Field Test of Integration Controls for Ductless Mini-Splits Heat Pumps in Minnesota

slipstream

Project Funder: Xcel Energy

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SUMMARY

This research project investigated the efficacy of controls designed to better integrate operation of mini-split heat pumps with existing electric-resistance heat, with the intent of maximizing the energy-savings potential of the heat pump. Three homes in the Twin Cities area of Minnesota were retrofitted with mini-split heat pumps, and monitoring equipment was installed to track electricity consumption and various space temperatures. After the units had operated for at least part of a heating and cooling season, integration controls were installed to coordinate operation of the two systems. Continued monitoring allowed for a comparison of electricity use and indoor conditions before and after installation of the controls, along with estimating the overall electricity savings associated with installation of the heat pumps themselves.

Key findings are as follows:

1. All three homes showed substantial energy-cost savings from installation of the mini-split systems. Weather-normalized energy-cost savings for the three homes were 26 percent, 29 percent and 62 percent in the year after the mini-split systems were installed.

2. All of the mini-split systems were able to provide warm conditioned air down to sub-zero conditions. The scope of the monitoring effort did not allow for measuring system output or efficiency but did provide for measuring the temperature of the air delivered by the systems. All three units provided 90 to 100F conditioned air down to -10F, and two of the units even maintained these delivery temperatures down to -18F.

3. While the HVAC contractors who installed the mini-split systems were experienced with basic mini-split system installation, none had any familiarity with integration controls for these systems. The contractors relied heavily on the heat-pump equipment distributors or manufacturer's representatives for technical advice, and in two cases, these representatives themselves needed to reach out to others for help in specifying the controls. Moreover, at two of the homes, installing the controls required multiple trips due to incorrect or missing parts at the job site. All of this suggests a general lack of experience and familiarity with integration controls for mini-split controls on the part of HVAC professionals in the Twin Cities area and likely in other areas where these controls have not been actively promoted by efficiency programs.

4. All three homeowners were highly motivated to minimize their heating costs and used little or no baseboard heat in the rooms with the new heat pumps once the systems were installed—even prior to installation of the controls. In fact, installation of the controls resulted in slightly higher heating costs at two of the three sites. For motivated households like these, integration controls are likely an unnecessary expense.

5. All three households were very happy with the mini-split systems but were indifferent to the integration controls. Homeowners mentioned substantial energy cost savings and improved comfort from the mini splits but did not care about the controls because they

simply stopped using the existing electric baseboard heat once the heat pump was in place.

6. Manual adjustments to the mini-split system tended to trigger backup electric baseboard operation. The integration controls for the three systems were primarily based on temperature droop: that is, the system called for backup heat whenever the indoor temperature dropped more than 3F below the setpoint temperature. In theory, this is meant to trigger backup heat when the capacity of mini split falls below the load it is trying to serve, resulting in a drop in indoor temperature. However, monitoring data prior to installation of the controls showed that the systems were able to maintain setpoint down to sub-zero temperatures, so in practice the backup heat was generally only triggered when the household changed the setpoint temperature abruptly or engaged the mini split system after it had been turned off for a period. The large difference between setpoint and sensed indoor temperature at these times caused the system to call for backup heat.

BACKGROUND AND STUDY OBJECTIVES

Mini-split heat pumps have grown in popularity in recent years and are increasingly the focus of energy-efficiency programs and beneficial electrification efforts intended to reduce reliance on fossil fuels for space heating. Ductless mini splits can readily be retrofitted into spaces that lack a central forced-air heating and cooling system, making them popular choice for homes with existing boiler-based heat as well as for spaces such as converted attics and porches that lack an existing means for space conditioning.

A ductless mini-split heat pump consists of two parts: an outdoor unit containing the compressor that drives the heating and cooling for the system and one or more wall-mounted indoor units (heads) that distribute warmed or cooled air to the rooms in which they are located. The two parts are connected by a cable bundle that contains electrical connections, refrigerant lines, and a drain line for condensate from the indoor unit (Figure 1).

The fact that these systems can readily be retrofitted into homes with existing space heating systems also creates a potential system-coordination issue, however. Mini-split systems are generally installed to be operated independently, with temperature sensed and controlled at the indoor head. If a separate heating (or cooling) system with its own thermostat is also present, the two systems may not be well coordinated. For example, if the thermostat for the existing system is set higher than that for the mini split during the heating season, the existing system will provide most of the heat to the space and the mini split will operate infrequently, if at all.

This is not ideal if the mini split can provide space heating at a lower cost than the existing system, which is especially the case when the existing heat is electric resistance. Homeowners may not be aware of suboptimal coordination between the two systems and may end up missing out on potential energy-cost savings from a mini-split system.

Figure 1. Example of a multi-head ductless mini-split system in Minneapolis.

Because of this, various products and solutions have been developed in recent years to integrate control of ductless mini-split systems with existing space heating systems. These generally provide a means for disabling the existing heating system unless the outdoor temperature drops below a pre-determined value, or the actual indoor temperature drops more than a given amount below the system setpoint (temperature droop).

Over the last several years, efficiency programs in New England and the Pacific Northwest have begun to incentivize—or even require—the installation of integration controls for heat pumps intended to partially offset existing space heating equipment. For example, Connecticut requires the installation of qualified integrated controls for heat pumps that partially offset existing fuel oil or propane heating systems. Vermont offers an incentive of up to $600 for installation of integrated controls, and Massachusetts offers a $500 incentive per control. The magnitude of these incentives suggest that New England utilities and regulators see integration of heat pumps with existing systems as an important step in maximizing the savings benefits from heat pumps that only partially offset existing heating systems.

There are a number of third-party and equipment-manufacturer options for integration controls, many of which are intended to integrate mini-splits with existing equipment that is controlled by a standard 24VAC thermostat. There are fewer options for homes with existing electric resistance heat, which is typically controlled by simple thermostatic dials on the baseboard units themselves or by 120VAC line-voltage thermostats. Integrating with a ductless mini split in these cases requires more complicated control strategies that typically involve installing relays to interrupt power to the existing baseboard heat.

The overarching objective of this project was to field test the installation of integration controls with ductless mini splits among income-eligible households with electric resistance heating in the Twin Cities, Minnesota portion of Xcel Energy's service territory. Specific objectives were:

1. Provide case studies of the energy savings, costs and cost-effectiveness of using mini splits to reduce electricity consumption in residential spaces that use electric-resistance heat.
2. Better understand the practical considerations, costs, and effectiveness of integrated controls for mini-split and backup heating system operation.
3. Better understand the extent to which Twin Cities HVAC firms employ backup system control when installing residential mini-split systems, and the strategies they use when they do so.

APPROACH

To recruit participants into the study, the project made use of Xcel Energy's partnership with the Energy Cents Coalition's weatherization program.[1] Energy Cents field staff identified homes in the St. Paul area with electric space heating during routine energy audits for the program and referred these to the project team for further investigation.

Electric space heating is uncommon in the Twin Cities area. Between December 2019 and October 2020, the project team received referrals for eight homes, and ultimately recruited three households into the study. Key reasons for eliminating homes from further consideration were minimal use of existing electric resistance heating and the presence of difficult-to-track heating fuels such as wood. Two of the recruited homes had electric resistance heat throughout the home and one home was served by electric heat in parts of the home and a gas forced-air system in the remainder.

The study design called for a split-season study in which a mini-split system would be installed at the beginning of the heating season and monitored until midway through the season, at which point integration controls would be retrofitted and monitoring would continue for the remainder of the heating season. However, the onset of the COVID19 pandemic delayed the ability to retrofit the controls, so two of the three sites were monitored for about an entire year after the mini splits were installed and before installation of the integration controls. These sites were then monitored for the entirety of the next heating season to gauge the impact of the controls. The

[1] https://www.energycents.org/weatherization

third site did not receive the mini-split installation until mid-April, 2021, so installation of controls was delayed until mid-February, 2022 and the post-controls monitoring period consisted of the .

For each home, circuit-level electricity monitors (eGauge EG4030 meters) were installed to track electricity use by the mini-split systems and the existing baseboard electric units at one-minute intervals. In addition, temperature loggers (Onset) were installed in various rooms and locations to track indoor and outdoor temperatures, as well as supply-air temperature for the mini-split systems. Room temperatures were recorded at 10-minute intervals, and supply-air temperatures were recorded on a one-minute basis.

In addition to direct analysis of the native-resolution data to better understand operating cycles and cold-weather behavior, daily kWh consumption and mean temperatures were used to estimate annual, weather-normalized mini-split and electric baseboard consumption. A similar process was used to estimate weather-normalized space-heating and cooling electricity consumption prior to installation of the mini-splits from monthly, whole-house utility billing records. Appendix B documents the modeled relationship between energy consumption and outdoor temperature in detail. All results are normalized here to average weather observed between 2001 and 2020 at the St. Paul downtown airport.

RESULTS

Table 1 summarizes the systems and annual energy-cost estimates before and after installation of the mini splits and integration controls at the three project sites. Each site is discussed in more detail in the sections that follow.

Table 1. Summary of systems and annual space-conditioning costs.

		Site 1	Site 2	Site 3
Existing HVAC Equipment		Baseboard electric heat throughout; window A/C unit	Forced-air gas and central A/C in main part of house; electric baseboard in 2nd floor bedroom and rear addition. Window A/C in 2nd floor bedroom	Baseboard electric heat throughout; portable A/C unit
Mini-split System		Two 12-kBtuh Fujitsu single-head systems serving living room and dining room ($12,170)	LG 24-kBtuh 2-head system serving 2nd floor bedroom and rear addition ($10,530)	Mitsubishi 9-kBtuh single-head system serving living room and dining room ($7,280)
Integration controls		3rd party thermostat and related parts control dining-room minisplit as Stage 1 heat and dining room baseboard as Stage 2, triggered based on 3F+ temperature droop. Multiple site trips needed for install due to incorrect parts. ($2,457)	LG wall-mount thermostats and field-supplied relays to engage baseboard heat based on 3F+ temperature droop. Two site trips needed for install due to missing part. ($1,390)	Mitsubishi relay kit and field-supplied relays to enable system to natively engage baseboard heat based on 3F+ temperature droop. (Incremental cost unknown)
Annual heating and cooling cost	*Prior to mini-split installation*	$1,290	$1,345	$1,695
	With mini split but without integration controls	$485	$1,000	$1,200
	With mini split and integration controls	$585	$950	$1,440

SITE 1

SITE DESCRIPTION

Site 1, located in the Railroad Island neighborhood of St. Paul, is a 1-story, 800 square-foot home that was heated completely with electricity and cooled with room air conditioners and fans prior to involvement in the study (Figure 2). The home is occupied by two adults and a small child.

Figure 2. Exterior view of the Site 1 home.

In January 2020, attic insulation and air-sealing work was performed on the home under Xcel's Good Cents program.

In July of 2020, a 12,000 Btuh Fujitsu mini-split heat pump was installed on one wall of the living room with the intent of offsetting baseboard heat for the living room and adjoining dining room. However, after the homeowner reported that the unit did not do an adequate job of conditioning the dining room, a second unit was later (August 2020) installed to serve the dining room

(Figure 3).[2] The installed cost for the two mini-split units was $6,340 and $5,850 for the living-room and dining-room units, respectively.

Figure 3. Interior view of two mini-split units at Site 1.

Both units were initially controlled by the stock manufacturer-supplied remote control, with operation of mini-splits and the existing baseboard electric heat at the homeowner's discretion.

In August 2021, controls were installed to integrate operation of the dining-room mini-split and the baseboard circuit for the dining room and bathroom. Three trips to the home by the heating contractor and Fujitsu distributor's representative were required to complete the installation due to a missing interface-control part on the first trip, arriving with the wrong part (second trip) and successful installation on the third trip.

The integration modifications to the dining room system consisted of replacing the original mini-split remote control with a wall-mounted, third-party thermostat with two-stages of heating control. Thermostat calls for first-stage heating energized the mini split; calls for second-stage heating energized the baseboard circuit for the dining room (see Appendix A). The thermostat was configured to call for second-stage heating whenever the sensed temperature in the room fell to 3F or more below the thermostat setpoint. The cost to install the controls was $2,457, including charges for multiple trips the site. The homeowner was told that the controls would allow the system to turn on the baseboard heat when the mini splits could not keep up with temperature being called for on the units, which would likely occur only in very cold weather.

Monitoring included tracking electricity consumption by the mini-split units and baseboard heat on a one-minute basis, along with temperature snapshots at the mini-split supply-air outlets every 90 seconds. Temperature and relative humidity were also recorded every 10 minutes in

[2] Each system used a AOU12RLS3H outdoor unit paired with a ASU12RLF1 indoor head.

the living room, dining room, kitchen and the two bedrooms. An outdoor sensor recorded temperature and humidity every 15 minutes. Data recovery for electricity was very high (>99%), but there were periods where data for the temperature and humidity sensors was not recovered due to communications issues.

FINDINGS

Monthly utility billing data (Figure 4) suggest that the home used about 10,300 kWh for space-heating in an average year prior to installation of the heat pumps (Table 2).[3] After the mini splits were installed, overall baseboard electricity use fell to near zero, and total weather-normalized space conditioning energy was reduced by about 6,400 kWh or more than 60 percent.[4] At an average residential rate of 12.5 cents/kWh, this translates into savings of more than $800 for heating and cooling the home, even after accounting for an increase of about $50 per year in space-cooling energy. The temperature data showed that the mini splits were able to maintain indoor room temperatures in the mid-70s with adequate supply-air temperature of 90 to 100F even when the outdoor temperature dropped to -18F.

After installation of the integration controls, overall baseboard electricity consumption was observably higher in the second heating season. Some of this was due to baseboard operation under integrated control with the dining-room mini-split unit, but most was due to increased mini-split electricity use. The dining-room unit showed a 75 percent increase in electricity consumption, while electricity use in the living room unit fell by about a third. Overall, electricity use for heating and cooling rose by about 16 percent in the second year of mini-split operation, though remained more than 50 percent below usage prior to their installation.

[3] The weatherization work performed by Good Cents occurred about six months into the available billing history for this period. Analysis of usage before and after the work suggests little difference in usage.

[4] The baseboard heat was used once in the first year following installation of the mini splits: this was a period of a few hours in one of the bedrooms on an evening when the outdoor temperature was about -10F.

Figure 4. Monthly whole-home electricity consumption for Site 1.

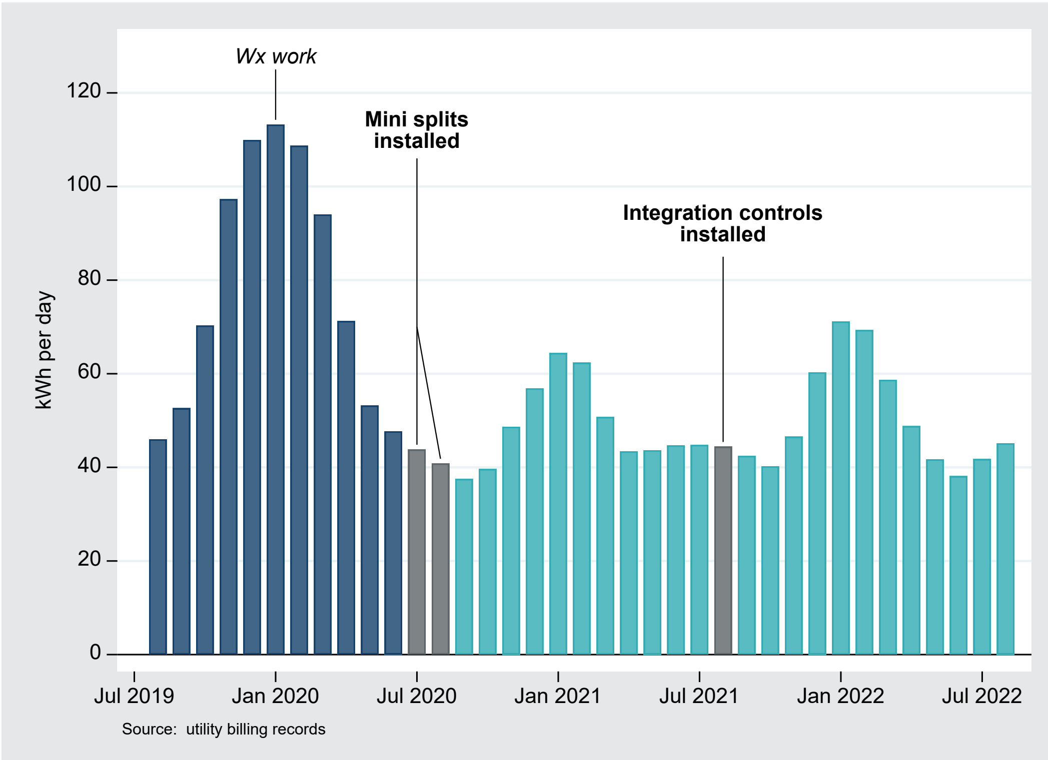


Table 2. Weather-normalized annual electricity use for heating and cooling at Site 1.

