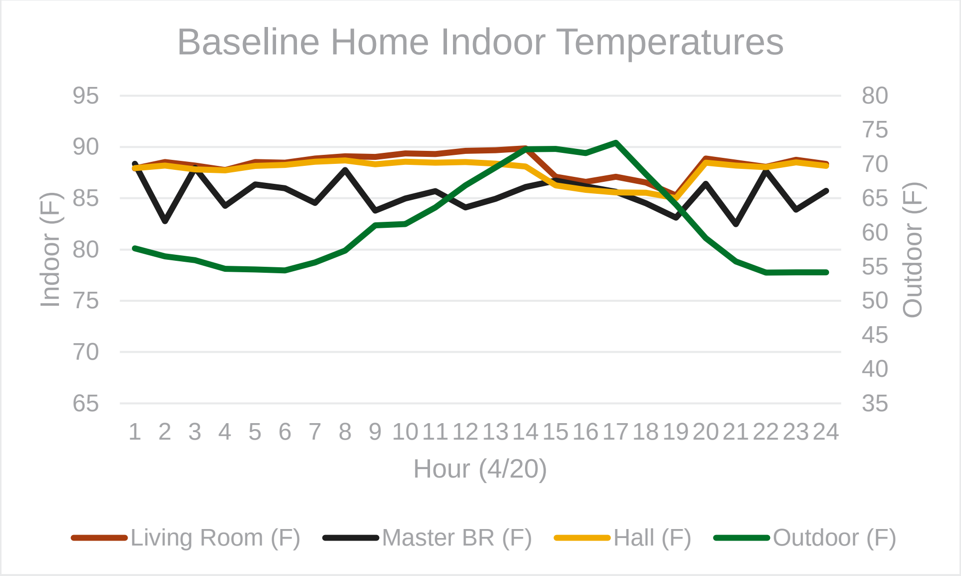

Figure 25 Heating Experiment – Zonal: Bedroom Setback Baseline Home Indoor Temperatures

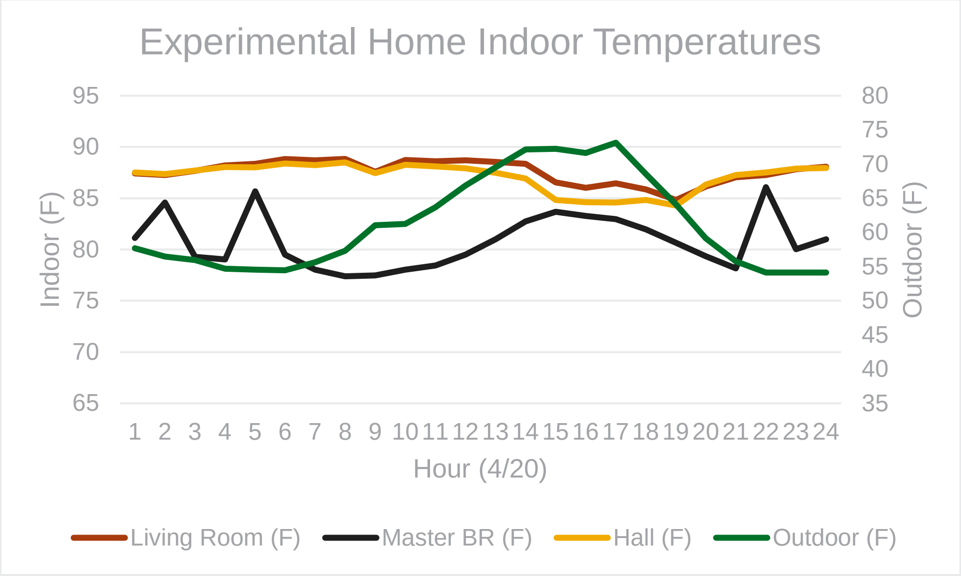

Figure 26 Heating Experiment – Zonal: Bedroom Setback Experimental Home Indoor Temperatures

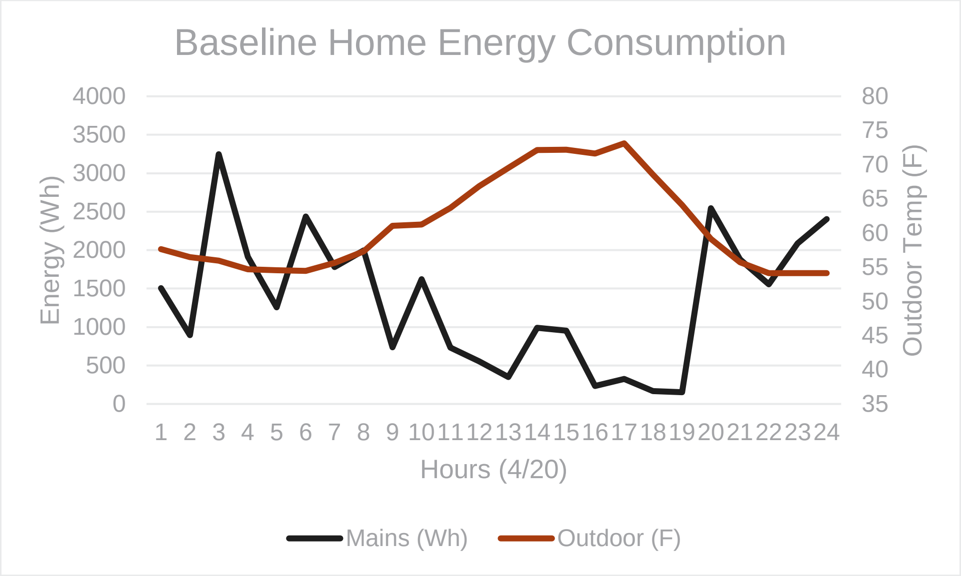

Figure 27 Heating Experiment – Zonal: Bedroom Setback Baseline Home Energy Consumption

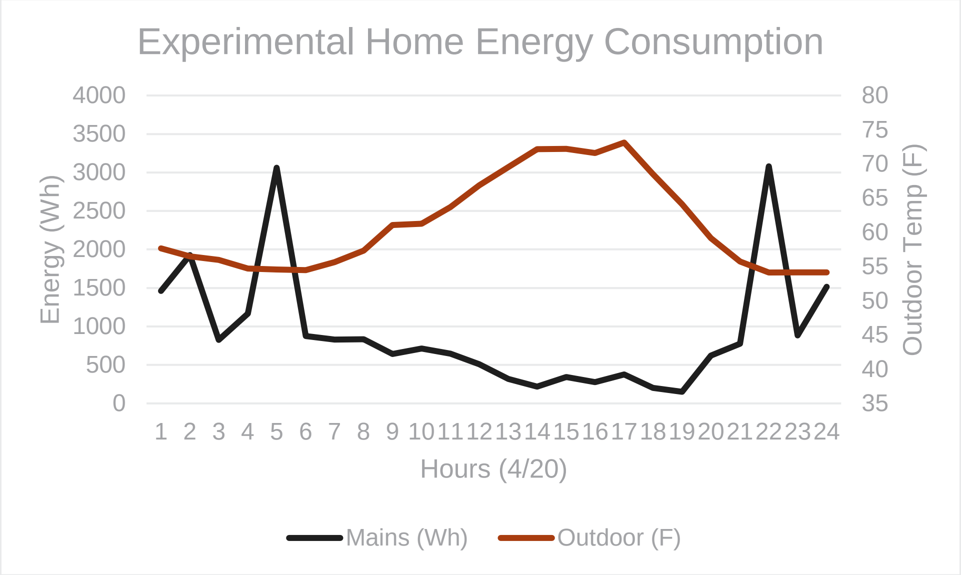

Figure 28 Heating Experiment – Zonal: Bedroom Setback Experimental Home Energy Consumption

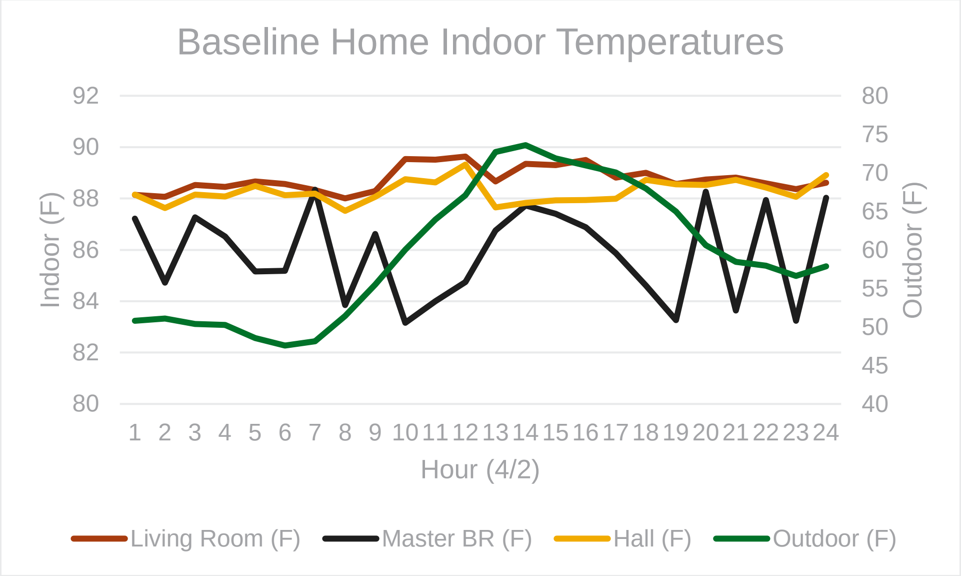

Figure 29 Heating Experiment – Zonal: Transfer Fans Baseline Home Indoor Temperatures

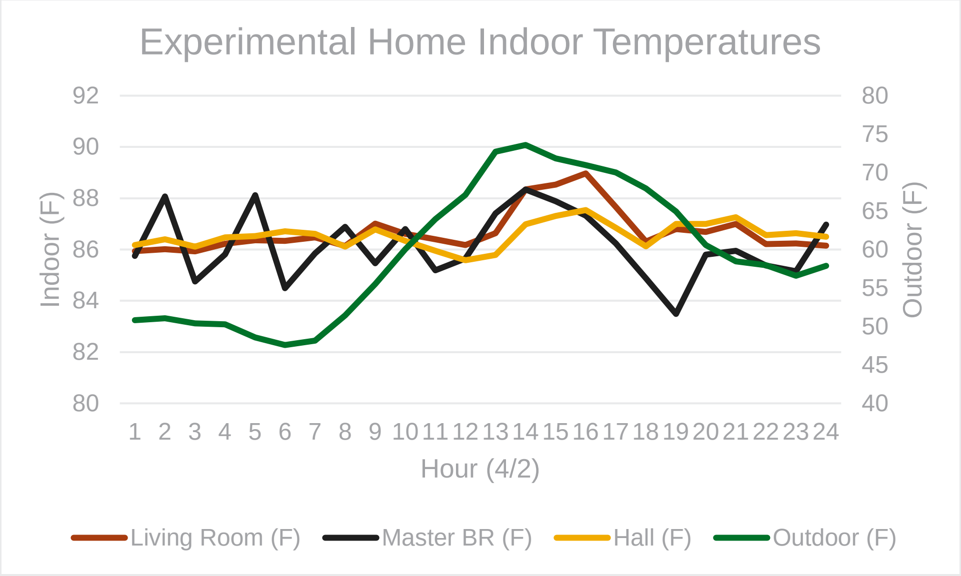

Figure 30 Heating Experiment – Zonal: Transfer Fans Experimental Home Indoor Temperatures

