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National Weatherization Assistance Program Impact Evaluation – A Pilot Monitoring Study of Cooling System Consumption and Savings under the WAP Program

Scott Pigg

September 2014

OAK RIDGE NATIONAL LABORATORY
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Environmental Sciences Division

NATIONAL WEATHERIZATION ASSISTANCE PROGRAM IMPACT EVALUATION – A PILOT MONITORING STUDY OF COOLING SYSTEM CONSUMPTION AND SAVINGS UNDER THE WAP PROGRAM

Scott Pigg, Energy Center of Wisconsin

September 2014

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ACRONYMS AND ABBREVIATIONS

CFM50	Cubic Feet per Minute @ 50 pascals
CFR	Code of Federal Regulations
DOE	Department of Energy
kWh	Kilowatt-hour
ORNL	Oak Ridge National Laboratory
PY	Program Year
WAP	Weatherization Assistance Program

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EXECUTIVE SUMMARY

The study described here was a pilot effort to investigate the efficacy of methods to monitor cooling electricity consumption and savings from homes treated under the federal Weatherization Assistance Program. Twelve homes were recruited for the study, of which eleven had monitoring equipment installed to track cooling-system and whole-house electricity consumption before and after weatherization. Indoor and outdoor temperature and humidity were also tracked. The homes were located in Kansas, Florida and Arizona. Ten of the eleven homes had a central cooling system (either a package unit combining a refrigerant system and air handling equipment or a central split system in which the refrigerant system and air handler were separate); one home used room air conditioners prior to weatherization, and a heat pump following weatherization.

There were issues leading to incomplete data recovery for six of the 11 sites. Pre-weatherization, normalized seasonal (April through October) cooling consumption ranged from less than 1,000 Kilowatt-hour (kWh) to more than 10,000 kWh among the sites. For the six sites with adequate pre- and post-weatherization cooling-system monitoring data, weatherization was associated with reductions in seasonal cooling-system energy use of between 20 and 40 percent. Key weatherization measures for these sites included cooling system replacement (3 sites), ceiling insulation (4 sites), air sealing (5 sites) and duct repair (2 sites).

The study indicates that cooling-system electricity consumption can be reasonably weather normalized using outdoor temperature or cooling degree days; more complicated approaches that used indoor/outdoor temperature difference or included outdoor humidity resulted in very similar estimates in most cases. However, two sites showed exhibited seasonal differences in the relationship between daily cooling electricity and outdoor temperature, which could stem from differences in sun angles or other factors. This suggests that split-season studies of weatherization savings may be less reliable than approaches in which the pre- and post-weatherization periods each encompass a full cooling season.

The data gathered for the project suggest that central cooling system energy use can be adequately estimated from interval data on compressor current draw, allowing for reduced monitoring equipment costs compared to tracking actual kWh consumption. Estimates of seasonal cooling energy use derived from daily whole-house electricity consumption and monthly utility histories generally agreed reasonably with values from direct monitoring of the cooling system, but confounding effects from other end-uses sometimes created differences.

1. INTRODUCTION

1.1 NATIONAL WEATHERIZATION ASSISTANCE PROGRAM EVALUATION OVERVIEW

The U.S. Department of Energy's (DOE) Weatherization Assistance Program (WAP) was created by Congress in 1976 under Title IV of the Energy Conservation and Production Act. The purpose and scope of the Program as currently stated in the Code of Federal Regulations (CFR) 10 CFR 440.1 is "to increase the energy efficiency of dwellings owned or occupied by low-income persons, reduce their total residential energy expenditures, and improve their health and safety, especially low-income persons who are particularly vulnerable such as the elderly, persons with disabilities, families with children, high residential energy users, and households with high energy burden." (*Code of Federal Regulations, 2011*)

At the request of DOE, Oak Ridge National Laboratory (ORNL) developed a comprehensive plan for a national evaluation of WAP that was published in 2007. DOE furnished funding to ORNL in 2009 for a national evaluation for Program Years (PY) 2007 and 2008, with a particular emphasis on PY 2008. ORNL subcontracted evaluation research to APPRISE Incorporated and its partners (the Energy Center of Wisconsin, Michael Blasnik and Associates, and Dalhoff Associates LLC). The Scope of Work (SOW) for the evaluation includes the following components.

<u>Impact Assessment</u> – Characterization of the weatherization network and the households that are income-eligible for WAP, measurement and monetization of the energy and nonenergy impacts of the program, and assessment of the factors associated with higher levels of energy savings, cost savings, and cost-effectiveness.

<u>Process Assessment</u> – Direct observation of how the weatherization network delivers services and assessment of how service delivery compares to national standards and documentation of how weatherization staff and clients perceive service delivery.