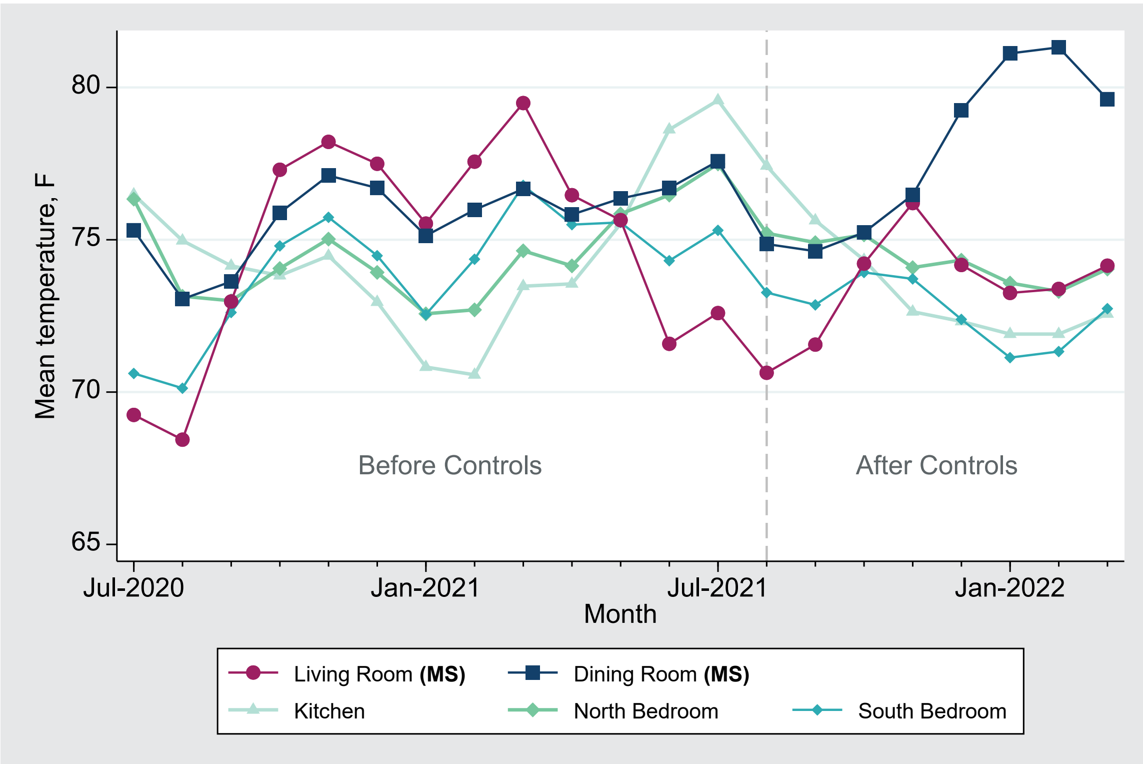
Operating Mode and Device		Before Mini-Split Installation (kWh/yr)	After Mini-Split Installation but prior to controls (kWh/yr)	After Mini-Split Installation and with controls (kWh/yr)
Heating	Baseboard electric	10,310	0	160
	Dining-room mini split	N/A	1,660	2,930
	Living-room mini split	N/A	1,800	1,150
	Total Heating	**10,310**	**3,460**	**4,240**
Cooling	Room A/C	0	0	0
	Dining-room mini split	N/A	25	65
	Living-room mini split	N/A	410	380
	Total Cooling	**0**	**435**	**445**
Total Space Conditioning		**10,310**	**3,895**	**4,685**
Total Operating Cost ($/yr)		$1,290	$485	$585

Notes:

1. Annual consumption normalized to 2001-2020 average weather for the St. Paul downtown airport. See Appendix B for details of regression fits of consumption versus outdoor temperature. Baseboard electricity use in the first year following installation of the mini splits was limited to 1 kWh in one bedroom on one occasion: no attempt was made to correct this value for weather.
2. Estimates for consumption prior to installation of the mini splits is from monthly utility billing data for the period from August 13, 2019 through June 14, 2020. No detectable cooling electricity was observed in this period.
4. Annual operating cost based on 12.5 cents per kWh.

Several factors likely played a role in the increase in electricity use in the second heating season following installation of the mini splits. First, the dining room was maintained at a temperature that was 5 to 6F higher compared to the prior heating season (Figure 5). This likely increased the heating load for the dining-room unit.

Figure 5. Mean monthly room temperature at Site 1.



Second, the homeowner reported that the dining-room outdoor unit began to ice up in December and remained that way through most of the heating season. This may have been because the dining room unit was installed much closer to the ground than the living room unit and thus more subject to being covered by snow (Figure 6).[5]

[5] The unit has since been raised further off the ground.

Figure 6. Exterior view of the Site 1 home showing the outdoor units for the two mini-split systems.

Third, the installation of the controls clearly resulted in the baseboard heat being energized in the second heating season. Some of this use may have been attributable to reduced mini-split capacity due to the compressor-icing issue, but some dining-room baseboard use was observed throughout the 2021/2022 heating season even before the icing occurred.

Figure 7, shows dining-room system operation and temperatures for two similarly cold days before and after installation of the controls. Prior to installation of the controls, the dining-room mini split operated continuously throughout the day. With the controls, the unit appeared to cycle off and on at full output, except for periods when the baseboard heat was energized. There was also less variation in the temperature in the dining room prior to installation of the controls. At the outset of the project the Fujitsu distributor's representative did state that the interface module required to integrate the mini split and the baseboard heat would modify the behavior of the unit such that it would not modulate in the same way — however, the compressor icing may have played a significant role as well.

Figure 7. Dining-room mini-split and baseboard operation and selected temperatures for comparable cold days before and after installation of controls at Site 1.

When interviewed at the conclusion of the monitoring period, the homeowner reported a significant drop in electricity costs associated with installation of the mini-split units, noting that "these systems have helped us out a lot." They also reported much improved indoor comfort during the winter and summer and especially appreciated the fact that the mini-split units operate automatically in response to changing weather. There was no perceived change in the operation of the system or indoor comfort when the integration controls were installed, and the homeowner did not pay attention to whether the existing baseboard heat was operating or not.

SITE 2

SITE DESCRIPTION

The Site 2 home, located in the Greater East Side neighborhood of St. Paul, is an older 1.5-story home with a 1-story rear addition over a tuck-under garage with about 2,440 ft^2 of floor area (Figure 8). The addition consists of a rec room that is open to the existing home's kitchen and, beyond the rec room, a small sunroom space at the rear, open to the rec room. The first floor of the original structure is conditioned with a forced-air natural gas furnace and central air conditioner. The rec room in the addition and the second-floor bedroom were heated with baseboard electric units and cooled with window air conditioner prior to the project. The sunroom has no permanent heating or cooling. The home is occupied by two adults and two children.

In March 2020, attic insulation and air-sealing work was performed on the home under Xcel's Good Cents program.

In July 2020, a 24 kBtuh LG mini-split system was installed with two indoor heads to offset the existing baseboard electric heat.[6] One indoor head was installed to serve the rec room in the home's addition and the other to serve the second-floor bedroom. The installation cost of the system was $10,530.

After operating as-installed for about a year, in August 20218 controls were installed to integrate the mini-split and electric-baseboard operation. The integration controls consisted of LG components and field-supplied relays to allow control of the baseboard heat by wall-mounted LG thermostats in the rooms served by each indoor head (see Appendix A). Note that at the time they were installed, this control strategy was applicable only to multi-head systems; LG representatives said there was no equivalent option for single-head systems.

Two trips were required for installation of the controls due to a missing factory wiring harness. The cost to install the controls was $1,390. After installation, the controls are set to trigger a call for auxiliary heat whenever space temperature fell 3F or more below setpoint. Because the controls did not bypass the existing dial thermostats on the baseboard heaters, however,

[6] The system consists of a LMV240HHV outdoor unit with two LSN120HSV5 indoor units.

occupants retained the ability to easily manually disable baseboard operation entirely by simply reducing the baseboard thermostat setpoints.

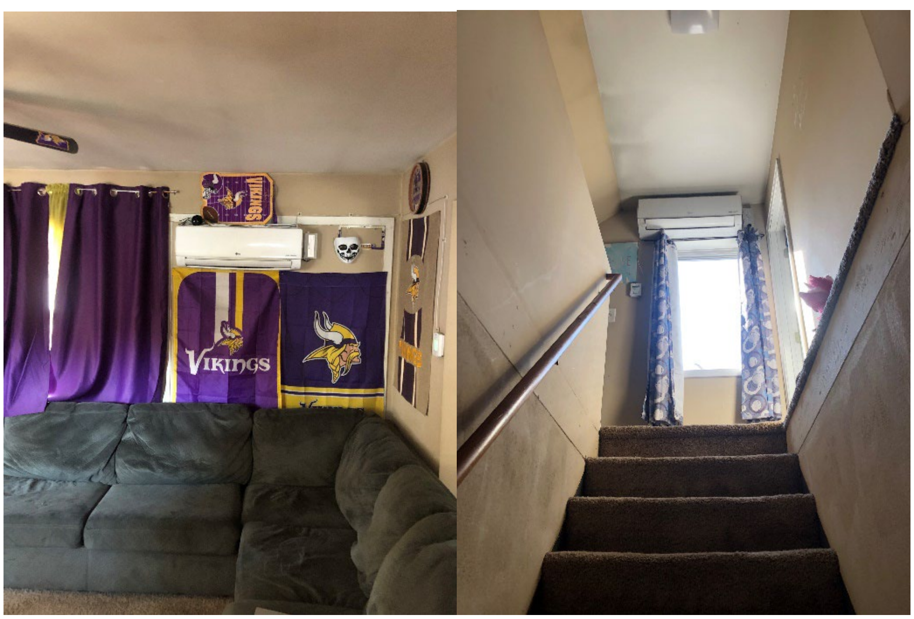
Monitoring in the home consisted of tracking electrical power to the mini split and baseboard heat, operation of the existing central heating and cooling system, and—after the controls were installed—tracking system calls for auxiliary baseboard heat. Temperature and humidity in the affected spaces were also monitored, as was the temperature at the supply-air outlet of each indoor mini-split head.

In February 2021, partway through the monitoring period, the homeowner replaced the central gas furnace that provides heat to the main part of the home. The original furnace was a non-condensing 66kBtuh model with an AFUE rating of 80%; it was replaced by a non-condensing 70kBtuh furnace, also with an AFUE rating of 80%.

Figure 8. The Site 2 home.

Figure 9. The outdoor unit for the Site 2 mini-split system.

Figure 10. The rec room (left) and 2nd-floor (right) indoor units for the Site 2 mini-split system.



FINDINGS

Analysis of monthly utility records (Figure 11 and Figure 12) indicate that the home used about 740 therms of natural gas and 5,600 kWh of electricity for space heating and 1,300 kWh of electricity for space cooling prior to installation of the mini-split system (Table 3).[7]

Following installation of the mini-split system, baseboard electricity was used only in the rec-room space—and only in the first heating season following installation of the mini split. No other baseboard operation was recorded during the monitoring period, presumably because the occupants manually turned the baseboard units off entirely. The supply-air temperature data for the mini-split system suggest that operation of the mini split is roughly equally split among serving just the first-floor head, serving just the second-floor head, and serving both heads simultaneously.

Natural-gas consumption by the furnace in the main part of the house also fell by about 28 percent on a weather-normalized basis after the mini-split system was installed. Although the furnace was replaced during this period, analysis of gas consumption from before and after the replacement suggest that this had little impact on gas usage for space heating.

Electricity use for space heating and cooling fell by about 10 percent after the integration controls were installed, but since there was little baseboard electric use prior to the controls, this decline cannot be attributed to reduced use of the baseboard heat.

Overall, the heating and cooling energy costs decreased by about 24 percent after installation of the mini-split system from a combination of near elimination of baseboard electric heat and a significant reduction in natural gas use. The data suggest that the integration controls had little effect on energy use and costs, because the occupants manually disabled the baseboard heat in the second year.

[7] The attic insulation and air-sealing work under Good Cents occurred about 8 months into this period. The utility billing data suggest about 775 therms/year of gas consumption for space heating prior to the weatherization work and 740 therms/year after.

Figure 11. Whole-home electricity consumption for Site 2.

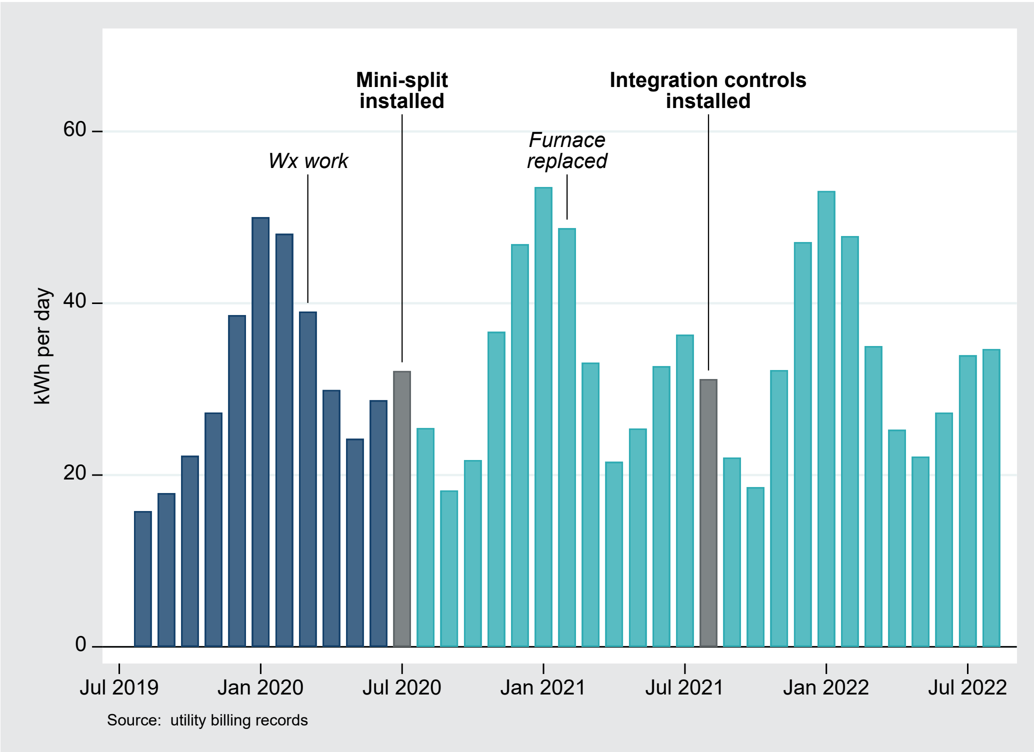


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Figure 12. Whole home natural-gas consumption for Site 2.