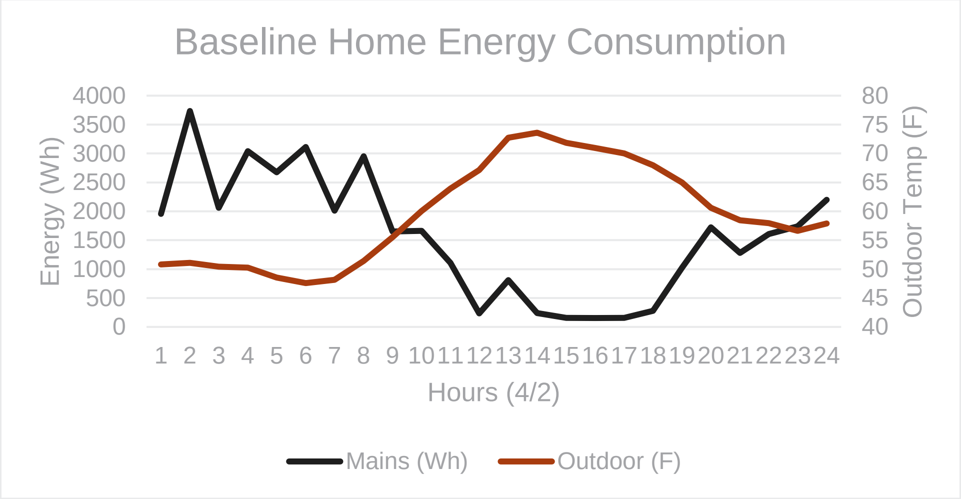

Figure 31 Heating Experiment – Zonal: Transfer Fans Baseline Home Energy Consumption

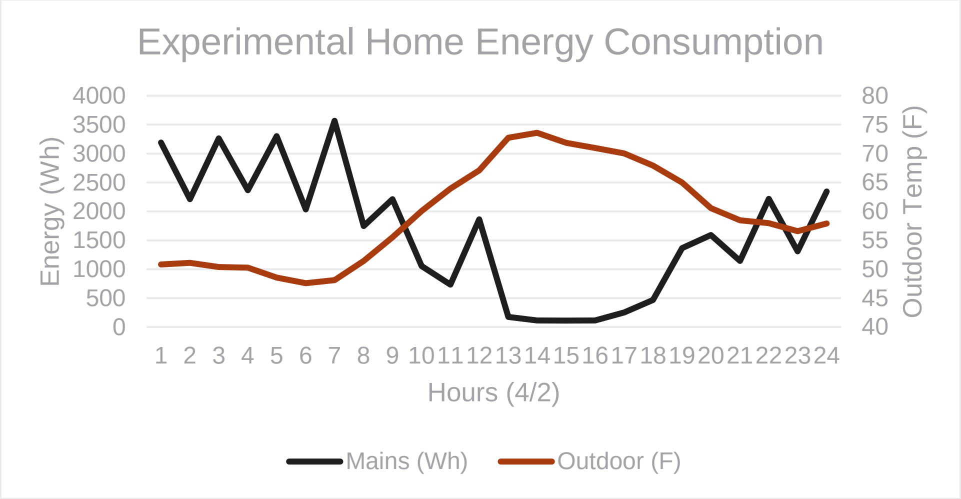

Figure 32 Heating Experiment – Zonal: Transfer Fans Experimental Home Energy Consumption

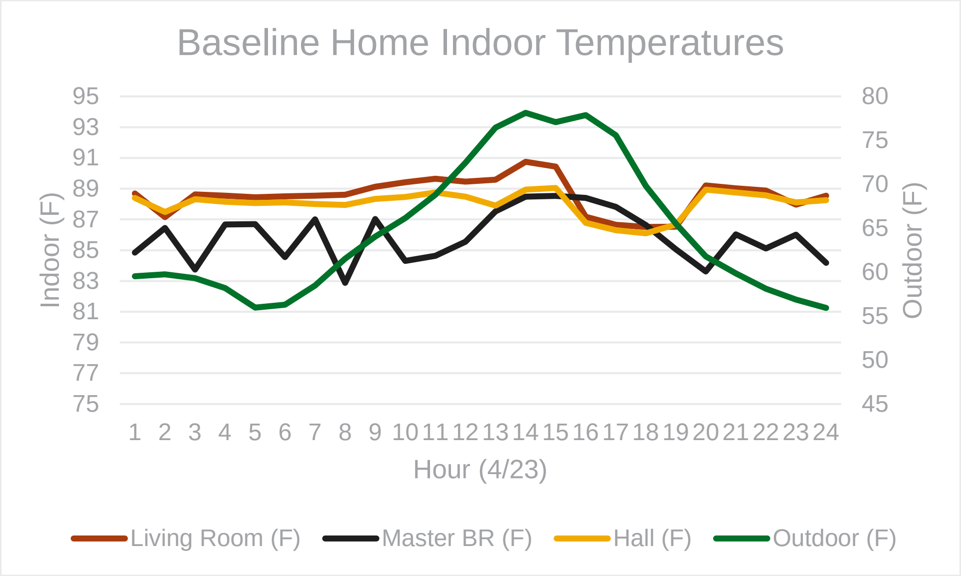

Figure 33 Heating Experiment – Zonal: Complex Schedule Baseline Home Indoor Temperatures

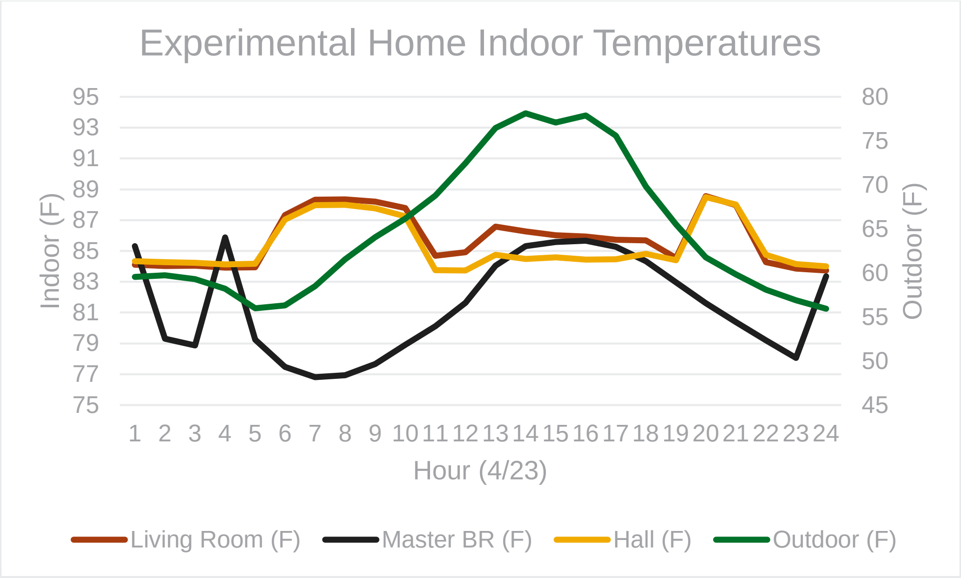

Figure 34 Heating Experiment – Zonal: Complex Schedule Experimental Home Indoor Temperatures

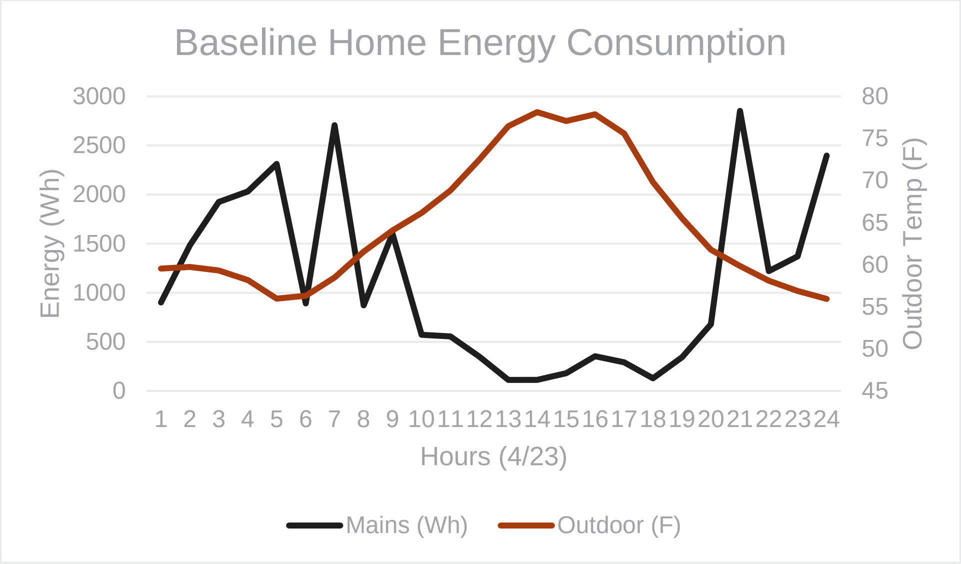

Figure 35 Heating Experiment – Zonal: Complex Schedule Baseline Home Energy Consumption

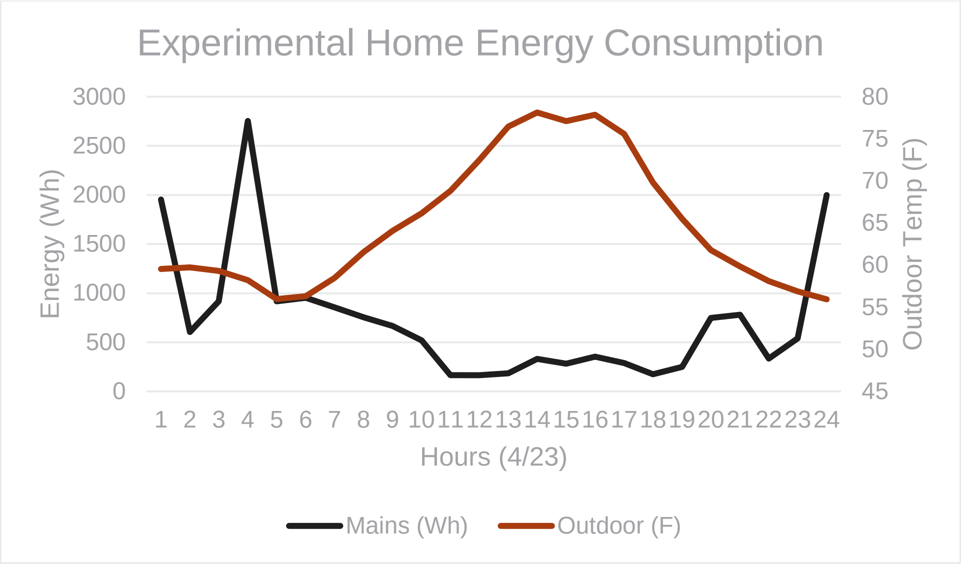

Figure 36 Heating Experiment – Zonal: Complex Schedule Experimental Home Energy Consumption

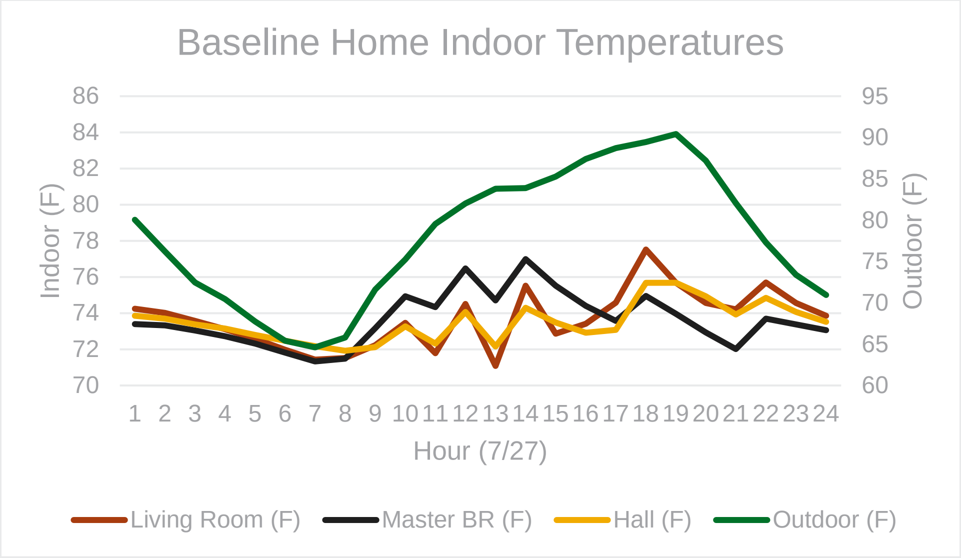

Figure 37 Cooling Experiment – Central: Experiment Calibration Baseline Home Indoor Temperatures