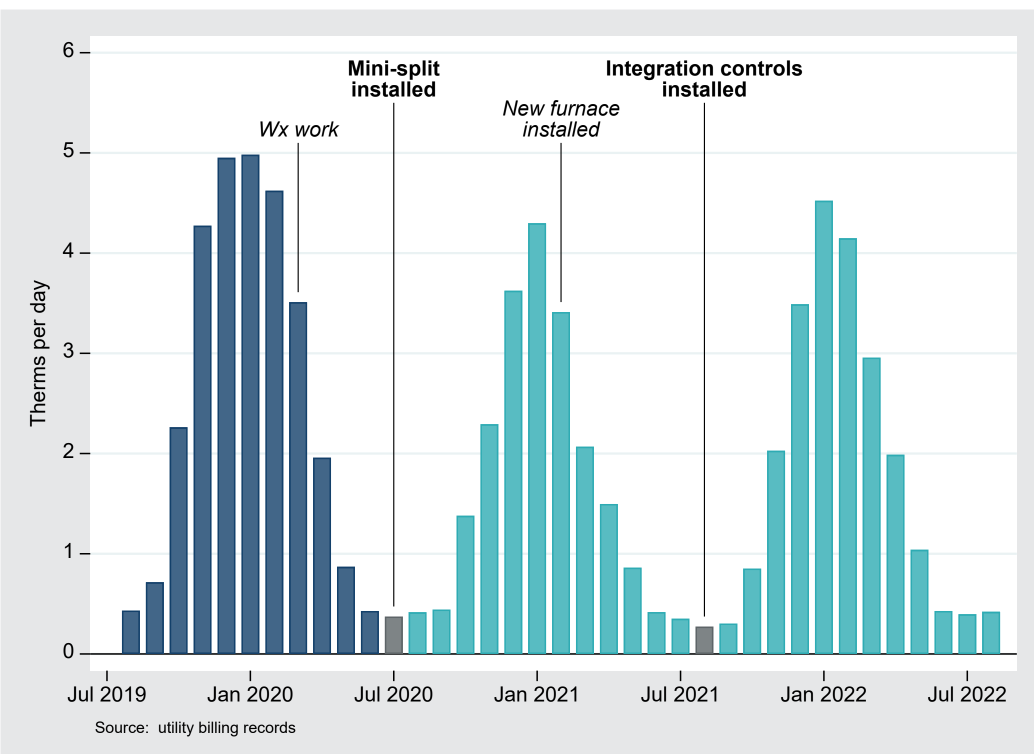


Table 3. Weather-normalized annual energy use and cost for heating and cooling at Site 2.

Operating Mode and Device		Before Mini-Split Installation kWh	Before Mini-Split Installation Therms	After Mini-Split installation but prior to controls kWh	After Mini-Split installation but prior to controls therms	After Mini-Split installation and with controls kWh	After Mini-Split installation and with controls therms
Heating	Gas furnace	5,600	740	340	535	220	545
	Baseboard electric		N/A	50	N/A	0	N/A
	Mini-split system	N/A	N/A	4,090	N/A	3,785	N/A
	Total Heating	**5,600**	**740**	**4,480**		**4,005**	
Cooling	Central A/C	1,300	N/A	855	N/A	1,055	N/A
	Mini-split system	N/A	N/A	490	N/A	310	N/A
	Total Cooling	**1,300**	N/A	**1,345**	N/A	**1,365**	N/A
Total Space Conditioning		**6,900**	**740**	**5,460**	**535**	**4,940**	**545**
Total Operating Cost		$1,345		$1,000		$950	

Notes:

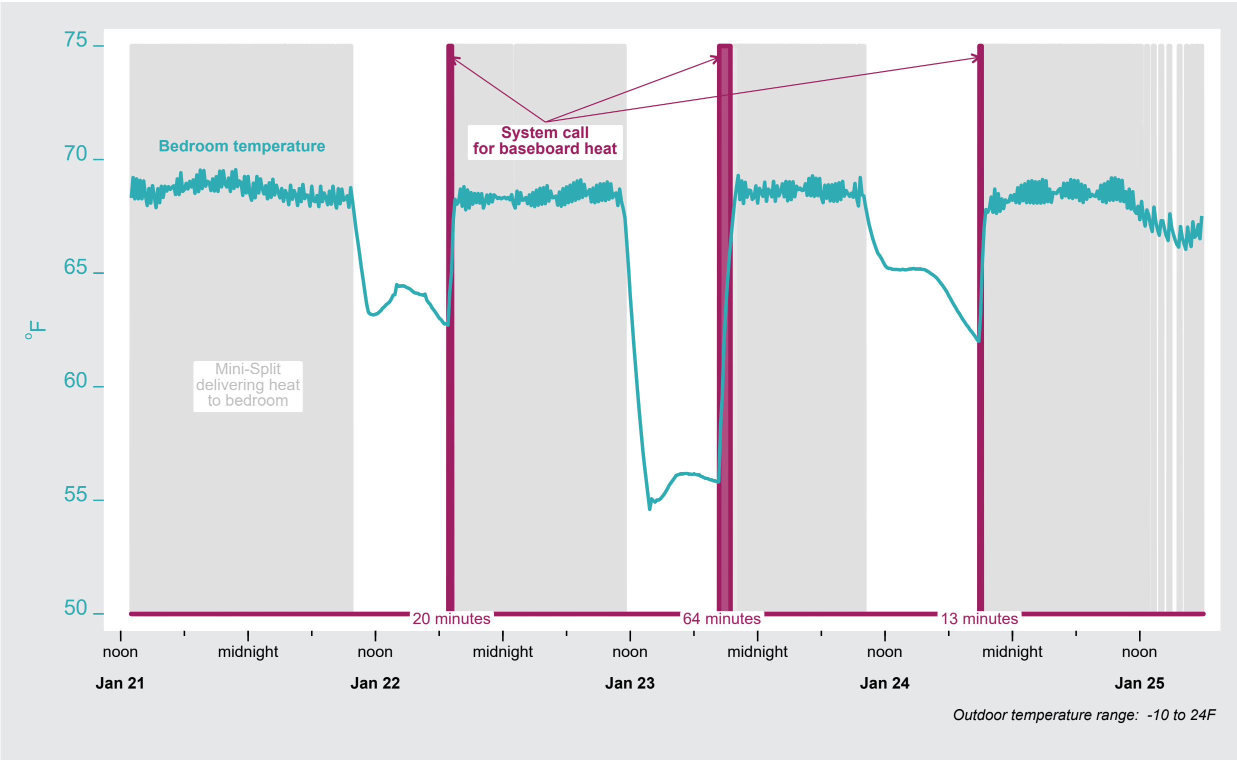
1. Annual consumption normalized to 2001-2020 average weather for the St. Paul downtown airport. See Appendix B for details of regression fits of consumption versus outdoor temperature.
2. Estimates for electric consumption prior to installation of the mini split is from monthly utility billing data for the period from September 2019 to July 2020.
3. Estimates for natural-gas consumption based on monthly utility billing data for the period August 2019 through July 2020.
4. Cooling use estimate prior to mini-split installation includes use of the 2nd-floor window air conditioner.
5. Annual operating cost based on overall average 12.5 cents per kWh and 65 cents per therm during the study period.

Figure 14 shows the operation of the mini split and baseboard heat along with selected temperatures for similarly cold days from the heating season prior to and following installation of the controls. In both cases, the mini-split system operated continuously throughout the day, with downward spikes in power consumption associated with defrost cycles. The baseboard electric units in the rec room operated in the first year but not in the second. The monitoring data also indicate that there were no calls by the system for backup electric baseboard on the first floor after installation of the controls.

The temperature data indicate that the occupants typically turn off the heat to the second floor during the day, and then re-enable it in the evening. After the controls were installed, this resulted in regular system calls for backup electric-resistance heat in the evening due to the large initial difference between the mini-split setpoint temperature and the actual space temperature (Figure 14). However, because the occupants had manually disabled the auxiliary baseboard heat, it did not actually come on during these periods. Had the occupants left the baseboard heat enabled, heating costs would likely have risen somewhat due to baseboard operation during these daily temperature recovery periods. As operated, the data show that the mini-split system was able to recover the setpoint temperature quickly without the backup heat, even in very cold weather.

Figure 13. Mini-split and baseboard operation and selected temperatures for similar cold days before and after installation of controls at Site 2.

Figure 14. Example of cold-weather system operation and space temperature in the second-floor bedroom after installation of the controls. Note that the baseboard heat did not actually operate during this period because it had been manually disabled by the household.



When interviewed at the end of the study, the household reported much improved comfort, making note of improved summer comfort in the rec room, which was not well served by the home's central A/C system prior to installation of the mini-split system. The interviewed homeowner noted they really love the new system and talk them up with friends and family. They were surprised at how much the units ran but have grown to trust that they do a good job of automatically maintaining setpoints, which has been a big benefit to the family.

The household did not notice any difference after installation of the integration controls, but also noted that they kept the existing baseboard turned off. The homeowner did state that they continue to rely on the original remotes that came with the system and only rarely use the wall thermostats that were installed with the integration controls.

SITE 3

SITE DESCRIPTION

Site 3, located in White Bear Lake, is a roughly 1,200 square-foot, single-story converted cabin (Figure 15). Prior to the study, the all-electric home had baseboard resistance-electric heating throughout the home, a 1,500-watt electric fireplace in the living room and a portable air conditioner. At the outset of the project, the home also had a non-functional sleeve air conditioner in the living room at the front of the home. No weatherization work was done on the home during the monitoring period. The home is occupied by an adult and two teenage children.

In March 2021, a 9kBtuh, single-head Mitsubishi mini split heat pump was installed, with the indoor head taking the place of the broken sleeve air conditioner, which was removed.[8] The heating contractor originally proposed a 15kBtuh model, but after review of utility records by the Project Team to estimate the prior heating load of the home, the smaller-capacity system was agreed to by all parties. The installed cost of the system was $7,280, which included removal of the existing sleeve A/C unit and repairing the wall in that location prior to installation of the indoor head.

The mini-split system was operated by the homeowner as originally installed until mid-February 2022, when modifications were made to integrate control of the living-room baseboard unit with the mini-split system.[9] The integration strategy took advantage of the heat-pump unit's built-in ability to control backup heat via a relay kit to control power to the living-room baseboard circuit (see Appendix A).[10] The system natively allows for setting backup heat *lockout* and *engage* temperatures. Backup heat is disabled entirely when the outdoor temperature is above the lockout temperature and allowed when the outdoor temperature is below the engage temperature—but will only be energized if the indoor temperature sensed by the unit is 3F or more below the setpoint temperature. The system appears to have been set with a lockout and engage temperatures of around 50F.[11] The homeowner was also asked to allow the baseboard heat to operate if called for by the system, with a promise of compensation for any electricity use by the living-room baseboard circuit.

Monitoring included electrical power to the mini split system and the various baseboard circuits, along with temperature and humidity in various rooms.[12] A temperature sensor was also installed to track supply-air temperature from the mini split.

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[8] The model number of the installed unit is MSZFH09NA.

[9] The contractor did not submit a separate invoice for the installation of controls.

[10] The integration control also included an entryway baseboard unit, though this unit was found to be non-functional.

[11] We were unable to verify these temperatures but observed baseboard heat operation up to outdoor temperatures of about 50F.

[12] Note however, that there were some issues with the temperature and humidity loggers falling or being moved by household members over the course of the study—and one logger went missing (though still reported data). This creates uncertainty in analyzing the temperature and humidity data at this site.

Figure 15. Site 3 prior to mini-split installation.

Figure 16. The outdoor unit of the mini-split system at Site 3.

Figure 17. The indoor unit of the mini-split system at Site 3.

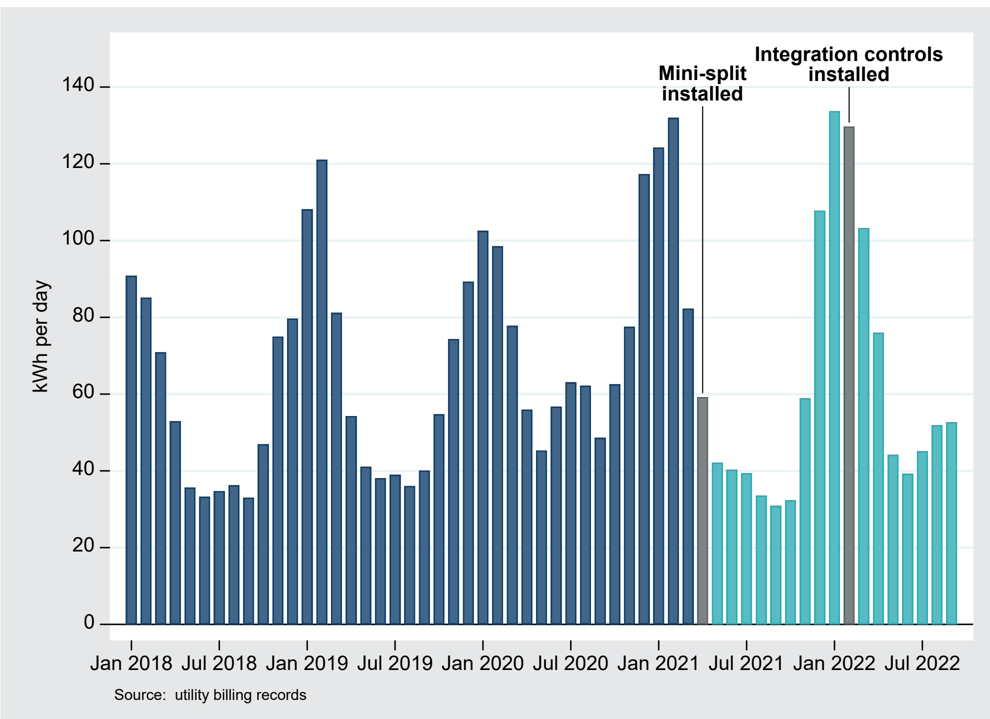
FINDINGS

Utility billing records in the year immediately preceding installation of the mini split suggest about 12,000 kWh per year for space heating and 1,600 kWh for cooling (Table 4), though there is considerable uncertainty in both estimates because both space heating and cooling electricity use was noticeably higher in the year immediately preceding the mini-split installation than in the two prior years (Figure 18). Also, all three summer months in 2020 had about the same number of cooling degree days, which makes it difficult to accurately estimate cooling energy use from monthly billing data.

Following installation of the mini split, electricity consumption for space heating appears to have dropped by about 25 percent — though this figure is also subject to the uncertainty in the amount of space heating consumption prior to installation of the mini split, as well as the fact that one of the bedrooms is maintained at very cold temperatures due to a medical condition for one of the household members (Figure 19).[13] There was no baseboard electric resistance used in the living room area where the mini split was located, but baseboard heat was used regularly in one of the bedrooms and in the bathroom.

Installation of the controls midway through the second heating season resulted in a weather-normalized increase of about 755 kWh per year in living-room baseboard heat.

Figure 18. Whole-home electricity consumption for Site 3.



[13] The situation is further complicated by the fact that the temperature logger for the other bedroom went missing at some point: it continued to report data, but it could not be located in the home. Data from this logger was not used.

Table 4. Weather-normalized annual electricity use for heating and cooling at Site 3.

Operating Mode and Device		Before Mini-Split Installation (kWh/yr)	After Mini-Split Installation but prior to controls (kWh/yr)	After Mini-Split Installation and with controls (kWh/yr)
Heating	Baseboard (total)	11,950	6,880	8,985
	Living room	Unknown	*0*	*755*
	Bedroom 1		*0*	*0*
	Bedroom 2		*4,330*	*5,185*
	Bathroom		*2,550*	*3,045*
	Mini Split	N/A	2,105	2,115
	Total Heating	**11,950**	**8,985**	**11,100**
Cooling	Room A/C	1,600	0	0
	Mini Split	N/A	620	435
	Total Cooling	**1,600**	620	435
Total Space Conditioning		**13,550**	9,605	11,535
Total Operating Cost ($/yr)		$1,695	$1,200	$1,440

Notes:

1. Annual consumption normalized to 2001-2020 average weather for the St. Paul downtown airport. See Appendix B for details.
2. Estimates for consumption prior to installation of the mini splits is from monthly utility billing data for the period from April 2020 to May 2021.
3. Annual operating cost based on 12.5 cents per kWh.

Figure 19. Recorded monthly indoor temperatures at Site 3.

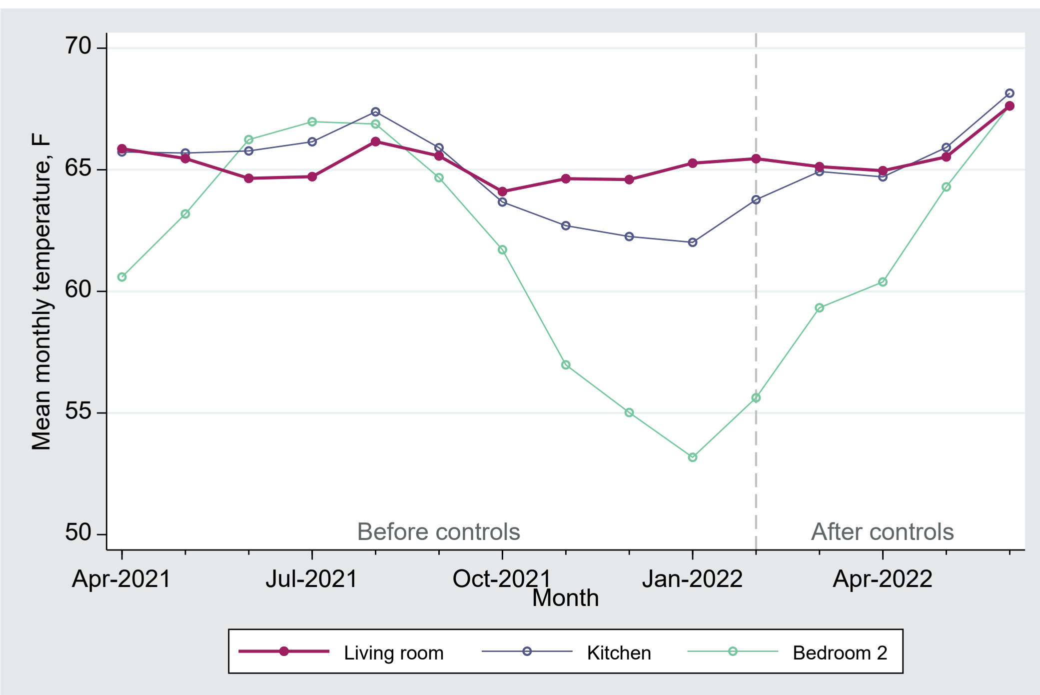
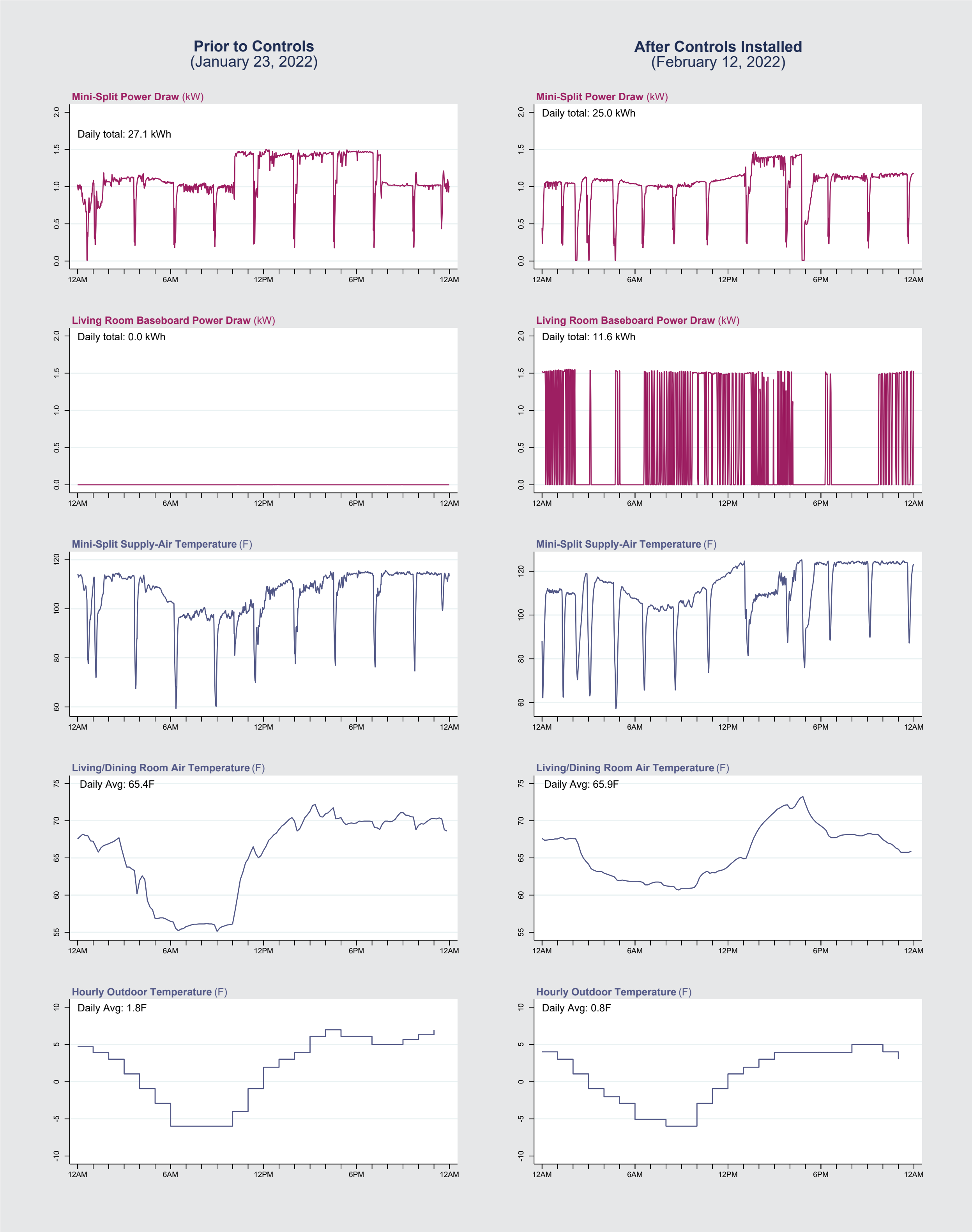


Figure 20 shows the mini-split and living-room baseboard operation and selected temperature data for similar cold days before and after installation of the integration controls. The mini-split operated continuously throughout both days, with downward spikes in power and supply-air temperature likely being associated with periodic defrost cycles. The living-room baseboard unit was not used at all prior to installation of the controls but engaged frequently after the controls were installed—indicating that the indoor temperature sensed by the unit was at least 3F below its setpoint.

Surprisingly, the recorded indoor temperature was not significantly different between the two days, and recovery from the apparent overnight temperature setback was, if anything, slower when the backup heat was operated. This may have something to do with the location of the temperature logger (on the far side of the room next to the thermostat for the baseboard unit) compared to the temperature being sensed by the system at the mini-split remote control.

The homeowner reported good satisfaction with the mini-split system for both heating and cooling but did note that the system didn't seem to cool quite as well in second summer. They reported that the unit was able to maintain comfortable temperatures in the living room, dining room and even in the kitchen at the back of the house. The homeowner reported that energy bill savings were less than expected but noted that it was necessary to continue to operate the bathroom baseboard to maintain temperature and keep pipes from freezing. The homeowner stated that they didn't really notice the integration controls and didn't really understand what they were doing and so didn't have a clear preference for having or not having controls.

Figure 20. Mini-split and baseboard operation and selected temperatures for similar cold days before and after installation of controls at Site 3.



CONCLUSIONS

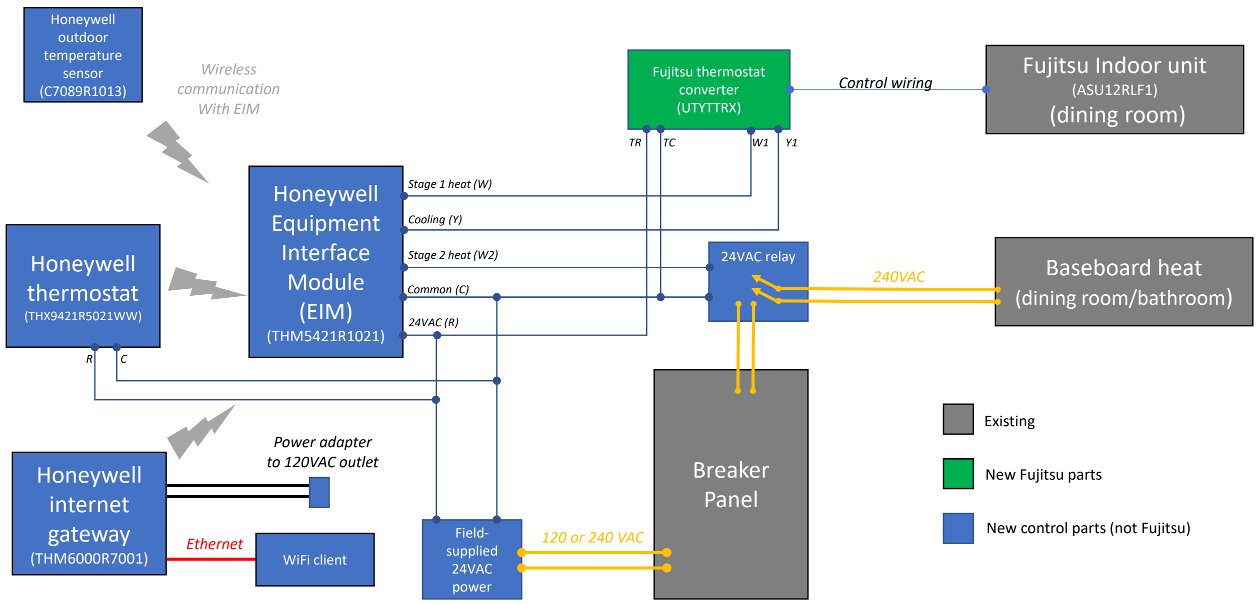
The three households in the study all enjoyed substantial reductions in energy costs following installation of the mini-split systems, and the systems were able to comfortably condition the indoor environment even under very cold conditions. Because the households were already motivated to minimize the use of expensive baseboard electric heat, integration controls were unnecessary for these homes. In fact, the temperature-droop-based controls slightly *increased* electricity consumption at two of the three sites by calling for baseboard heat when recovering from temperature setback or after the system had been temporarily turned off. The third site would likely also have seen a similar increase in electricity consumption for space heating had the household not manually disabled the baseboard heat entirely to prevent it from operating.

A more natural market for integration controls would thus seem to be higher-income households where heating and cooling costs are less of a pressing concern. Alternatively, providing effective household education about how to maximize the energy-cost savings potential for mini-split heat pumps could also be an effective strategy and avoid the expense of integration controls, though this study did not test that hypothesis.

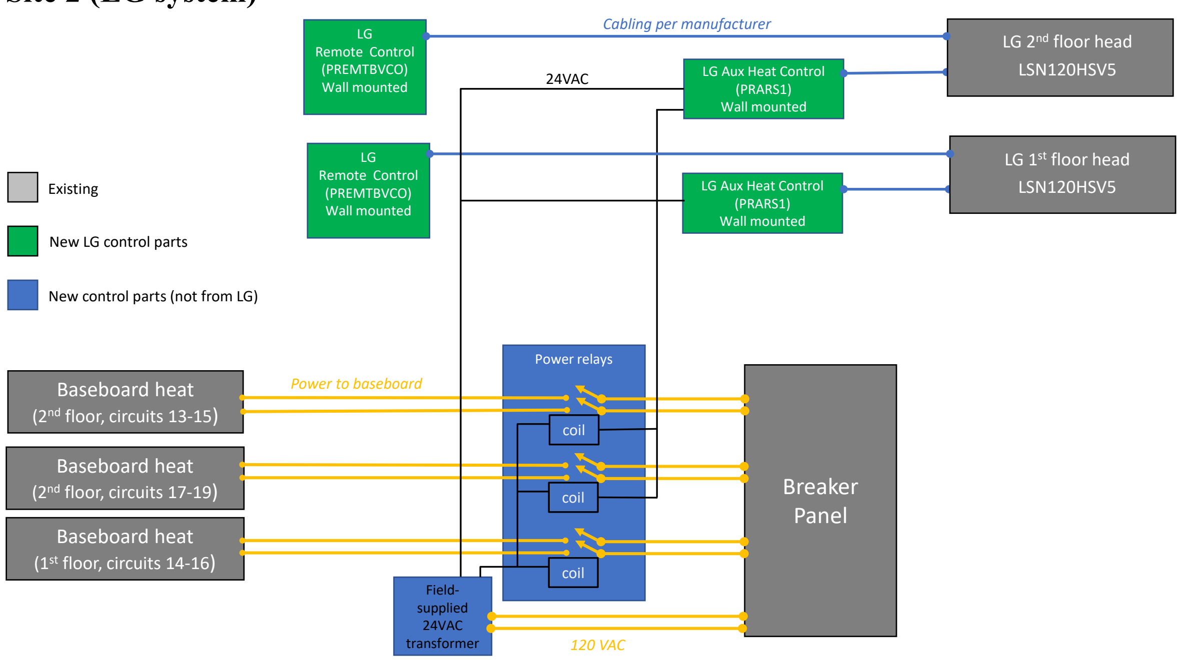
In addition, the three Twin-Cities-area contractors—and in some cases the technical-support representatives they rely on—were unfamiliar with integration controls, requiring multiple trips to the home in two of three cases. This suggests that efforts to promote the adoption of these controls in areas where they have historically not been employed needs to be paired with concomitant contractor training and support.

APPENDIX A — INTEGRATION CONTROLS WIRING DETAILS

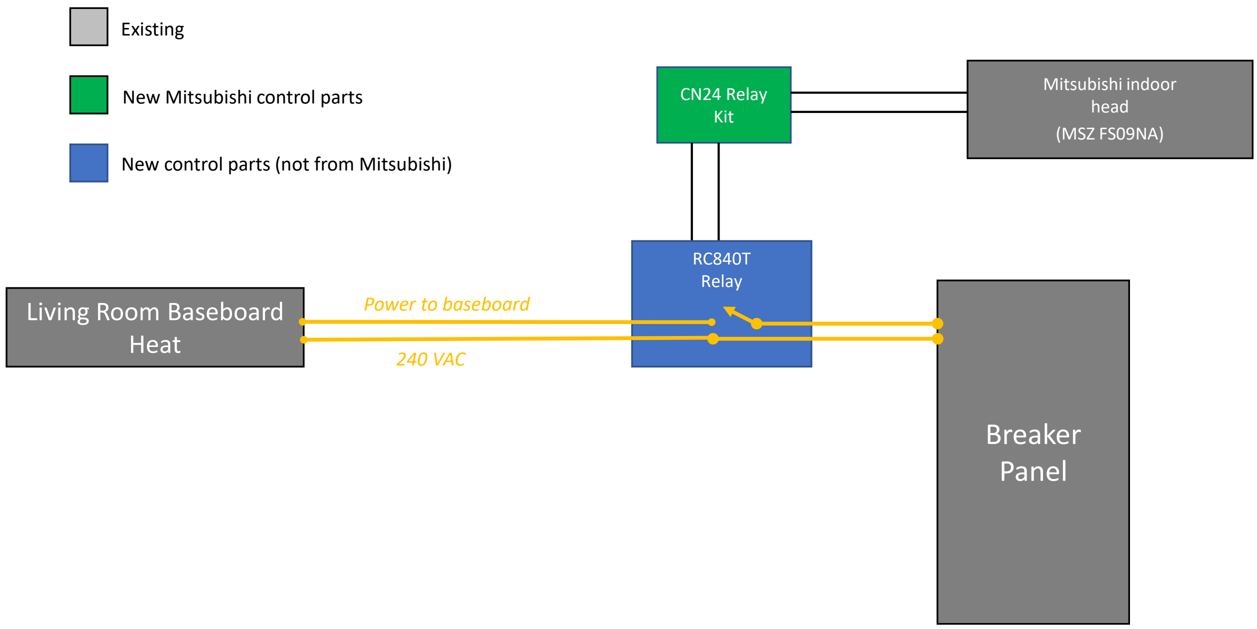
Site 1 (Fujitsu system)



Site 2 (LG system)



Site 3 (Mitsubishi system)