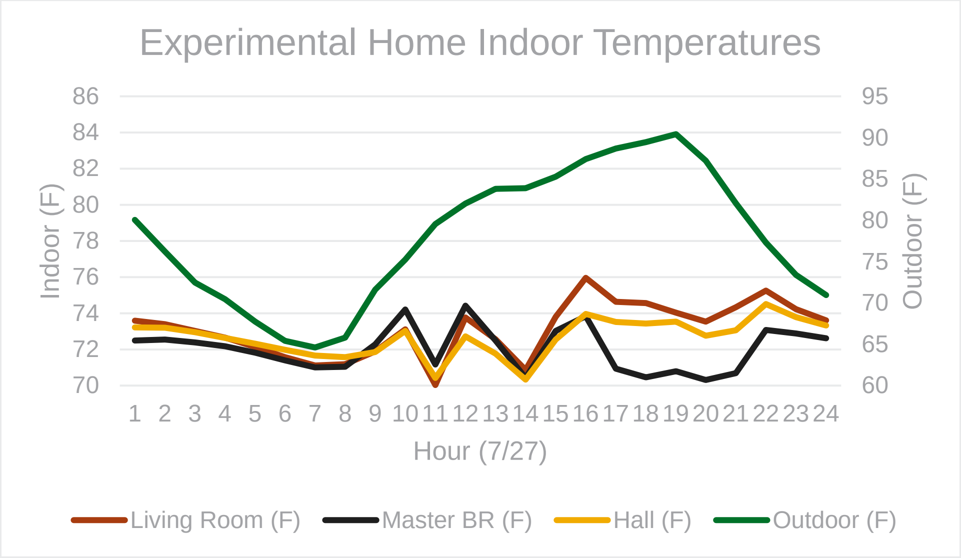

Figure 38 Cooling Experiment – Central: Experiment Calibration Experimental Home Indoor Temperatures

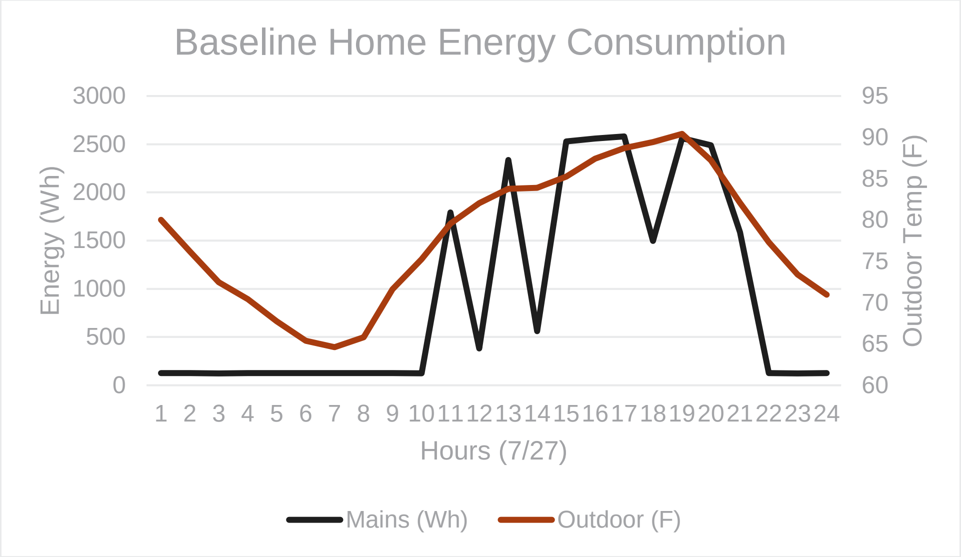

Figure 39 Cooling Experiment – Central: Experiment Calibration Baseline Home Energy Consumption

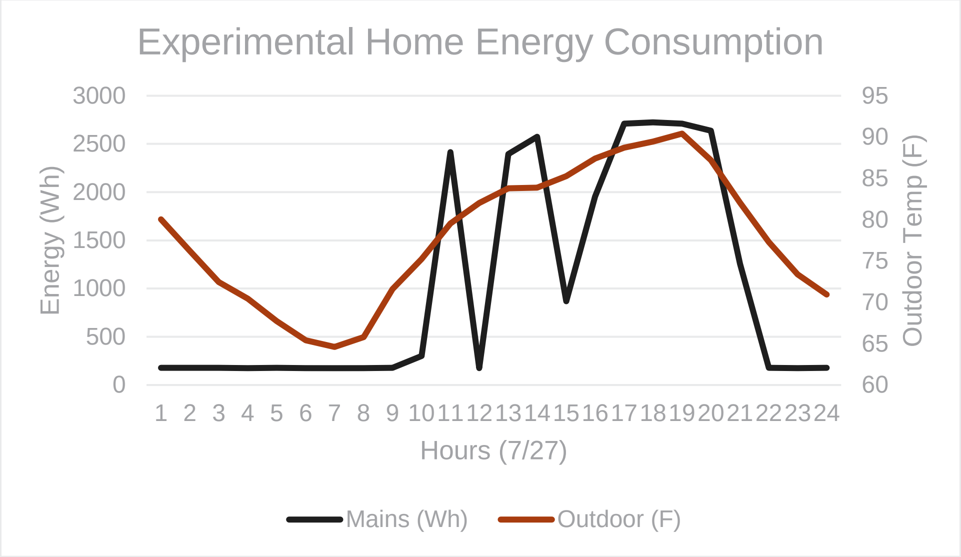

Figure 40 Cooling Experiment – Central: Experiment Calibration Experimental Home Energy Consumption

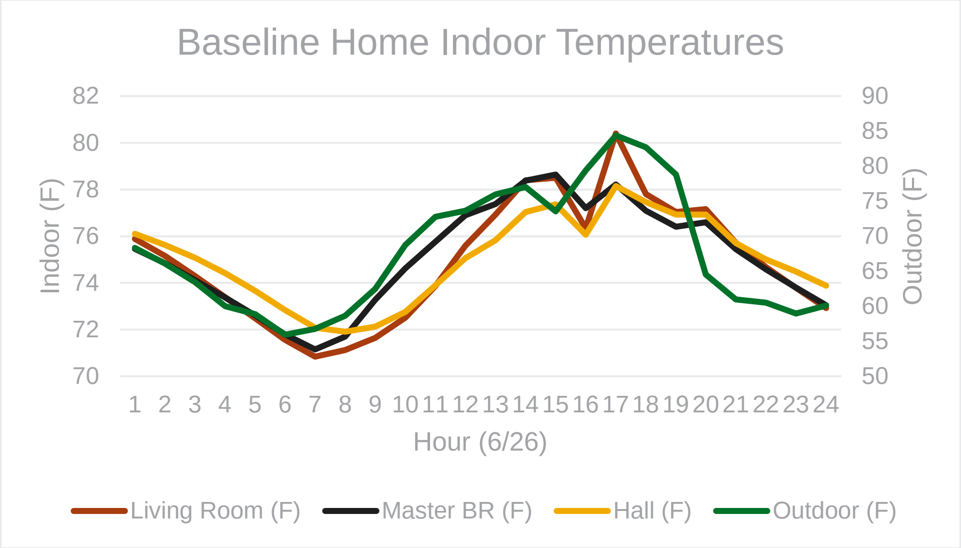

Figure 41 Cooling Experiment – Central: Central Fan Only Baseline Home Indoor Temperatures

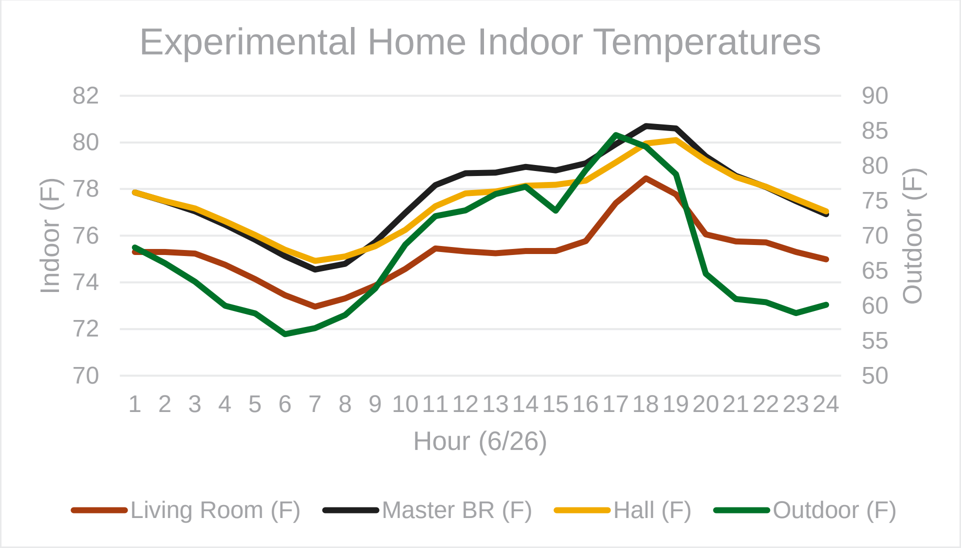

Figure 42 Cooling Experiment – Central: Central Fan Only Experimental Home Indoor Temperatures

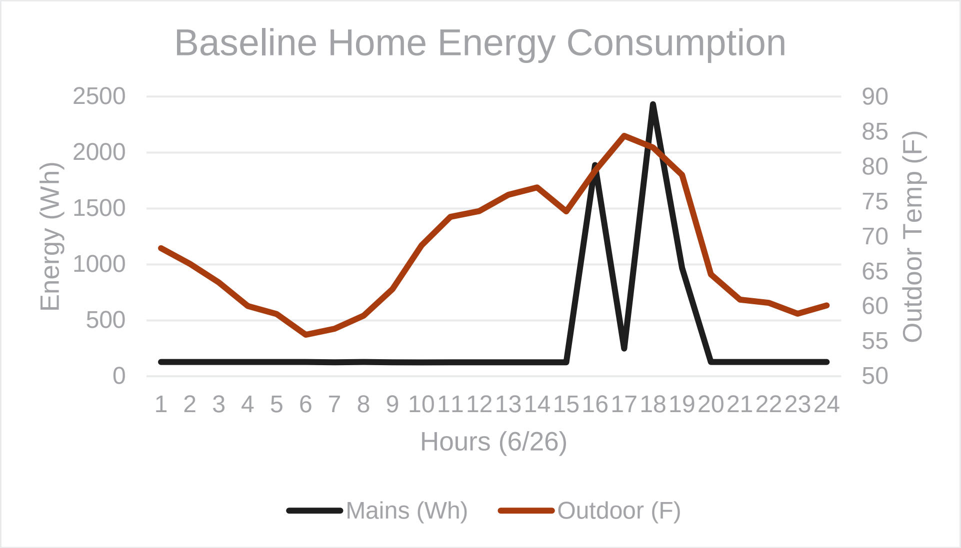

Figure 43 Cooling Experiment – Central: Central Fan Only Baseline Home Energy Consumption