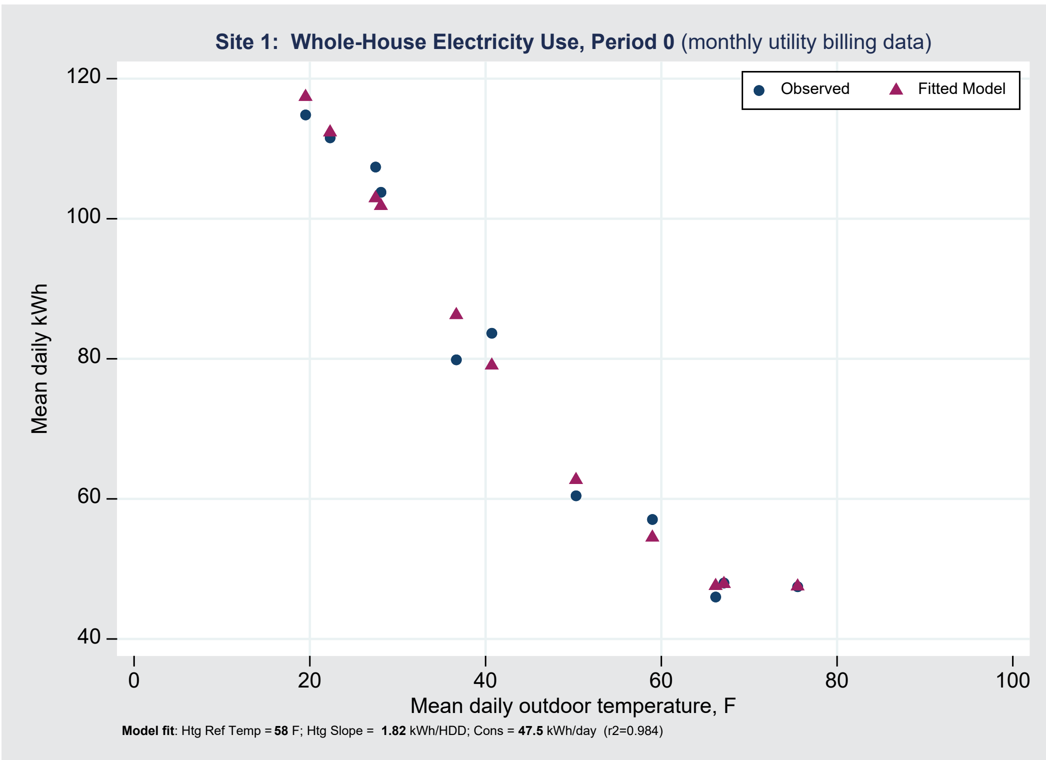


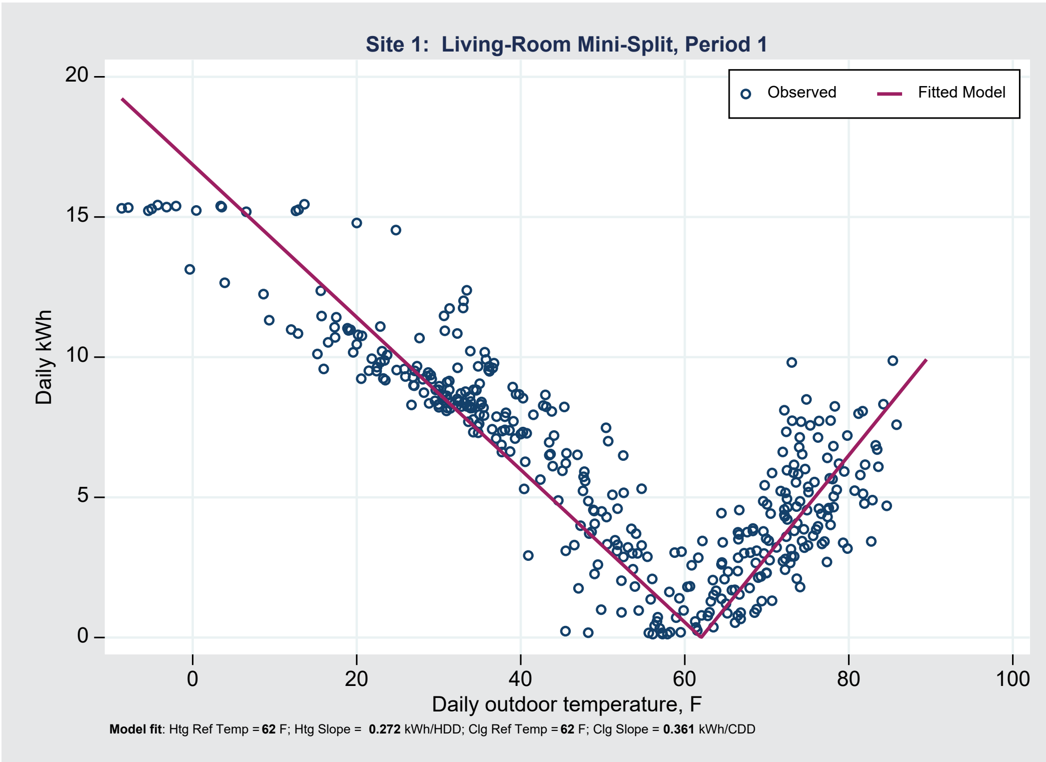
APPENDIX B — WEATHER-NORMALIZATION FITS

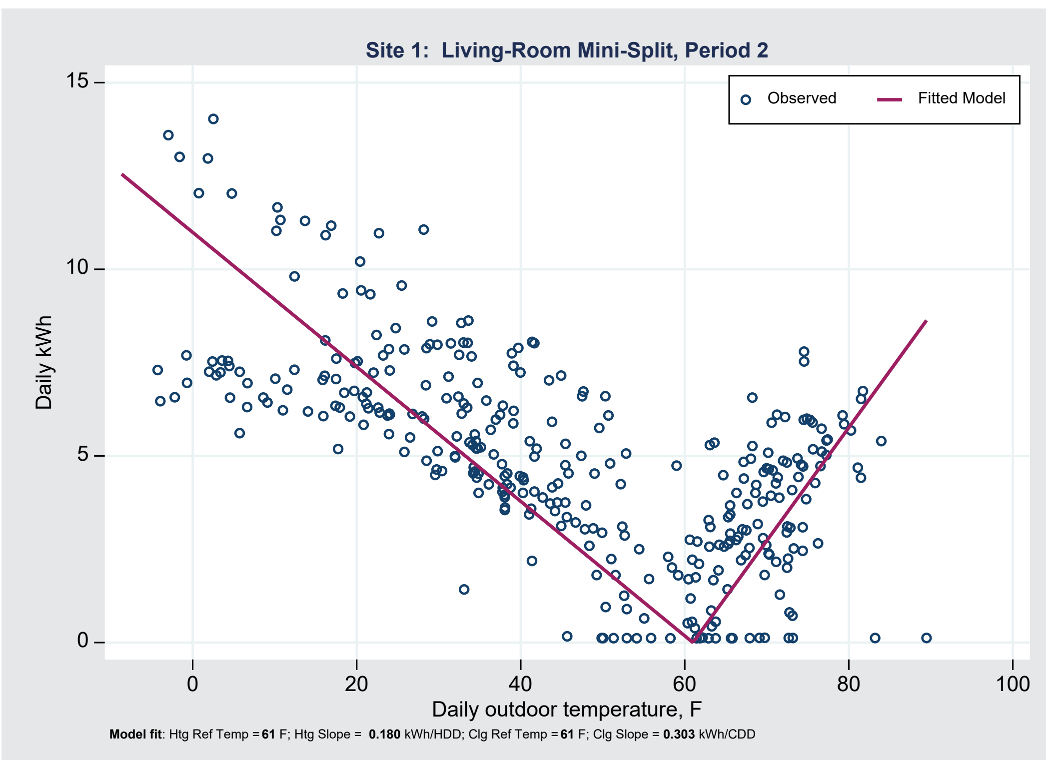
Period 0 — Prior to installation of mini-split system (from monthly utility data)

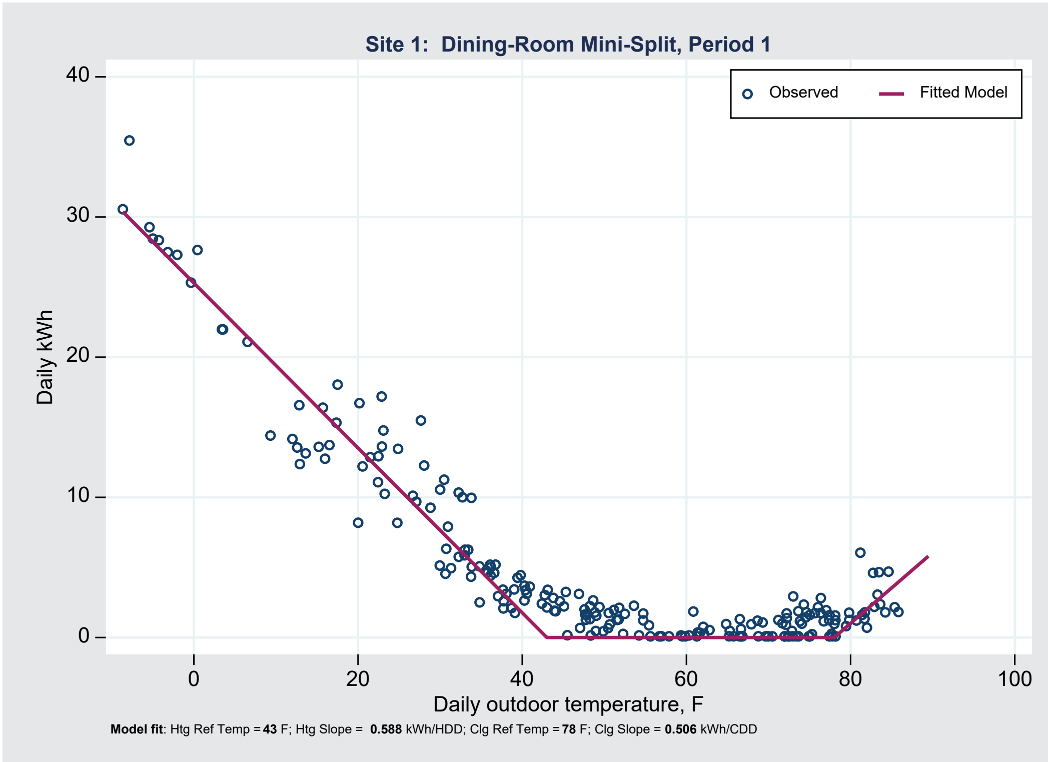
Period 1 — After installation of mini-split system but prior to installation of integration controls (from daily field-monitoring data)

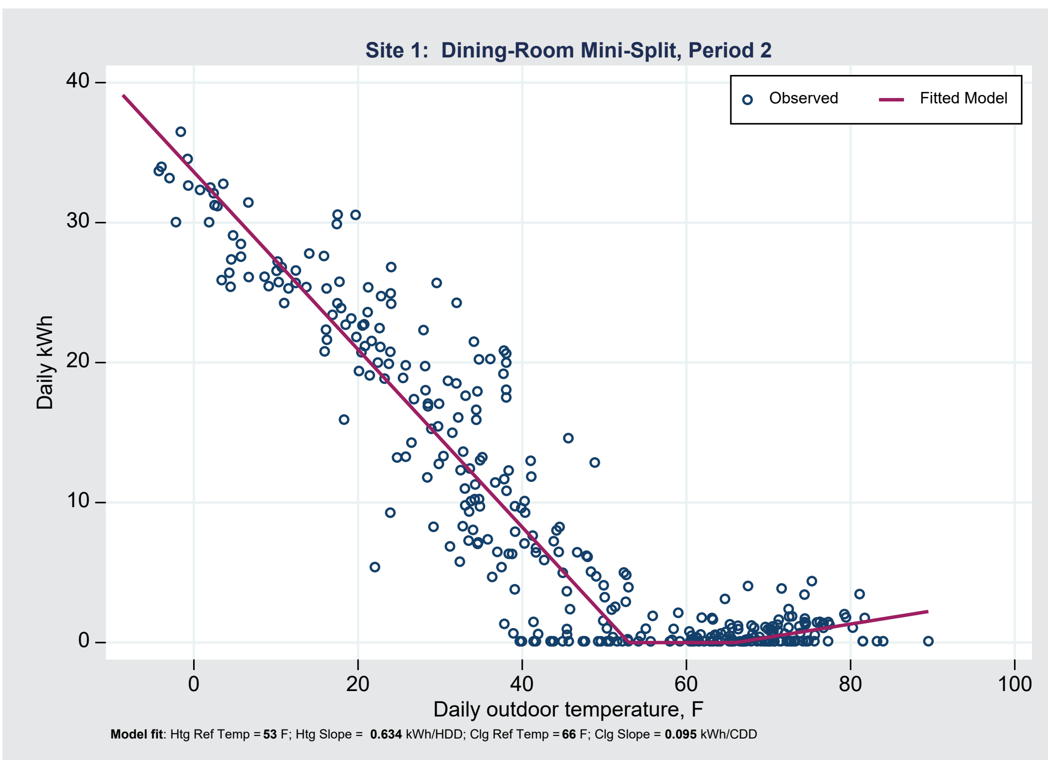
Period 2 — After installation of mini-split system and after installation of integration controls (from daily field-monitoring data)

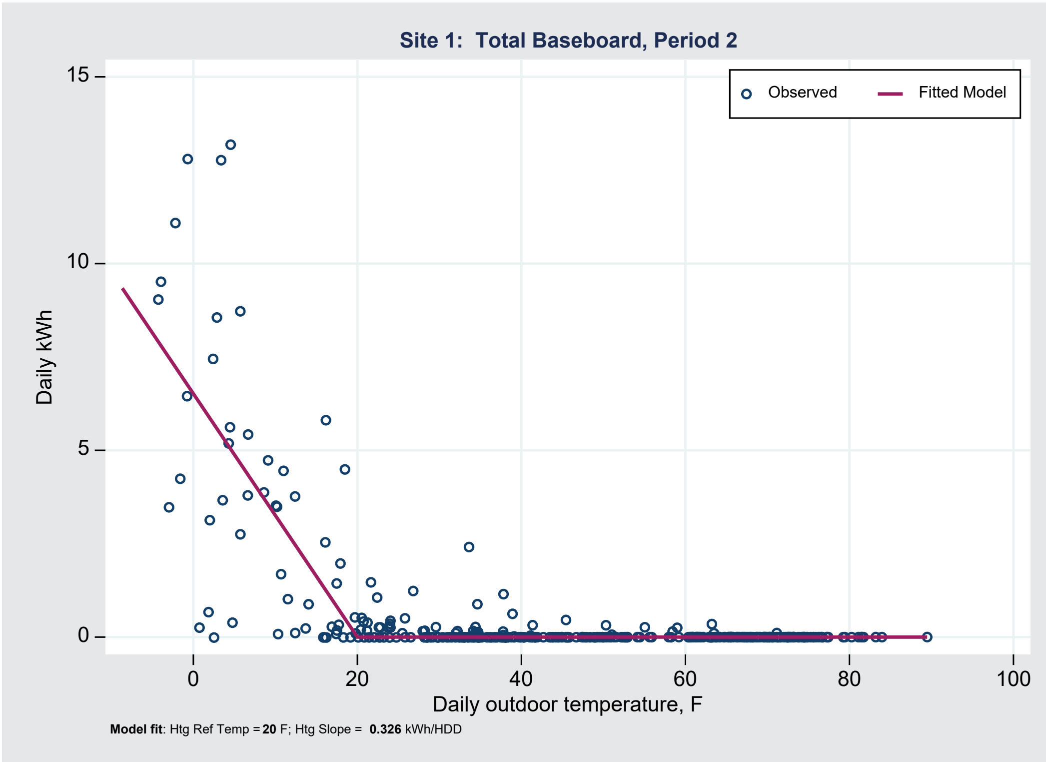


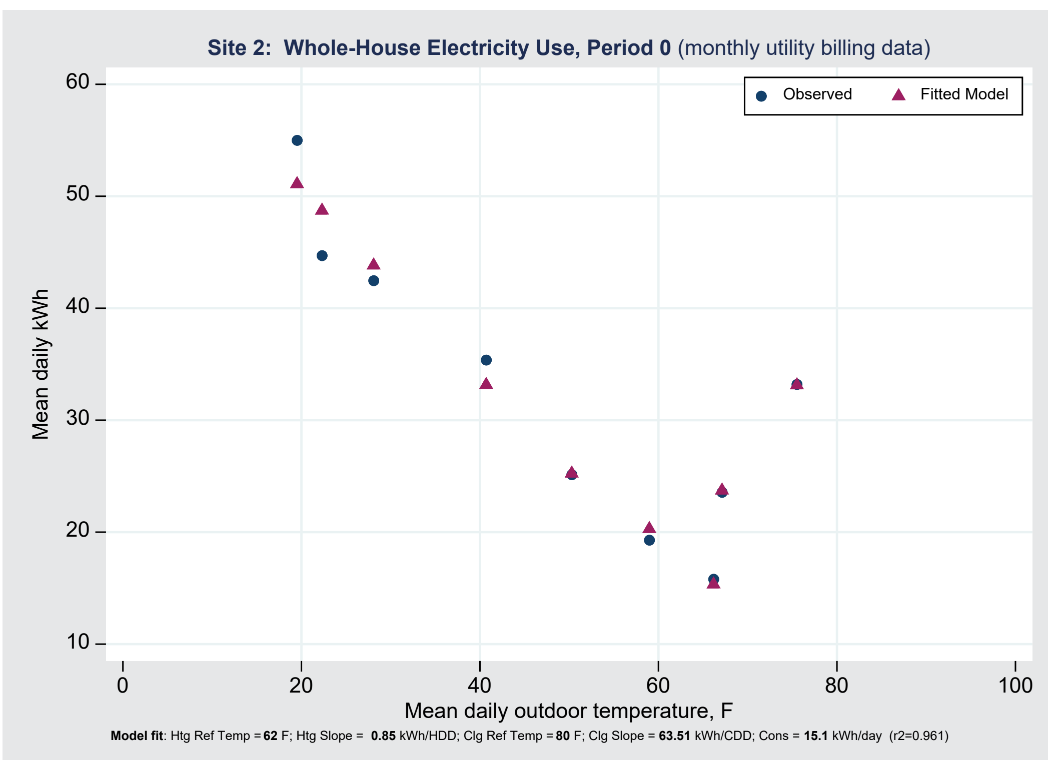

Site 1: Living-Room Mini-Split, Period 1
Observed
Fitted Model
Daily kWh
Daily outdoor temperature, F
20
15
10
5
0
0
20
40
60
80
100
Model fit: Htg Ref Temp = **62** F; Htg Slope = **0.272** kWh/HDD; Clg Ref Temp = **62** F; Clg Slope = **0.361** kWh/CDD

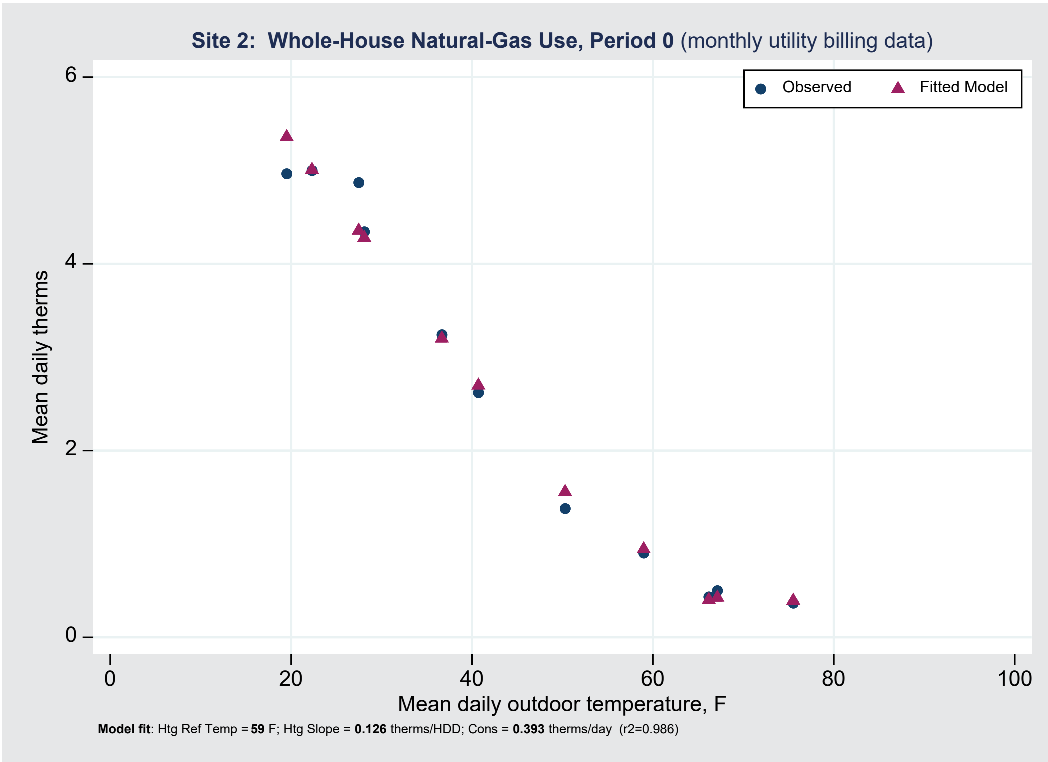

Site 1: Living-Room Mini-Split, Period 2
Observed
Fitted Model
Daily kWh
Daily outdoor temperature, F
15
10
5
0
0
20
40
60
80
100
Model fit: Htg Ref Temp = **61** F; Htg Slope = **0.180** kWh/HDD; Clg Ref Temp = **61** F; Clg Slope = **0.303** kWh/CDD

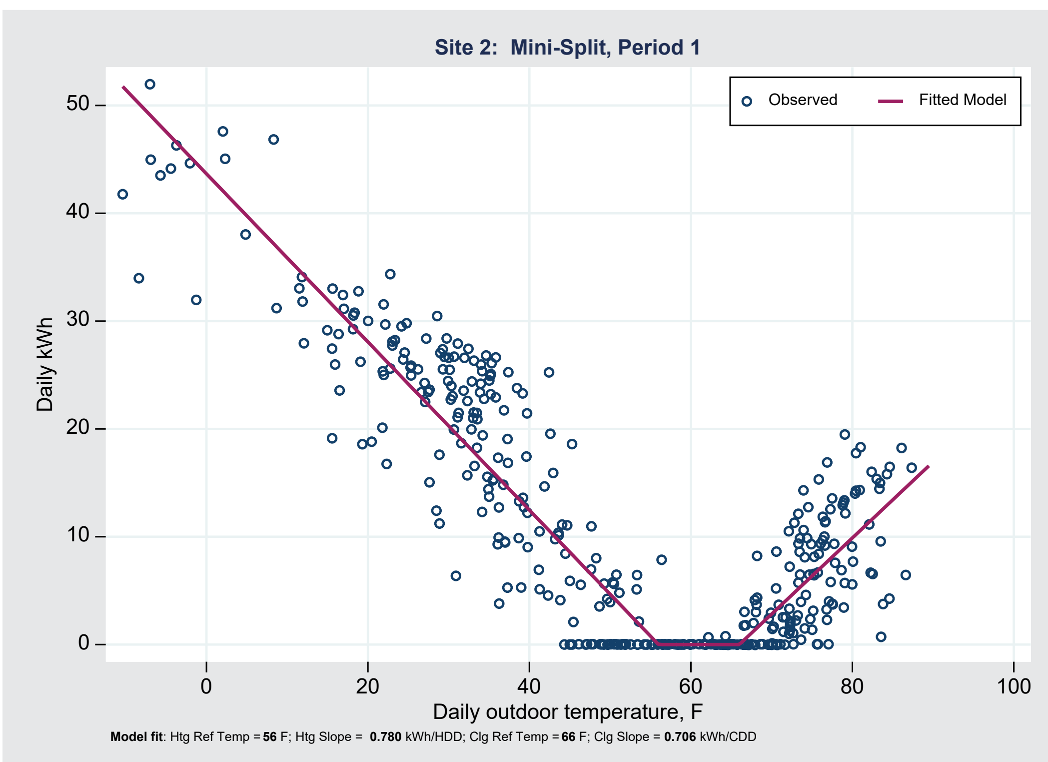

Site 1: Dining-Room Mini-Split, Period 1
Observed
Fitted Model
Daily kWh
40
30
20
10
0
0
20
40
60
80
100
Daily outdoor temperature, F
Model fit: Htg Ref Temp = **43** F; Htg Slope = **0.588** kWh/HDD; Clg Ref Temp = **78** F; Clg Slope = **0.506** kWh/CDD

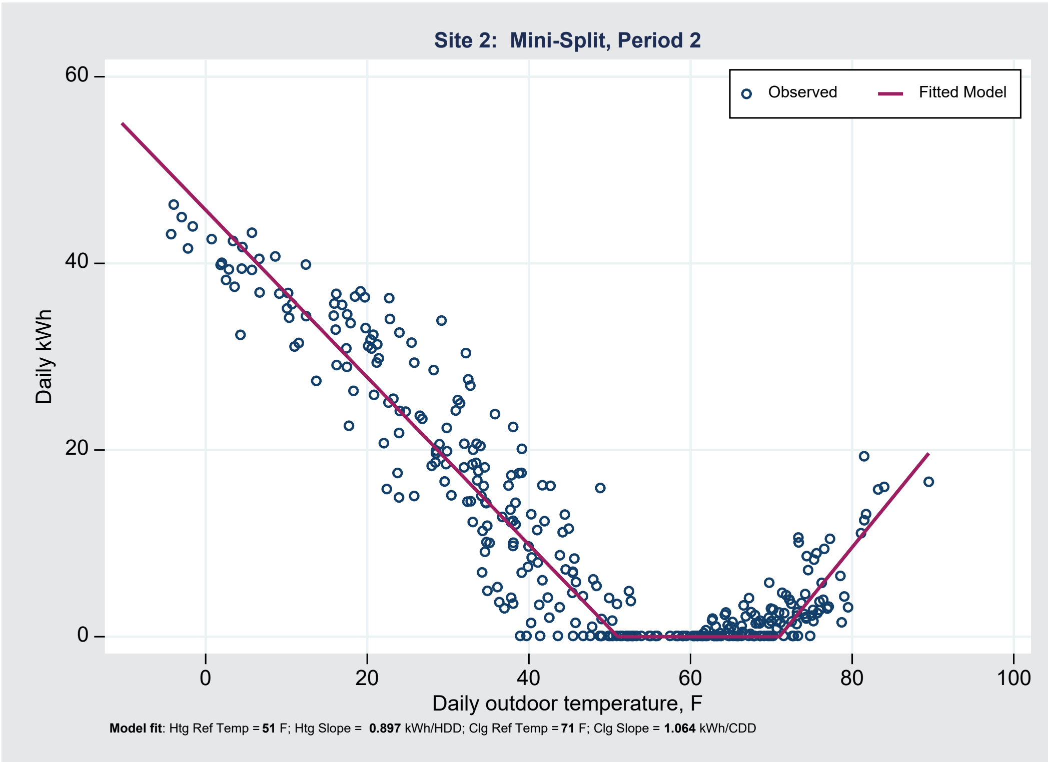

Site 1: Dining-Room Mini-Split, Period 2
Observed
Fitted Model
Daily kWh
40
30
20
10
0
0
20
40
60
80
100
Daily outdoor temperature, F
Model fit: Htg Ref Temp = **53** F; Htg Slope = **0.634** kWh/HDD; Clg Ref Temp = **66** F; Clg Slope = **0.095** kWh/CDD

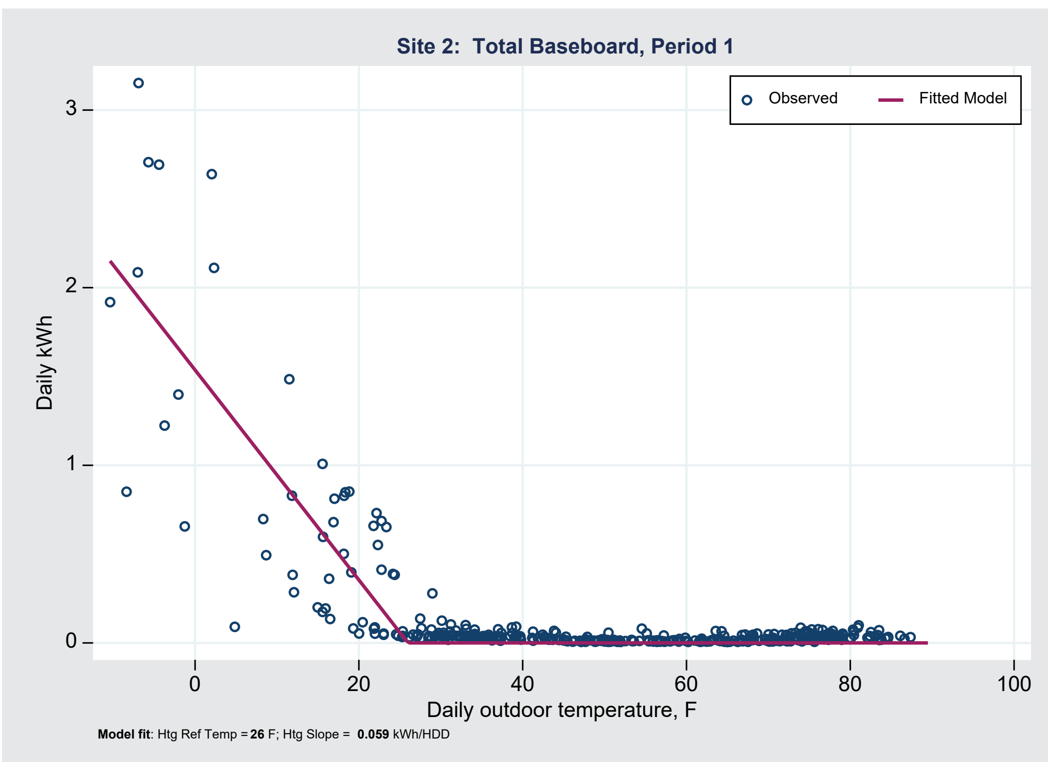

Site 1: Total Baseboard, Period 2
Observed
Fitted Model
Daily kWh
15
10
5
0
0
20
40
60
80
100
Daily outdoor temperature, F
Model fit: Htg Ref Temp = 20 F; Htg Slope = 0.326 kWh/HDD

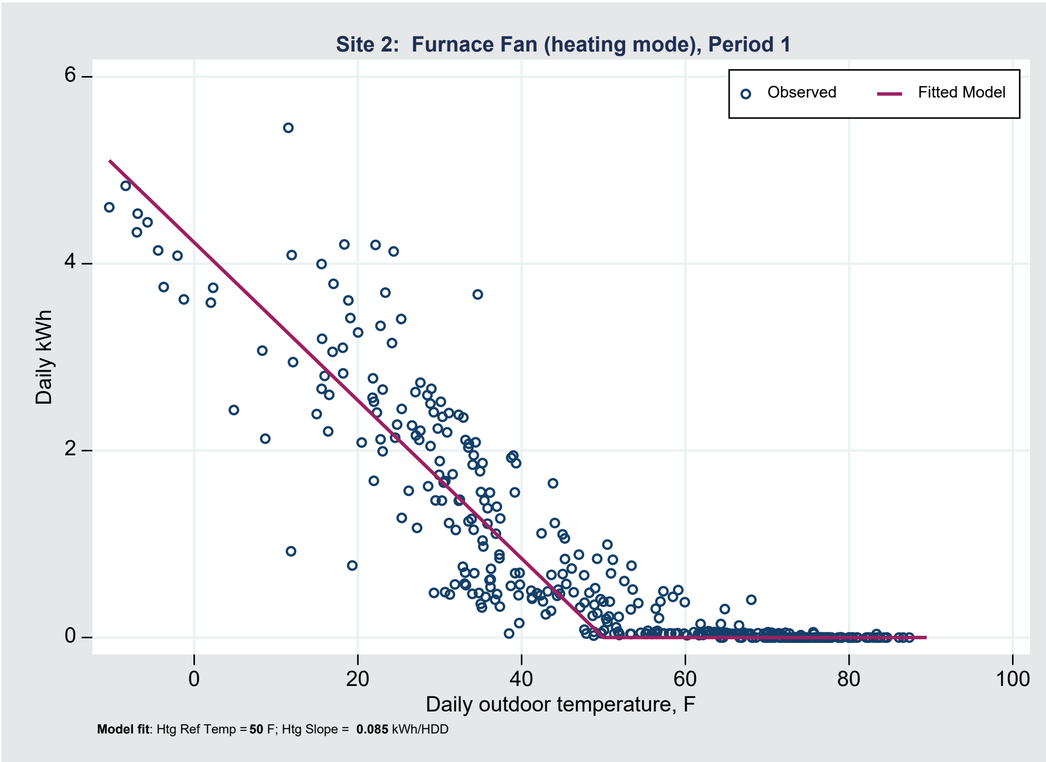

Site 2: Whole-House Electricity Use, Period 0 (monthly utility billing data)
Observed
Fitted Model
Mean daily kWh
60
50
40
30
20
10
0
20
40
60
80
100
Mean daily outdoor temperature, F
Model fit: Htg Ref Temp = 62 F; Htg Slope = 0.85 kWh/HDD; Clg Ref Temp = 80 F; Clg Slope = 63.51 kWh/CDD; Cons = 15.1 kWh/day (r2=0.961)