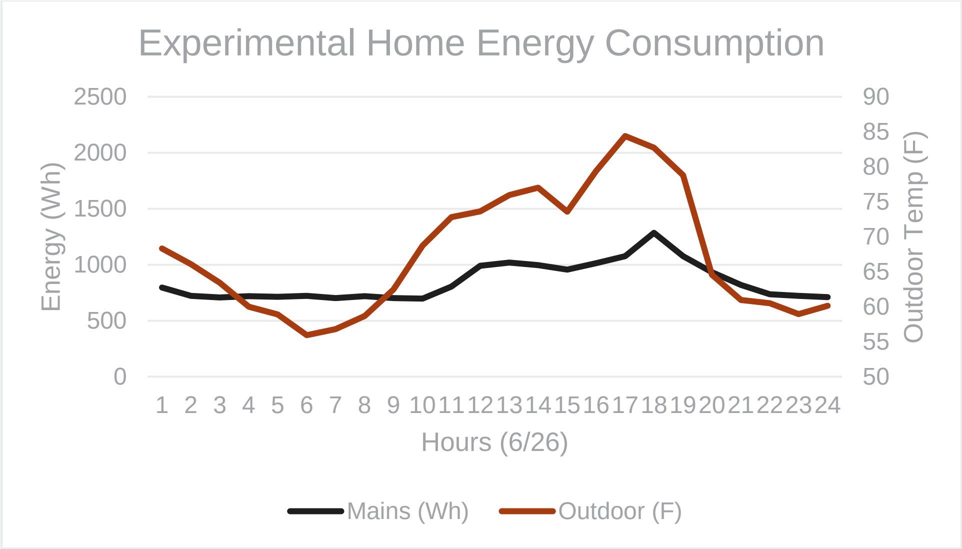

Figure 44 Cooling Experiment – Central: Central Fan Only Experimental Home Energy Consumption

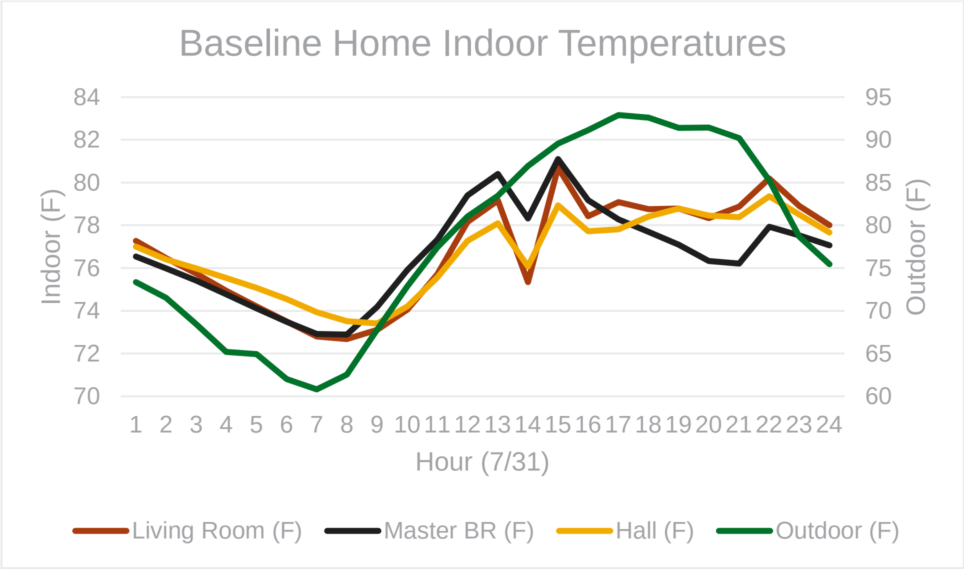

Figure 45 Cooling Experiment – Central: CAC Offset Baseline Home Indoor Temperatures

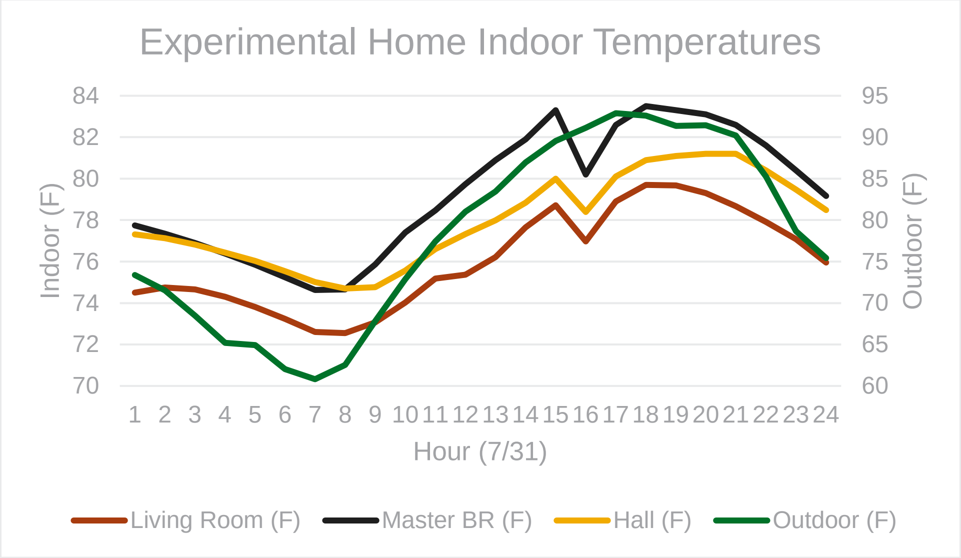

Figure 46 Cooling Experiment – Central: CAC Offset Experimental Home Indoor Temperatures

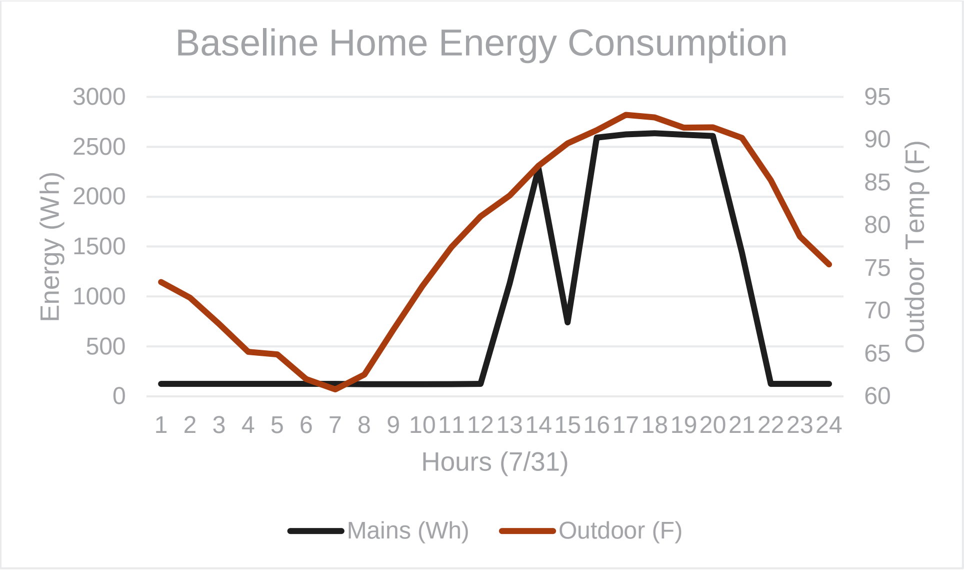

Figure 47 Cooling Experiment – Central: CAC Offset Baseline Home Energy Consumption

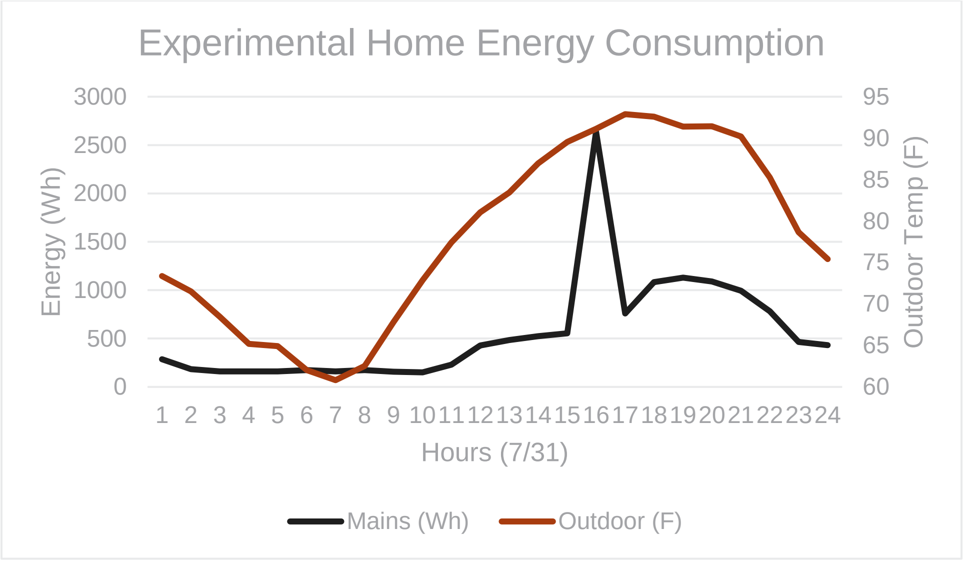

Figure 48 Cooling Experiment – Central: CAC Offset Experimental Home Energy Consumption

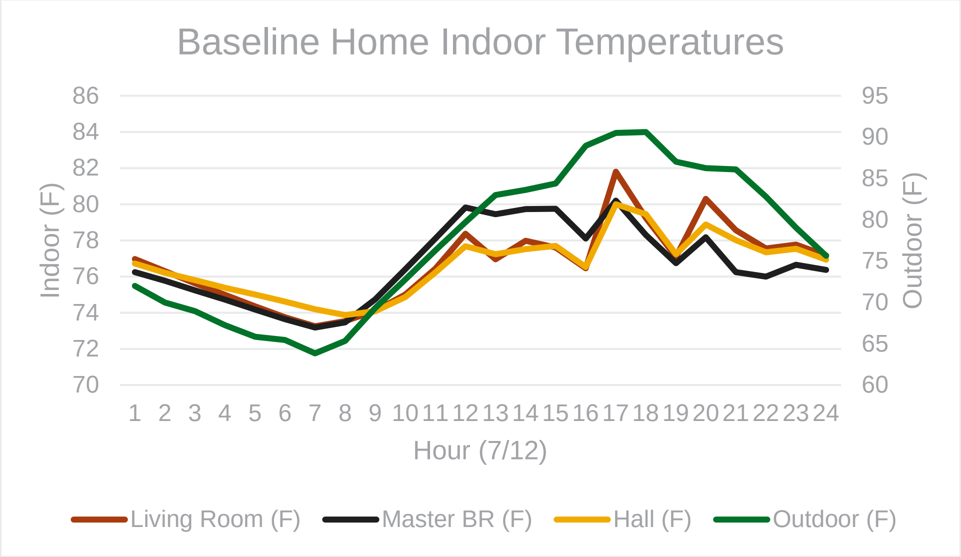

Figure 49 Cooling Experiment – Central: Complex Schedule Baseline Home Indoor Temperatures

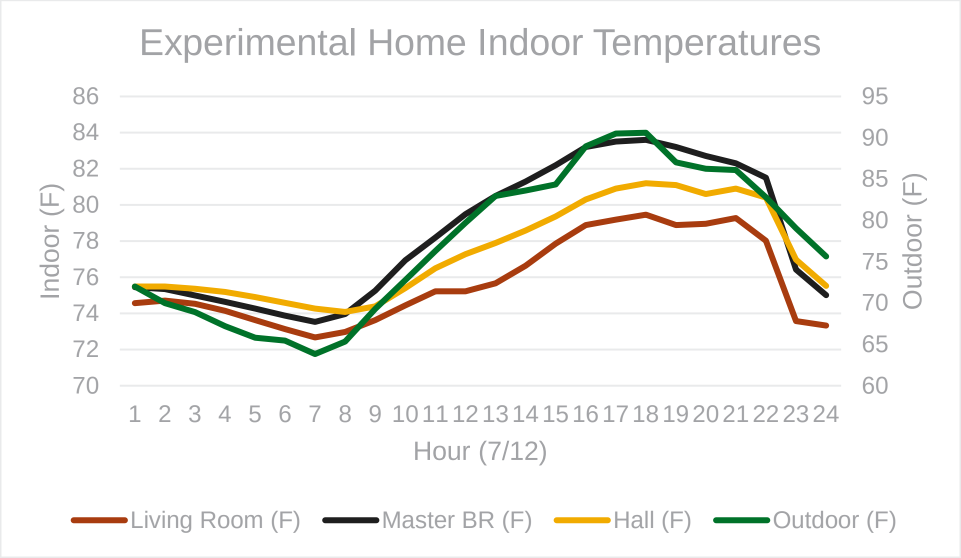

Figure 50 Cooling Experiment – Central: Complex Schedule Experimental Home Indoor Temperatures