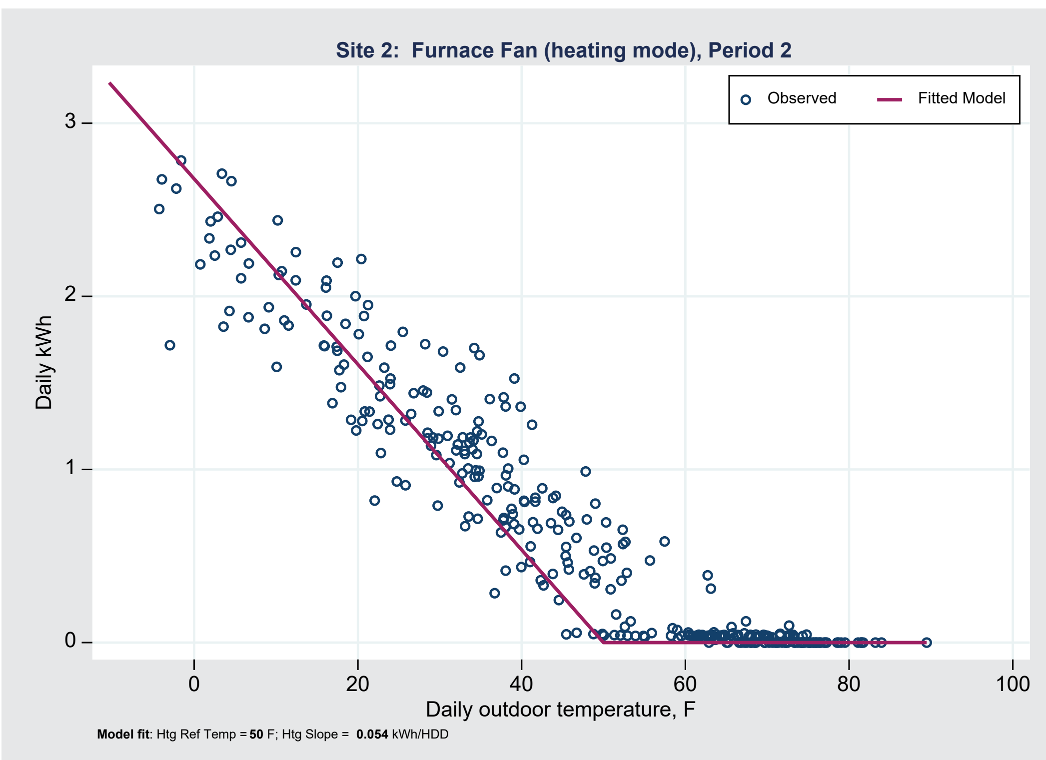

Site 2: Whole-House Natural-Gas Use, Period 0 (monthly utility billing data)
Observed
Fitted Model
Mean daily therms
0
2
4
6
0
20
40
60
80
100
Mean daily outdoor temperature, F
Model fit: Htg Ref Temp = 59 F; Htg Slope = 0.126 therms/HDD; Cons = 0.393 therms/day (r2=0.986)

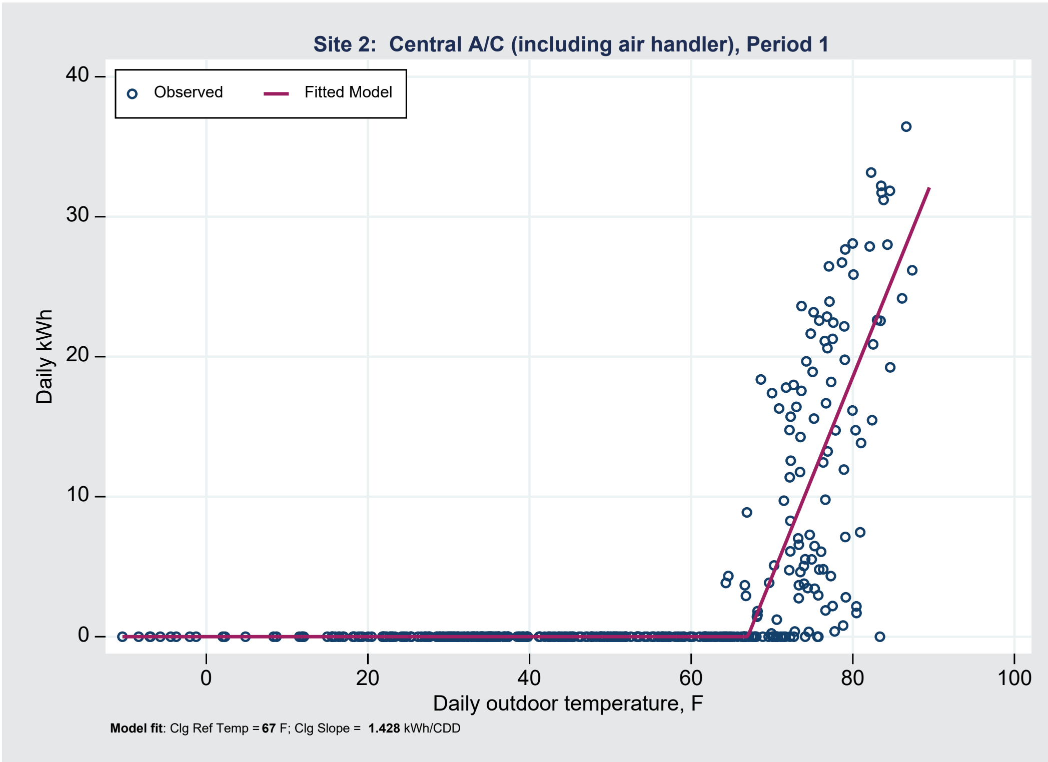

Site 2: Mini-Split, Period 1
Observed
Fitted Model
Daily kWh
0
10
20
30
40
50
0
20
40
60
80
100
Daily outdoor temperature, F
Model fit: Htg Ref Temp = 56 F; Htg Slope = 0.780 kWh/HDD; Clg Ref Temp = 66 F; Clg Slope = 0.706 kWh/CDD

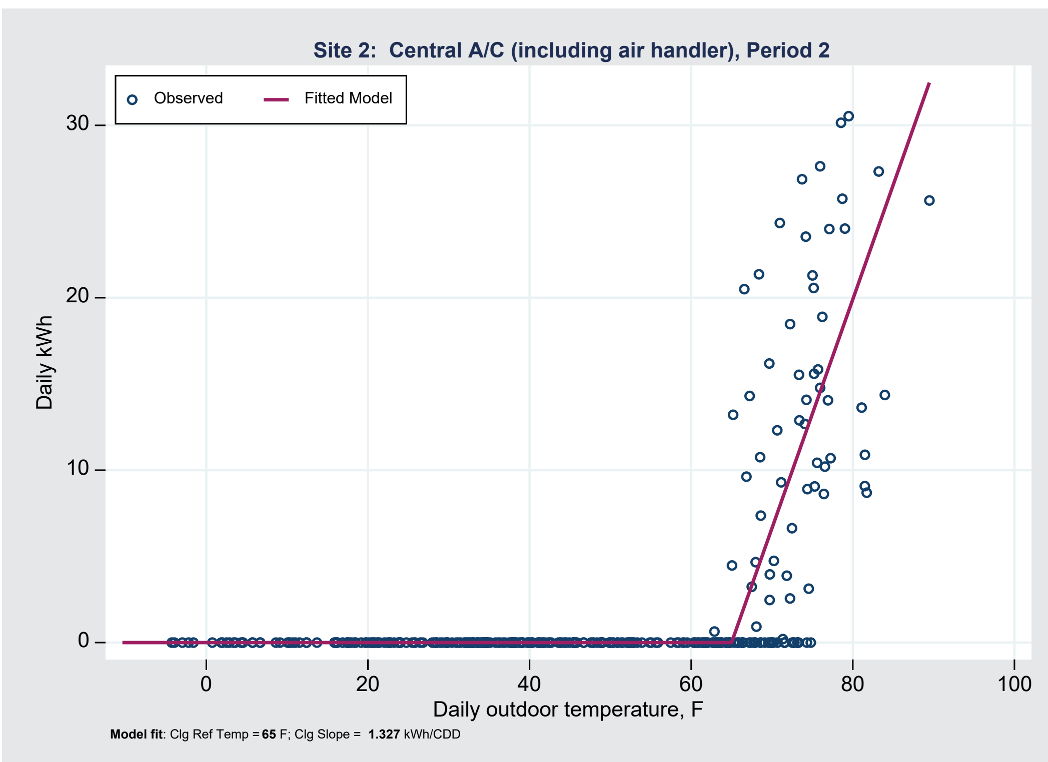

Site 2: Mini-Split, Period 2
Observed
Fitted Model
Daily kWh
60
40
20
0
0
20
40
60
80
100
Daily outdoor temperature, F
Model fit: Htg Ref Temp = **51** F; Htg Slope = **0.897** kWh/HDD; Clg Ref Temp = **71** F; Clg Slope = **1.064** kWh/CDD


Site 2: Total Baseboard, Period 1
Observed
Fitted Model
Daily kWh
3
2
1
0
0
20
40
60
80
100
Daily outdoor temperature, F
Model fit: Htg Ref Temp = **26** F; Htg Slope = **0.059** kWh/HDD

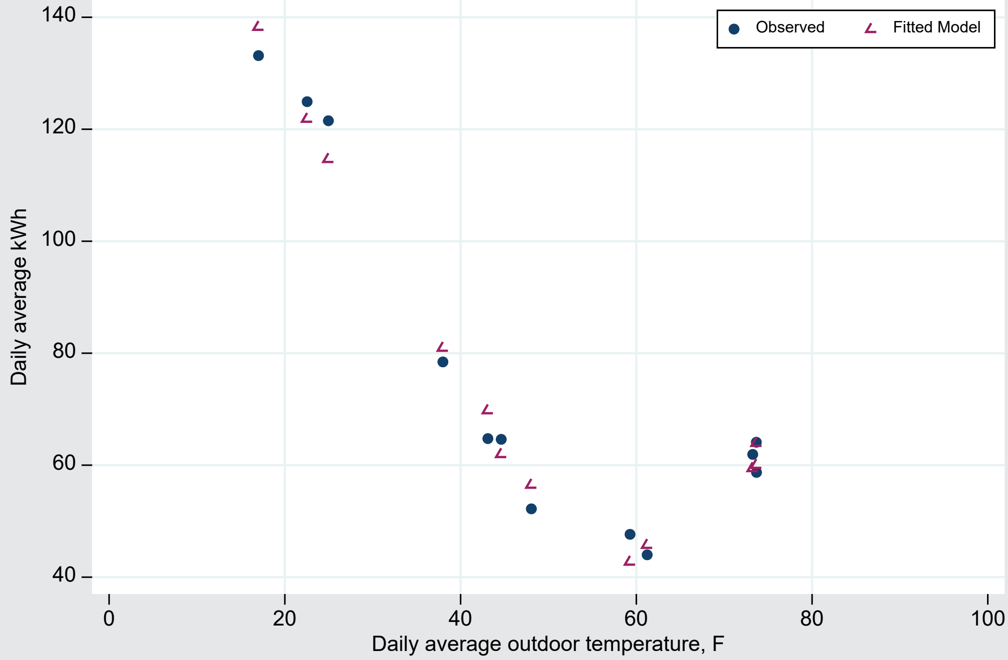

Site 2: Furnace Fan (heating mode), Period 1
Observed
Fitted Model
Daily kWh
Daily outdoor temperature, F
0
2
4
6
0
20
40
60
80
100
Model fit: Htg Ref Temp = **50** F; Htg Slope = **0.085** kWh/HDD


Site 2: Furnace Fan (heating mode), Period 2
Observed
Fitted Model
Daily kWh
Daily outdoor temperature, F
0
1
2
3
0
20
40
60
80
100
Model fit: Htg Ref Temp = **50** F; Htg Slope = **0.054** kWh/HDD


Site 2: Central A/C (including air handler), Period 1
Observed
Fitted Model
Daily kWh
Daily outdoor temperature, F
0
10
20
30
40
0
20
40
60
80
100
Model fit: Clg Ref Temp = 67 F; Clg Slope = 1.428 kWh/CDD

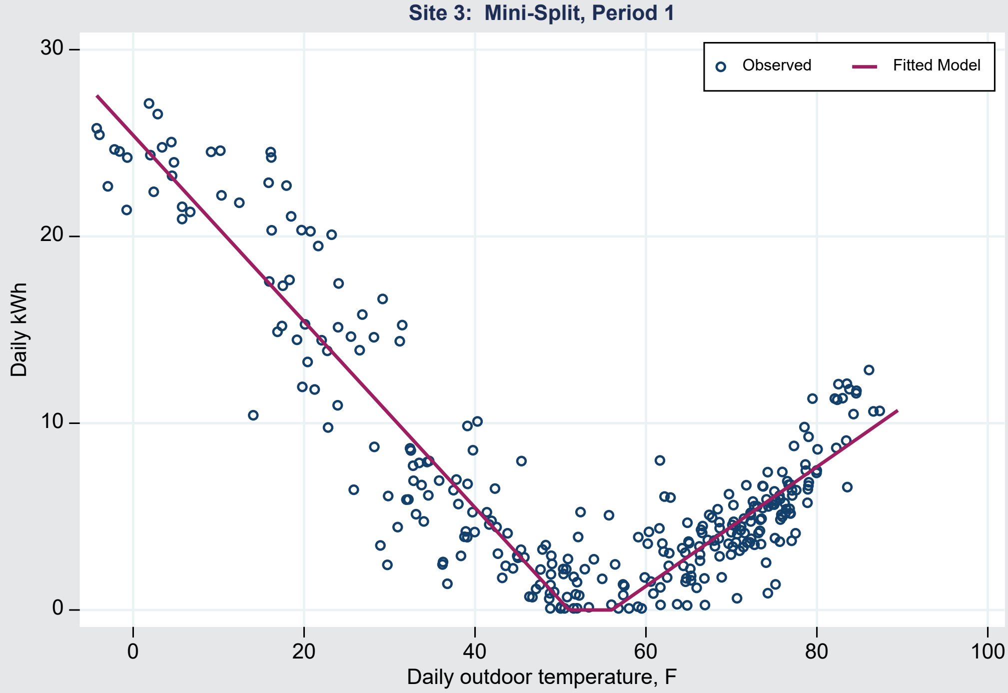

Site 2: Central A/C (including air handler), Period 2
Observed
Fitted Model
Daily kWh
Daily outdoor temperature, F
0
10
20
30
0
20
40
60
80
100
Model fit: Clg Ref Temp = 65 F; Clg Slope = 1.327 kWh/CDD

Site 3: Whole-House Electricity Use, Period 0 (monthly billing data)