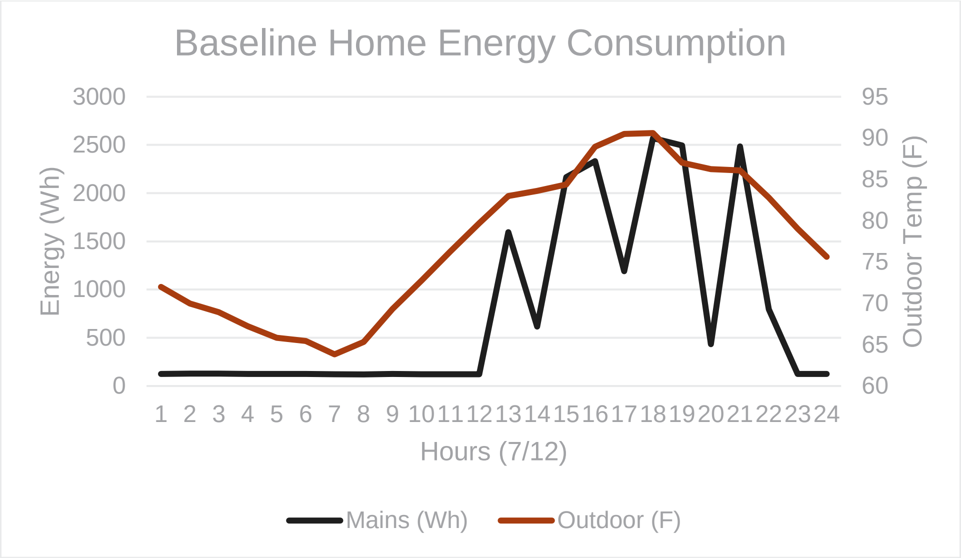

Figure 51 Cooling Experiment – Central: Complex Schedule Baseline Home Energy Consumption

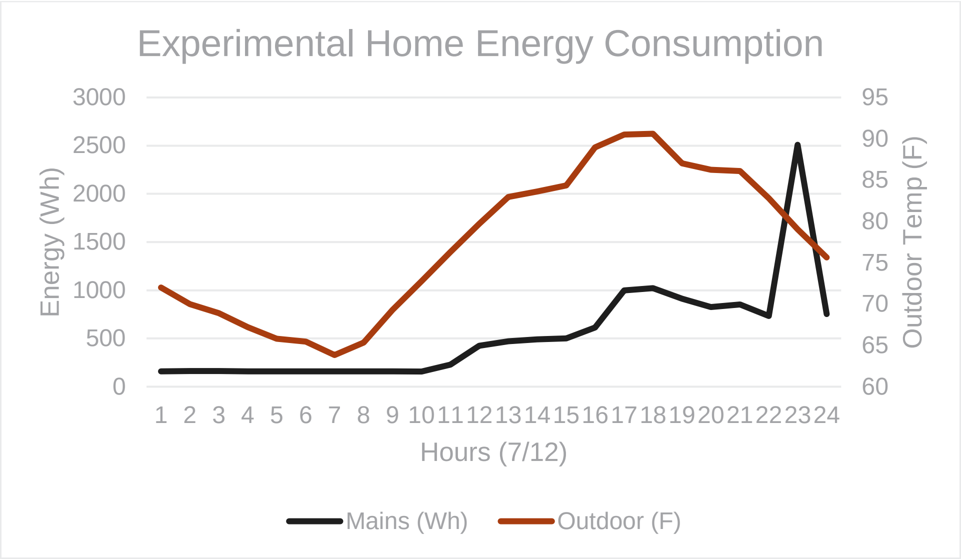

Figure 52 Cooling Experiment – Central: Complex Schedule Experimental Home Energy Consumption

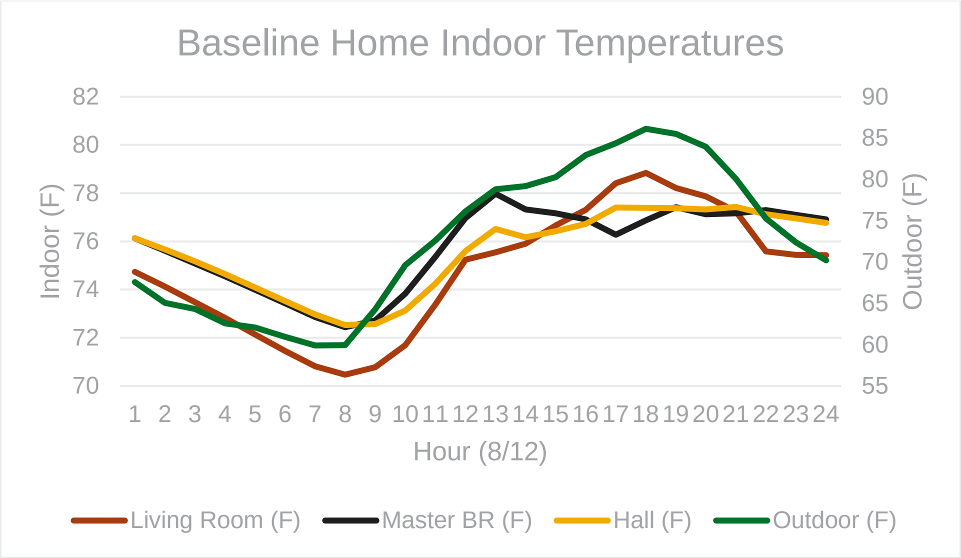

Figure 53 Cooling Experiment – Zonal: Experiment Calibration, Doors Open Baseline Home Indoor Temperatures

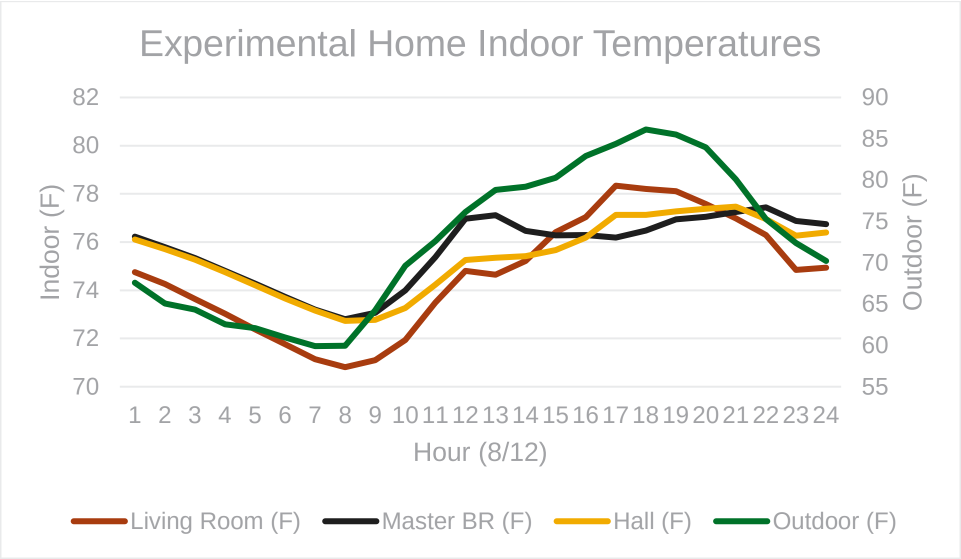

Figure 54 Cooling Experiment – Zonal: Experiment Calibration, Doors Open Experimental Home Indoor Temperatures

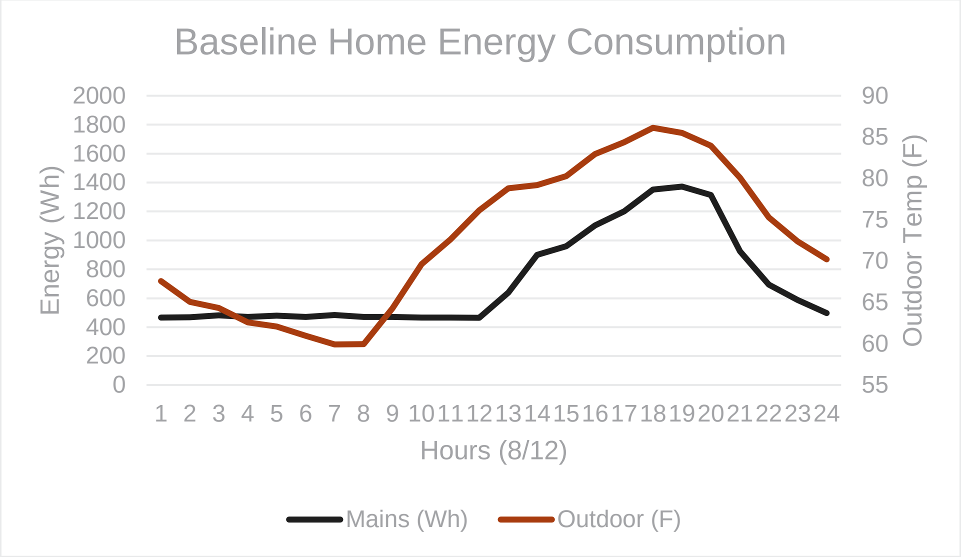

Figure 55 Cooling Experiment – Zonal: Experiment Calibration, Doors Open Baseline Home Energy Consumption

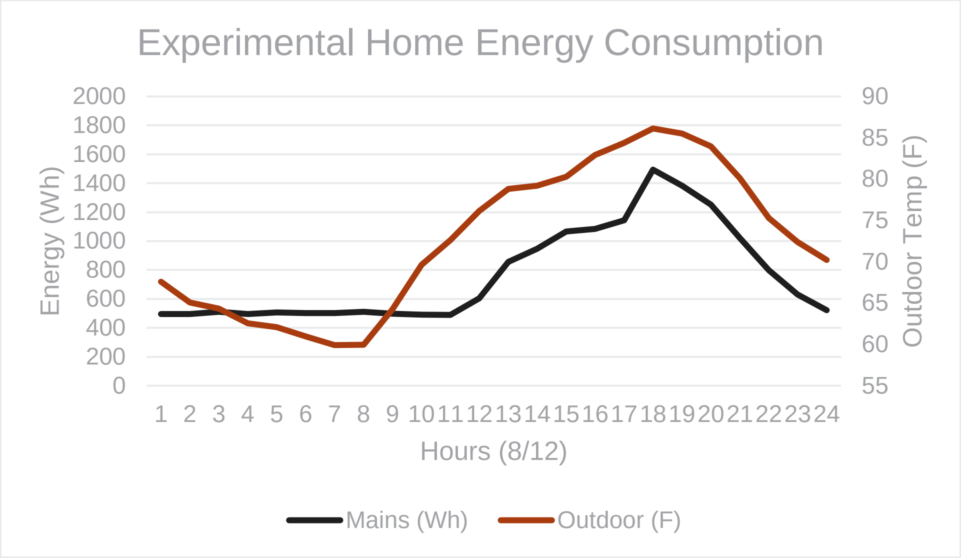

Figure 56 Cooling Experiment – Zonal: Experiment Calibration, Doors Open Experimental Home Energy Consumption

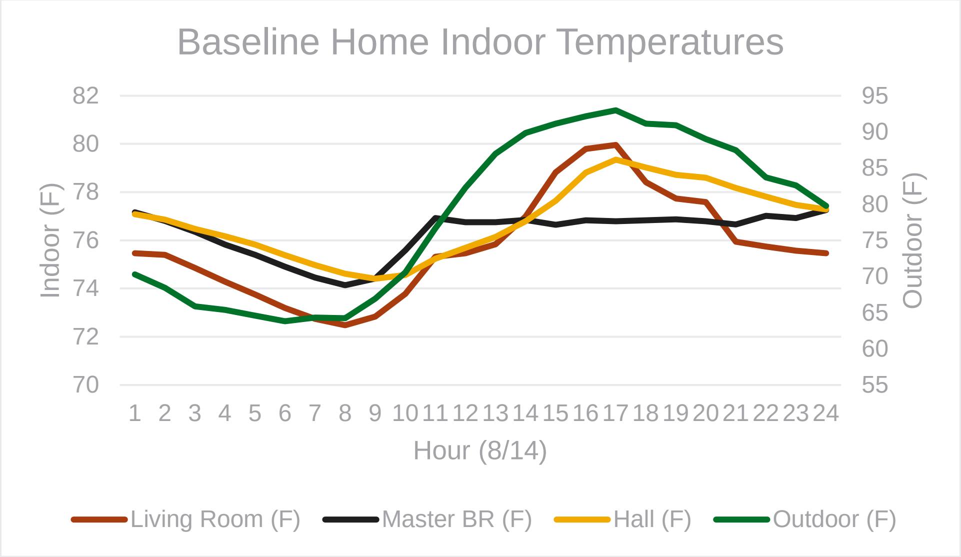

Figure 57 Cooling Experiment – Zonal: Home Calibration, Doors Closed Baseline Home Indoor Temperatures

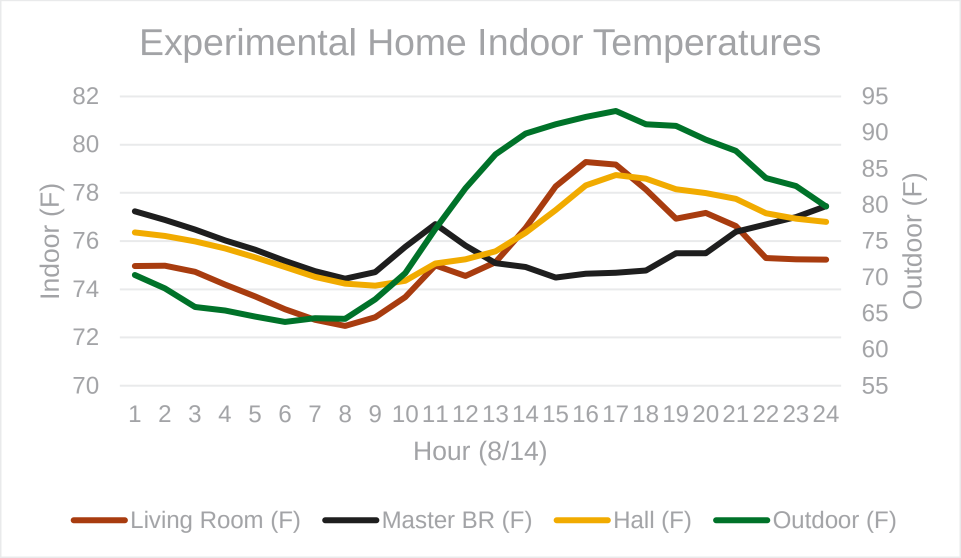

Figure 58 Cooling Experiment – Zonal: Home Calibration, Doors Closed Experimental Home Indoor Temperatures

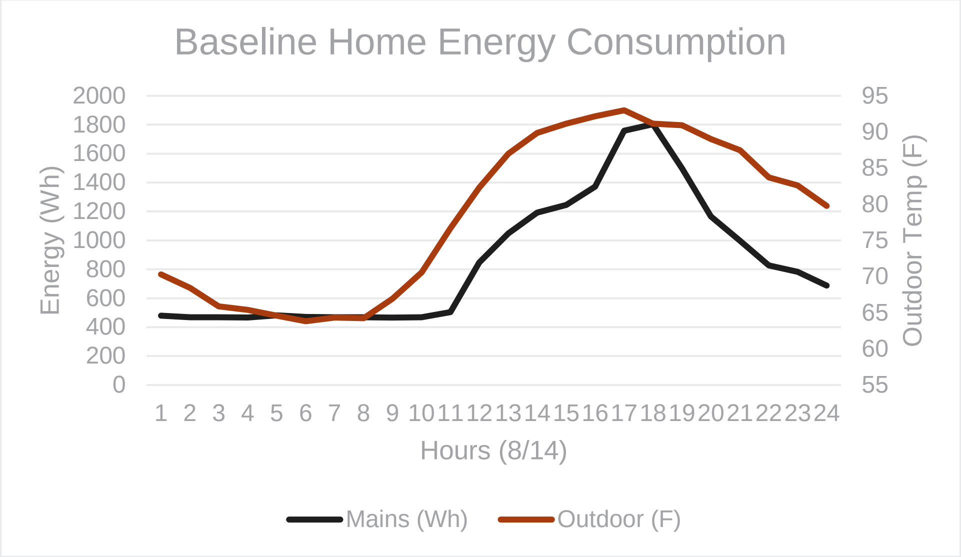

Figure 59 Cooling Experiment – Zonal: Home Calibration, Doors Closed Baseline Home Energy Consumption

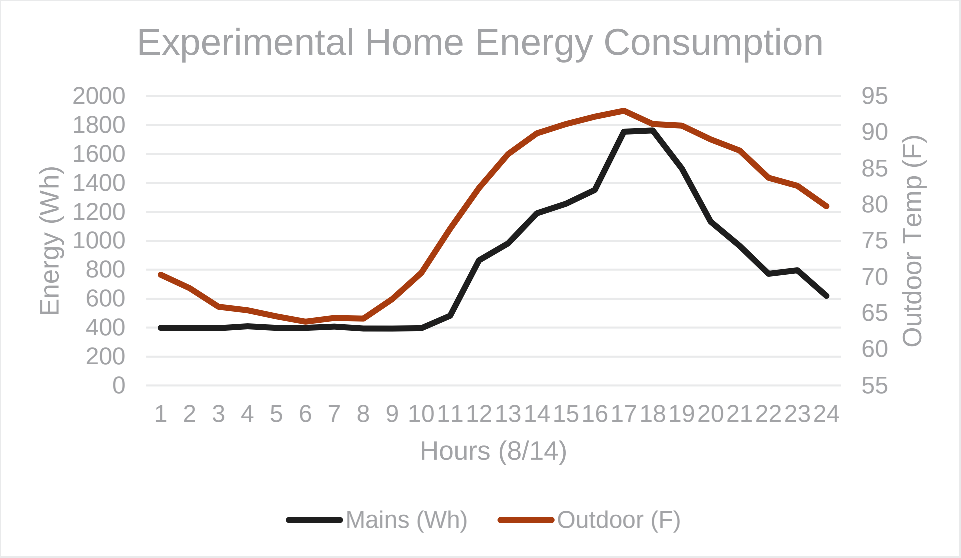

Figure 60 Cooling Experiment – Zonal: Home Calibration, Doors Closed Experimental Home Energy Consumption

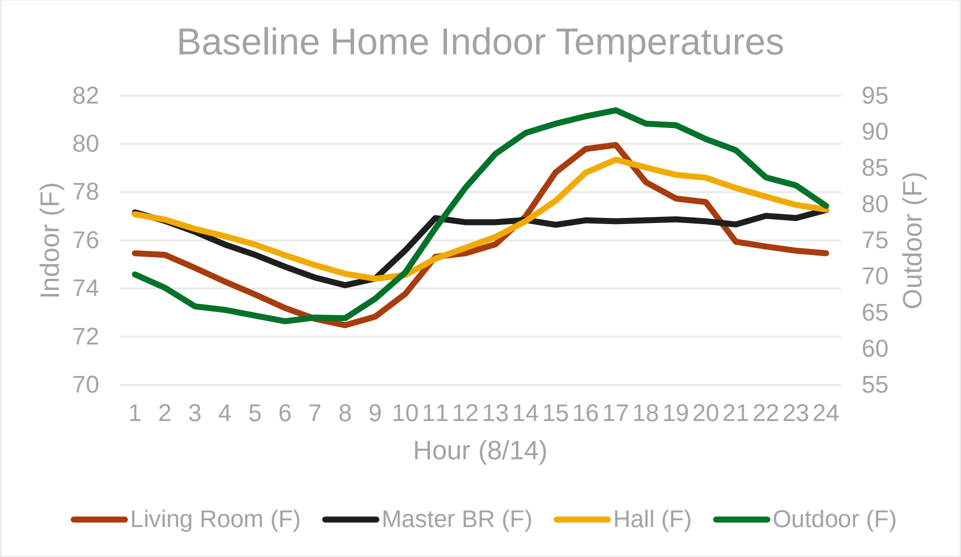

Figure 61 Cooling Experiment – Zonal: Home Calibration, Doors Closed Baseline Home Indoor Temperatures

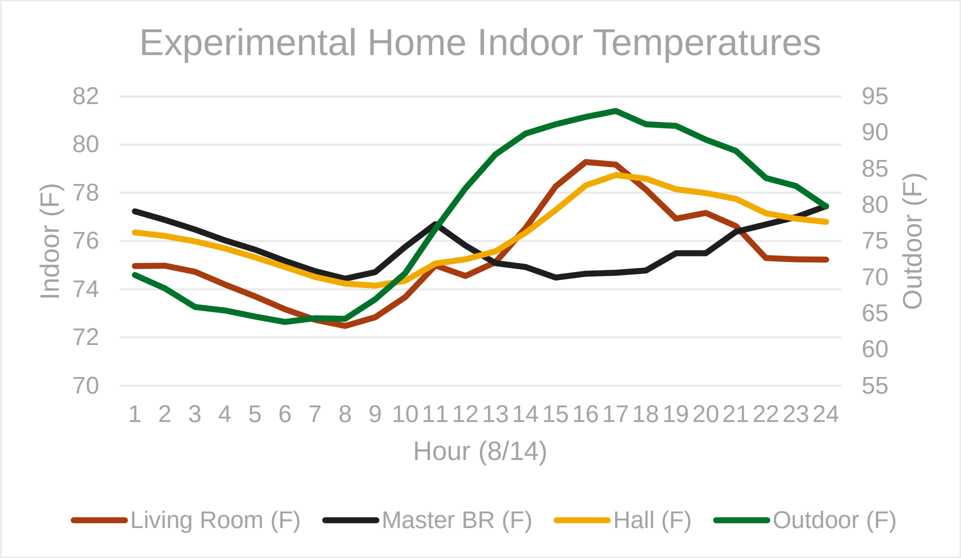

Figure 62 Cooling Experiment – Zonal: Home Calibration, Doors Closed Experimental Home Indoor Temperatures

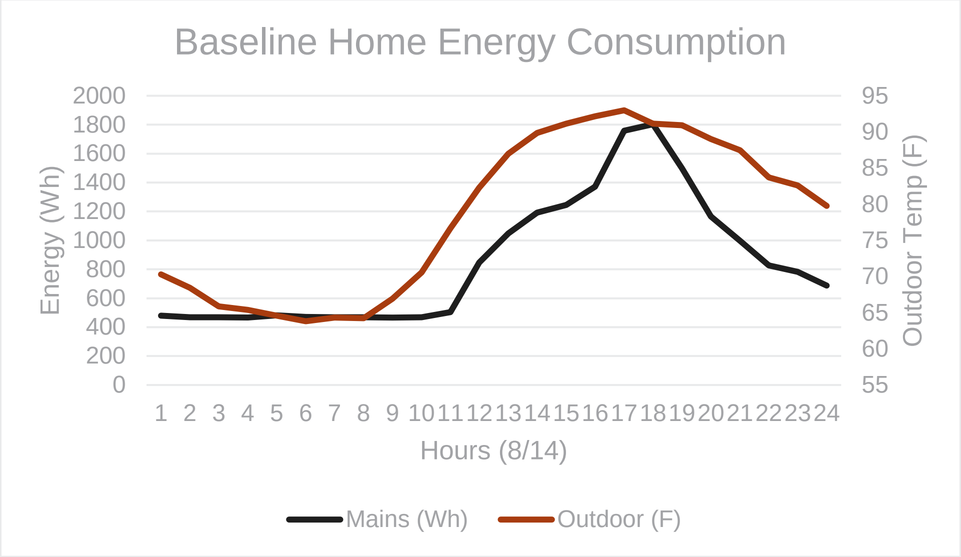

Figure 63 Cooling Experiment – Zonal: Home Calibration, Doors Closed Baseline Home Energy Consumption