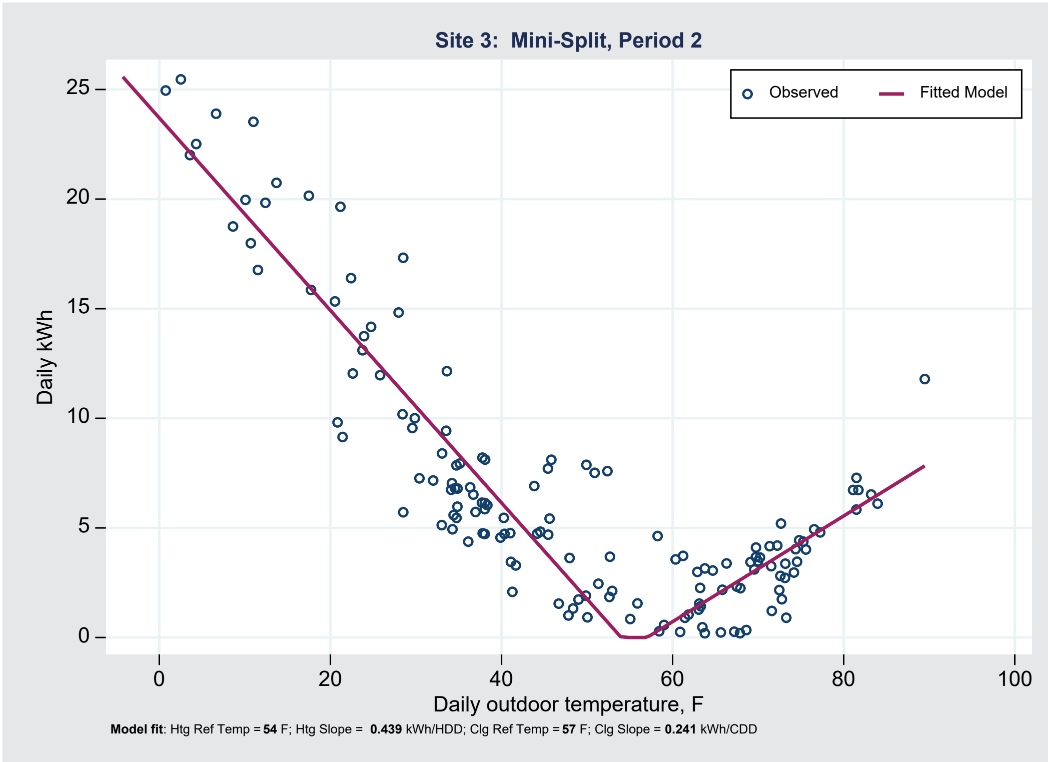


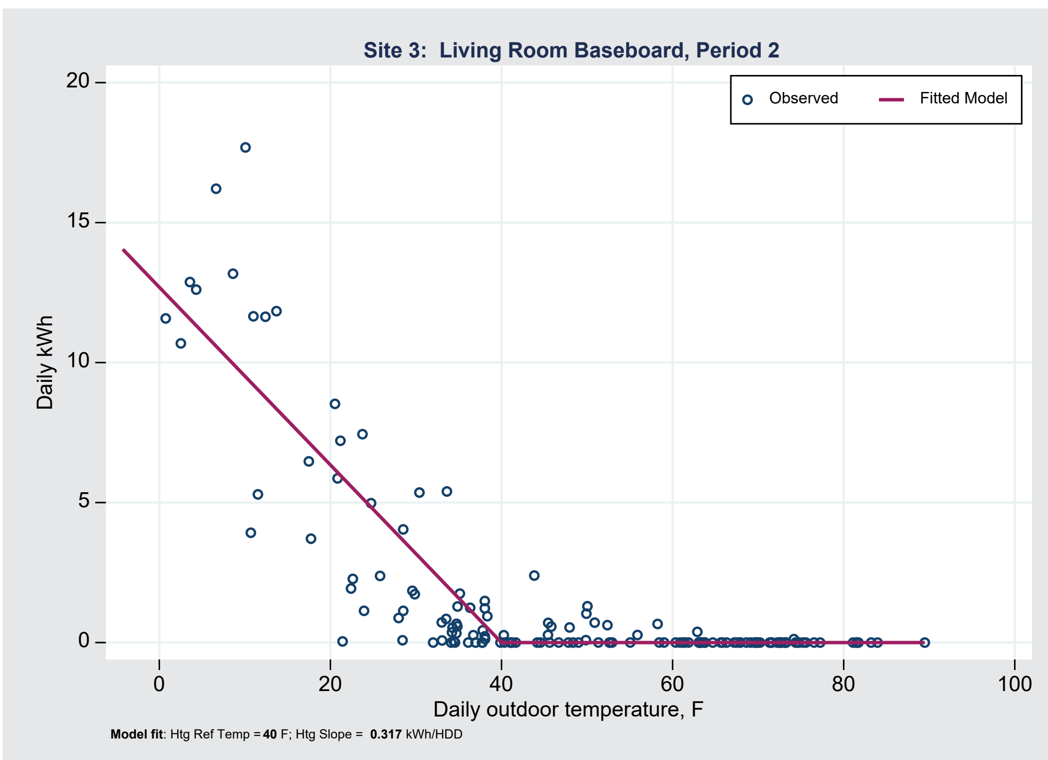
Model fit: Htg Ref Temp = **50** F; Htg Slope = **2.97** kWh/HDD; Clg Ref Temp = **72** F; Clg Slope = **6.71** kWh/CDD; Cons = **40.4** kWh/day (r2=0.976)

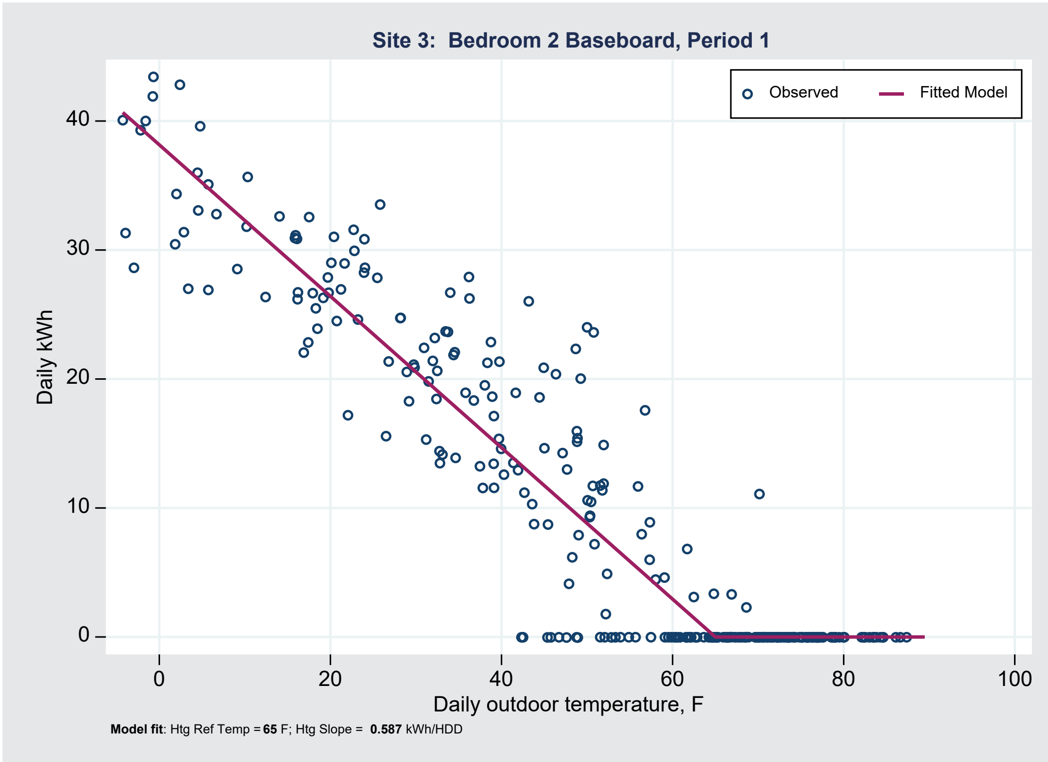
Site 3: Mini-Split, Period 1

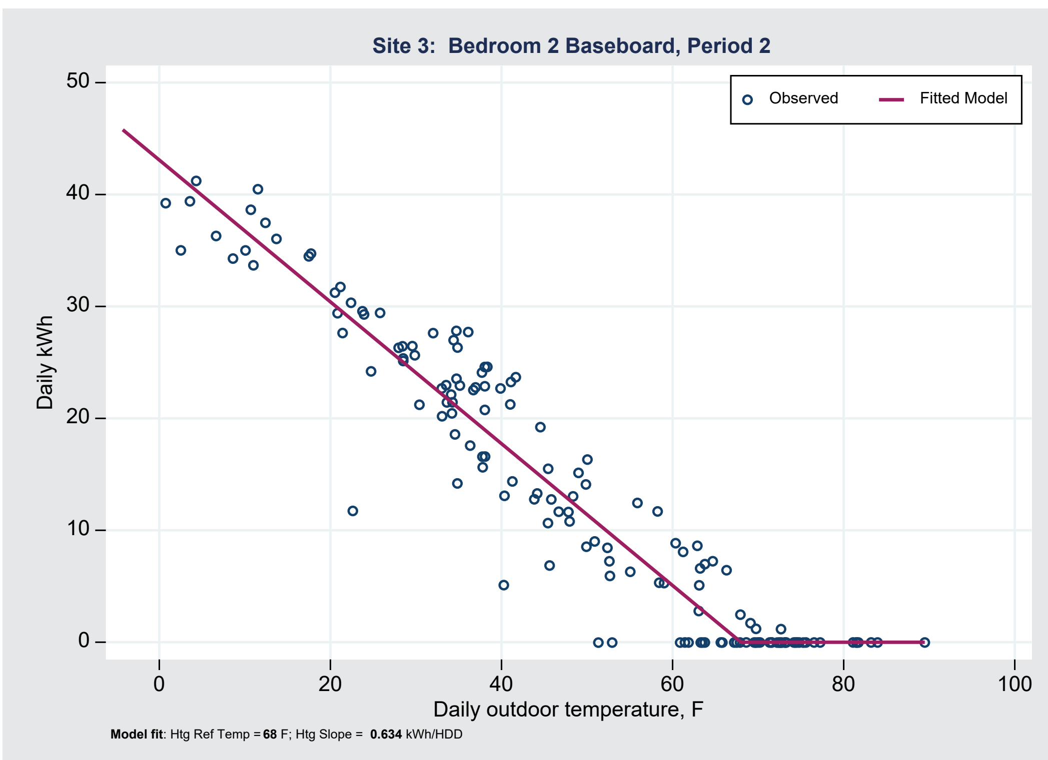


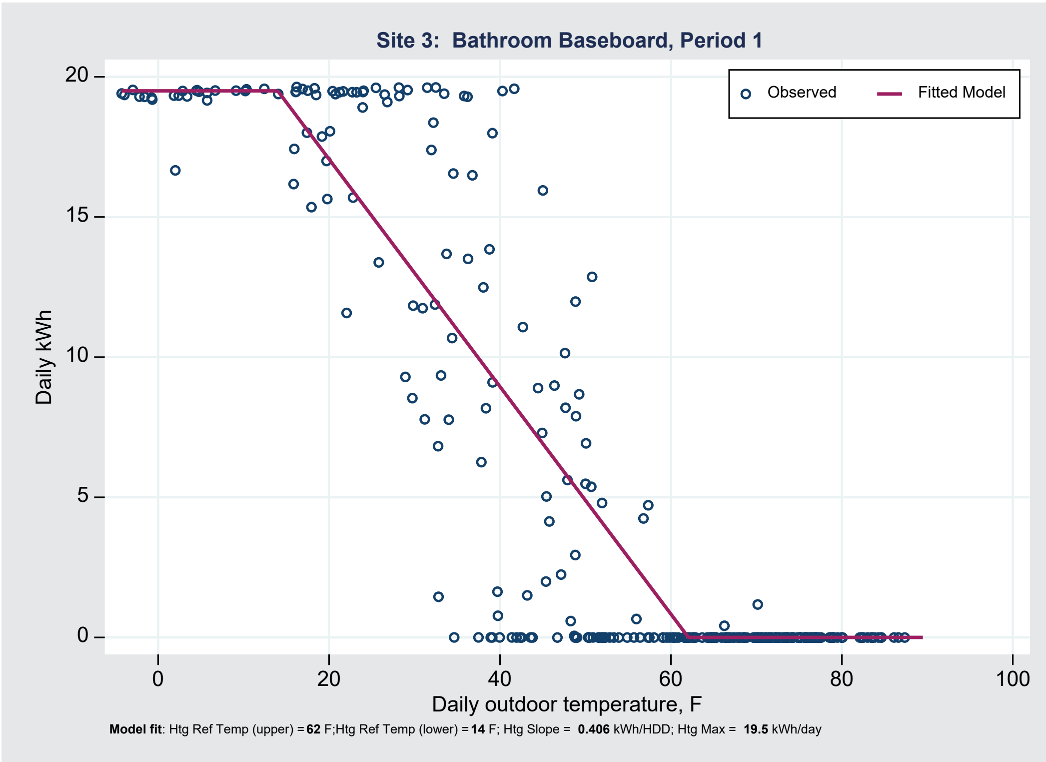
Model fit: Htg Ref Temp = **51** F; Htg Slope = **0.498** kWh/HDD; Clg Ref Temp = **56** F; Clg Slope = **0.319** kWh/CDD

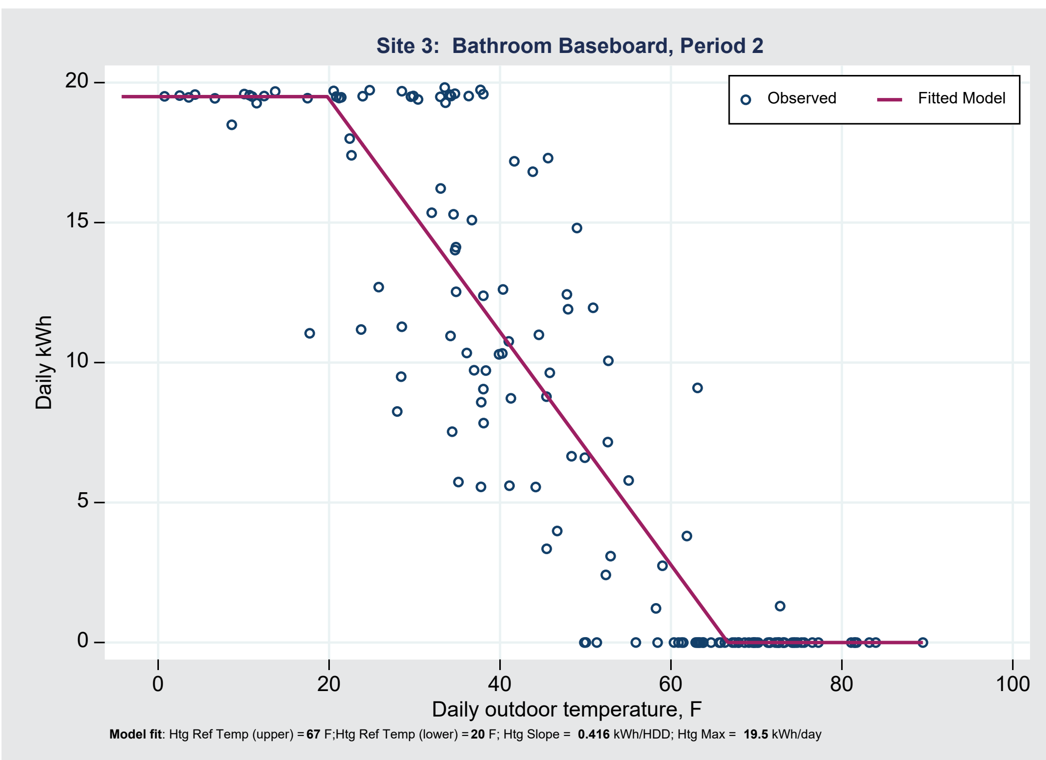

Site 3: Mini-Split, Period 2
Observed
Fitted Model
Daily kWh
Daily outdoor temperature, F
Model fit: Htg Ref Temp = 54 F; Htg Slope = 0.439 kWh/HDD; Clg Ref Temp = 57 F; Clg Slope = 0.241 kWh/CDD


Site 3: Living Room Baseboard, Period 2
Observed
Fitted Model
Daily kWh
Daily outdoor temperature, F
Model fit: Htg Ref Temp = 40 F; Htg Slope = 0.317 kWh/HDD


Site 3: Bedroom 2 Baseboard, Period 1
Observed
Fitted Model
Daily kWh
0
10
20
30
40
0
20
40
60
80
100
Daily outdoor temperature, F
Model fit: Htg Ref Temp = 65 F; Htg Slope = 0.587 kWh/HDD


Site 3: Bedroom 2 Baseboard, Period 2
Observed
Fitted Model
Daily kWh
0
10
20
30
40
50
0
20
40
60
80
100
Daily outdoor temperature, F
Model fit: Htg Ref Temp = 68 F; Htg Slope = 0.634 kWh/HDD


Site 3: Bathroom Baseboard, Period 1
Observed
Fitted Model
Daily kWh
20
15
10
5
0
0
20
40
60
80
100
Daily outdoor temperature, F
Model fit: Htg Ref Temp (upper) = **62** F;Htg Ref Temp (lower) = **14** F; Htg Slope = **0.406** kWh/HDD; Htg Max = **19.5** kWh/day


Site 3: Bathroom Baseboard, Period 2
Observed
Fitted Model
Daily kWh
20
15
10
5
0
0
20
40
60
80
100
Daily outdoor temperature, F
Model fit: Htg Ref Temp (upper) = **67** F;Htg Ref Temp (lower) = **20** F; Htg Slope = **0.416** kWh/HDD; Htg Max = **19.5** kWh/day