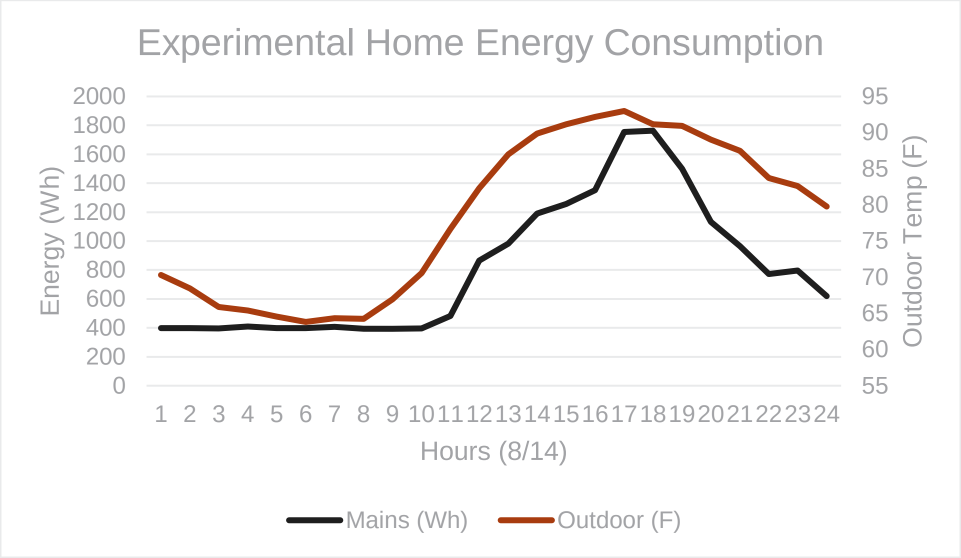

Figure 64 Cooling Experiment – Zonal: Home Calibration, Doors Closed Experimental Home Energy Consumption

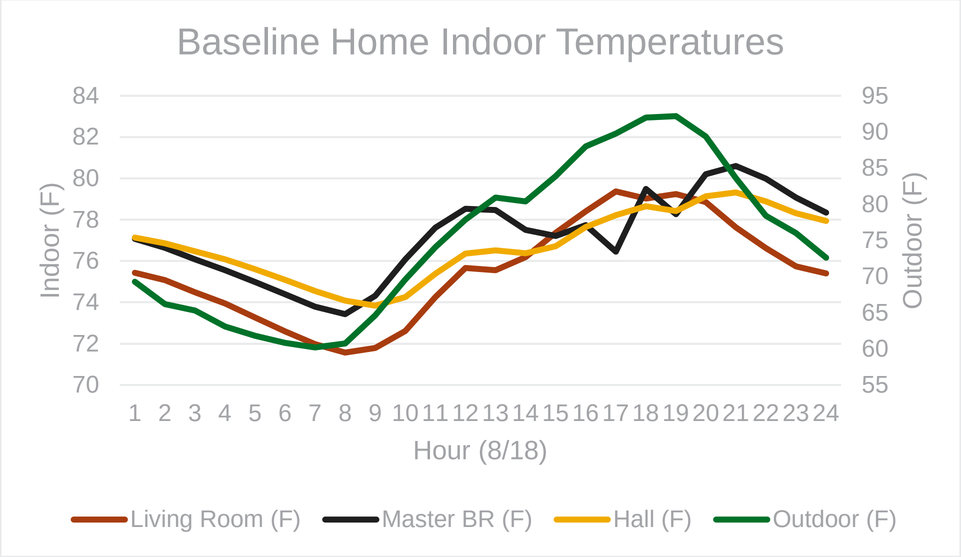

Figure 65 Cooling Experiment – Zonal: Bedroom Setback Baseline Home Indoor Temperatures

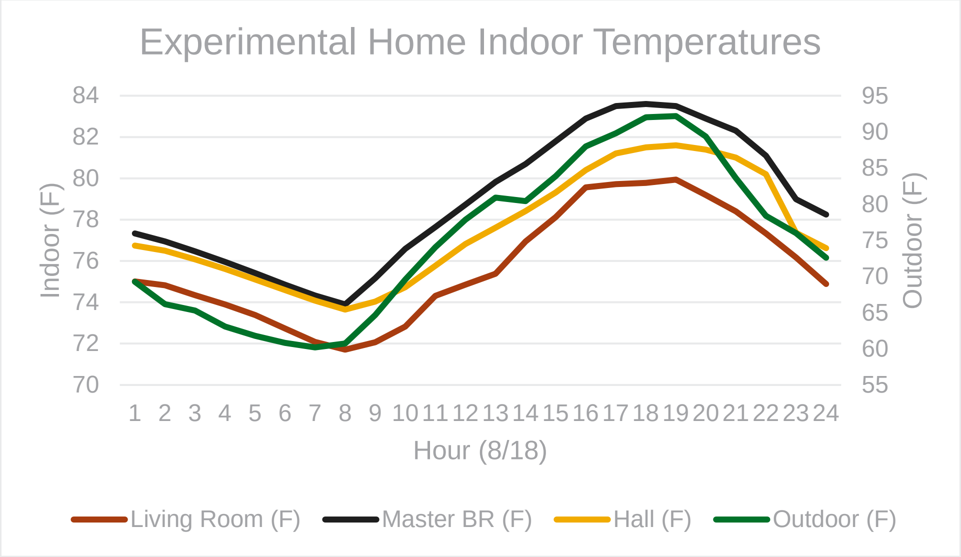

Figure 66 Cooling Experiment – Zonal: Bedroom Setback Experimental Home Indoor Temperatures

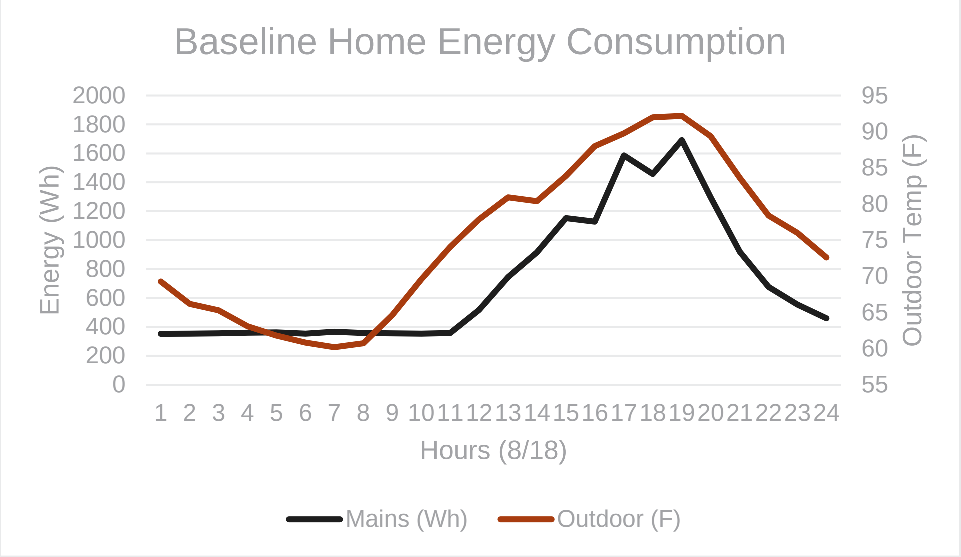

Figure 67 Cooling Experiment – Zonal: Bedroom Setback Baseline Home Energy Consumption

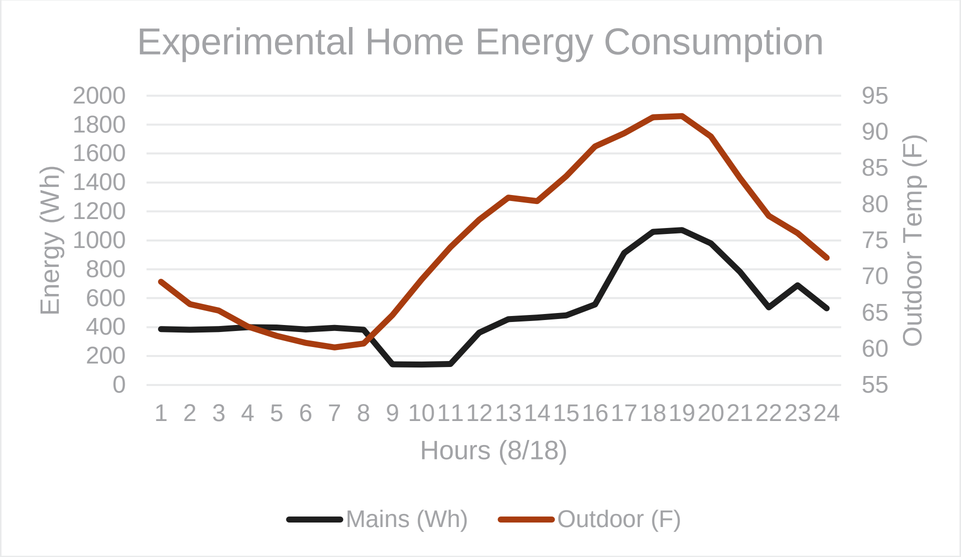

Figure 68 Cooling Experiment – Zonal: Bedroom Setback Experimental Home Energy Consumption

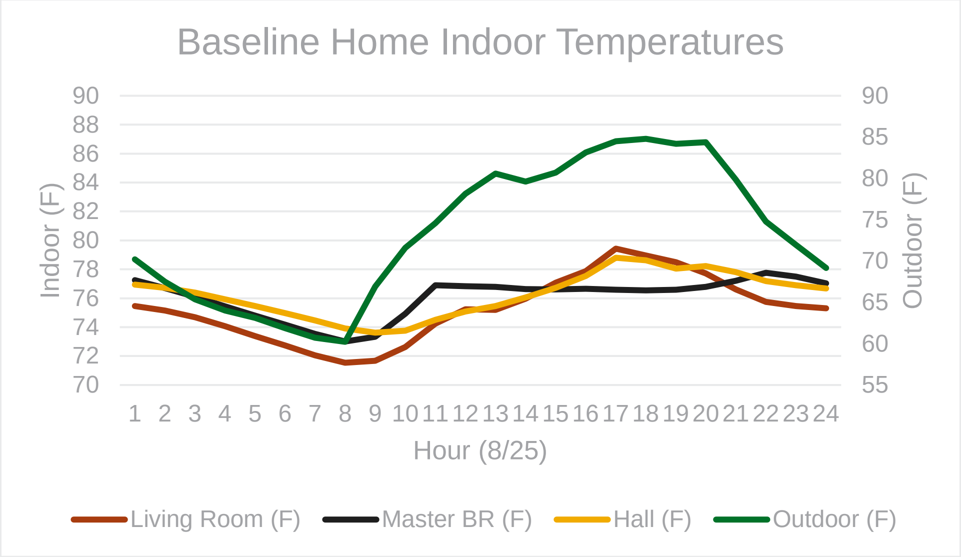

Figure 69 Cooling Experiment – Zonal: Transfer Fans Baseline Home Indoor Temperatures

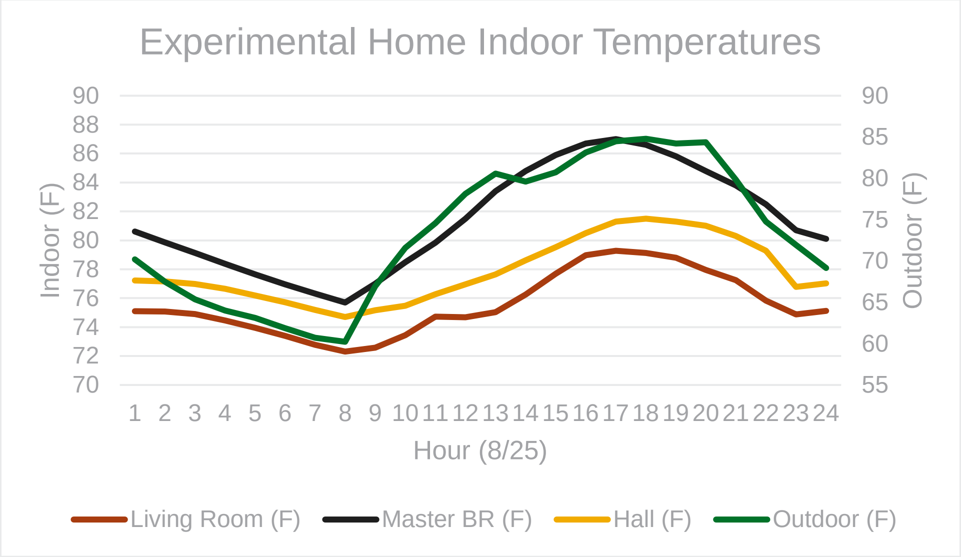

Figure 70 Cooling Experiment – Zonal: Transfer Fans Experimental Home Indoor Temperatures

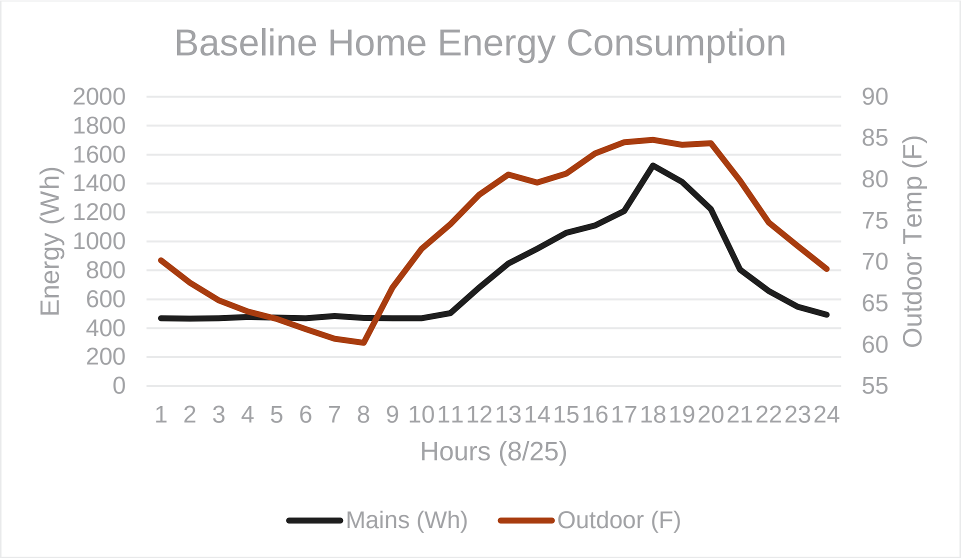

Figure 71 Cooling Experiment – Zonal: Transfer Fans Baseline Home Energy Consumption

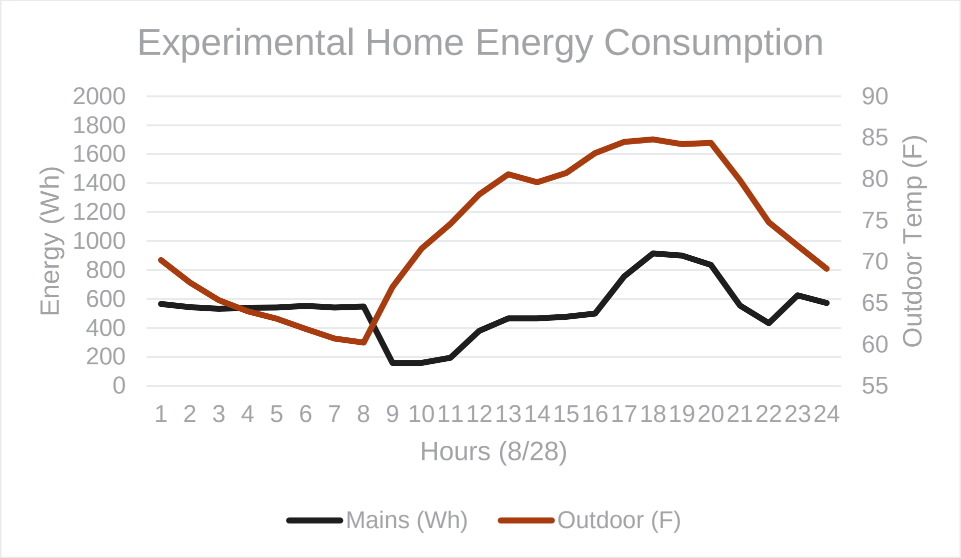

Figure 72 Cooling Experiment – Zonal: Transfer Fans Experimental Home Energy Consumption

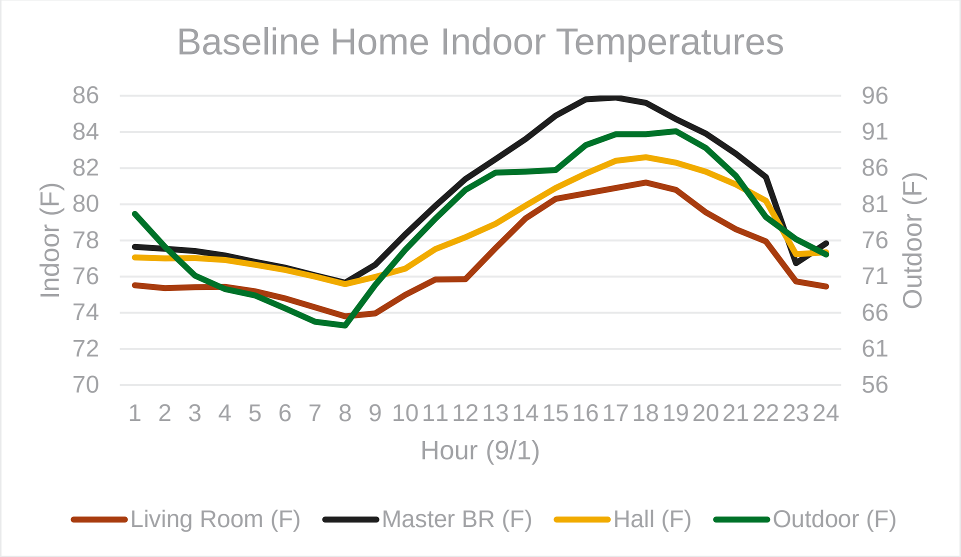

Figure 73 Cooling Experiment – Zonal: Complex Schedule Baseline Home Indoor Temperatures

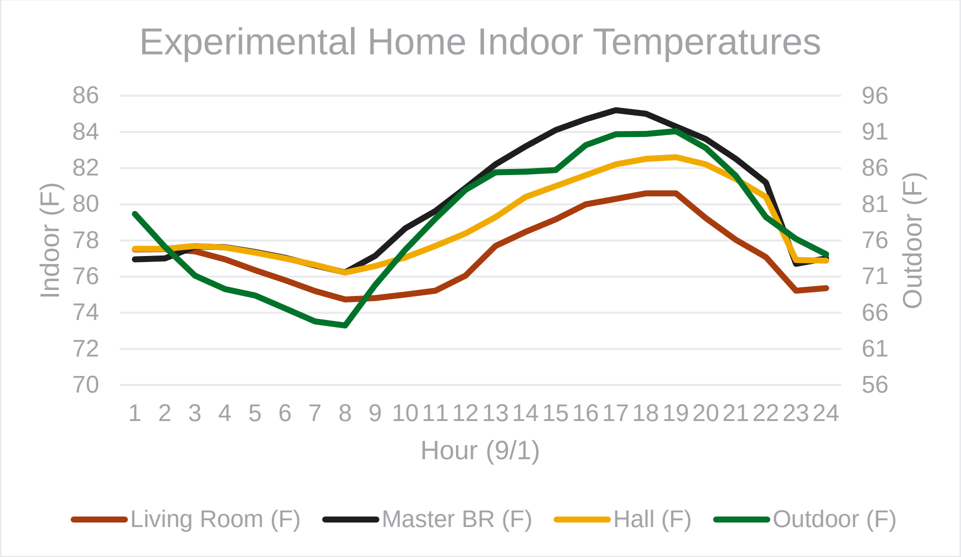

Figure 74 Cooling Experiment – Zonal: Complex Schedule Experimental Home Indoor Temperatures

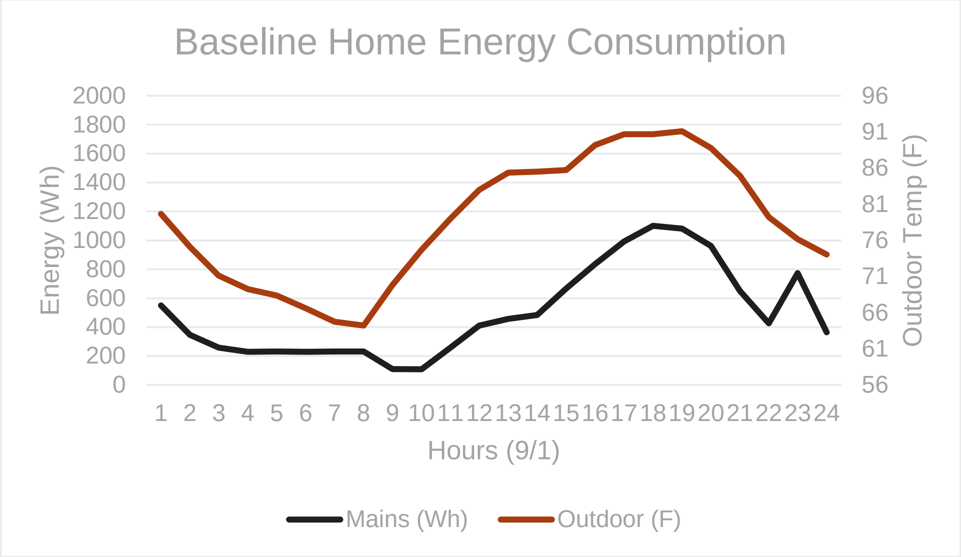

Figure 75 Cooling Experiment – Zonal: Complex Schedule Baseline Home Energy Consumption

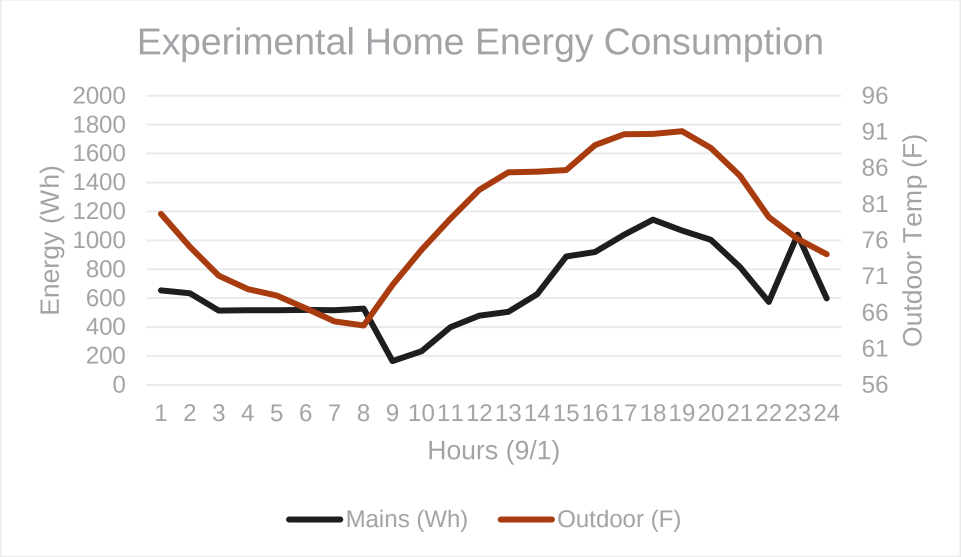

Figure 76 Cooling Experiment – Zonal: Complex Schedule Experimental Home Energy Consumption

Pacific Northwest
National Laboratory

902 Battelle Boulevard
P.O. Box 999
Richland, WA 99354
1-888-375-PNNL (7665)

www.pnnl.gov