<u>Special Technical Studies</u> – Examination of the performance of the program with respect to technical issues such as air sealing, duct sealing, furnace efficiency, and refrigerators.

<u>Synthesis Study</u> – Synthesis of the findings from this evaluation into a comprehensive assessment of the success of the program in meeting its goals and identification of key areas for program enhancement.

The field study described here falls under the Special Technical Studies component of the larger evaluation effort.

1.2 OBJECTIVES

Electricity consumption for air conditioning is understood to be a significant expense in hot climates, as well as a growing component of energy consumption in more moderate climates as the saturation of the technology increases in these regions. Yet in the context of the WAP, consumption—and weatherization-induced savings—for this end use has been less well studied than has space-heating.

The pilot project described here was intended as a small-scale effort to explore methods to measure air conditioning electricity consumption and the savings in air conditioning costs that result from weatherization. Lessons learned from this study are intended to be applied to a larger-scale field study of air conditioning electricity use and savings.

2. METHODOLOGY

The study targeted 12 homes; four each in three geographic areas meant to represent hot-humid (Florida), hot-dry (Arizona) and moderate (Kansas) climates. At each site, monitoring equipment (described in more detail below) was installed in late spring and early summer of 2012 to track space-cooling and whole-house electricity consumption (equipment could not be installed at one site, as described below). In mid-summer, the homes received weatherization services while the monitoring continued. Monitoring equipment was removed in late fall 2012, at which point information about measures installed, weatherization costs and utility billing histories were obtained.

Monitoring at each site included tracking whole-house electricity consumption, cooling-system electricity consumption, as well as outdoor and indoor temperature and relative humidity (

Table 1). The panel-level metering to track whole-house and cooling-system electricity consumption consisted of a single 4-channel data logger, two pulse-output devices that converted electricity consumption into pulses to be counted by the data logger, five current sensors, and voltage connections to the main electrical panel (Fig. 1). One of the pulse-output devices and two of the current sensors were required for monitoring whole-house consumption, which was logged on one channel of the data logger; the remaining items allowed for monitoring up to three circuits on the main electric panel. First priority here was given to monitoring the central cooling system, either a central split system requiring two channels (one channel for the compressor and one for the air handler) or a package cooling system requiring one data logger channel. Any remaining available channels were used for monitoring an electric water heater, an electric range or other loads—though data for these loads are not presented in this report.

In some cases, the panel-level metering equipment fit inside the home's electric panel (Fig. 2), but in many cases, there was insufficient room for this, and the equipment was mounted in a separate electrical enclosure near the main panel (Fig. 3). One Arizona site was found to have an electrical panel that was too tightly packed to allow for any current sensors (Fig. 4); no equipment was therefore installed at this site and it was dropped from the study.

Outdoor temperature and relative humidity were monitored with a weather-proof data logger mounted in a radiation shield, and placed in an outdoor location near the home with minimal sun exposure. Nearby hourly airport data on temperature and humidity were also downloaded for the analysis phase of the project. The airport data were found to be highly correlated with the on-site logger data. They were generally favored for the analysis presented here because the long histories available allowed the modeled relationship between cooling-system consumption and outdoor consumption to be normalized to 20-year average conditions.

Indoor temperature and relative humidity was monitored with separate temperature/RH loggers: most analysis was conducted using a logger that was hung from the main thermostat, but additional loggers were deployed in other locations for some sites.

The approach to monitoring the single site with room air conditioners was to attach a plug-in electricity meter to each cooling unit, and also record air temperature at the supply outlet for the unit.

Table 1. Monitoring parameters.

Parameter	Device	Instances per site	Data type and interval
Whole-house electricity consumption	Continental Controls, WattNode Pulse WNB-3Y-208-P, connected to Onset UX-120-017 pulse logger	1	5-minute integrated kWh
Circuit-level electricity consumption	Continental Controls, WattNode Pulse WNB-3Y-208-P Opt P3, connected to Onset UX-120-017 pulse logger	Up to 3	5-minute integrated kWh
AC compressor current draw	Onset CTV-A, split-core AC current sensor, connected to Onset U12-006 external data logger	1	5-minute snapshots of Amps
Room AC electricity consumption	WattsUp Pro.NET plug-in power meter	3 (one site only)	10-minute integrated kWh; 10-minute snapshots of Amps
Outdoor temperature and RH	Onset U23-002 external temp/RH logger, with radiation shield	1	10-minute snapshots of outdoor temperature and RH
Indoor temperature and RH	Onset U10-003 temp/RH logger	Varies	10-minute snapshots of indoor temperature and RH
Room AC supply-air temperature	Onset U12-014 thermocouple logger, with Type K thermocouple	3 (one site only)	5-minute snapshots of temperature

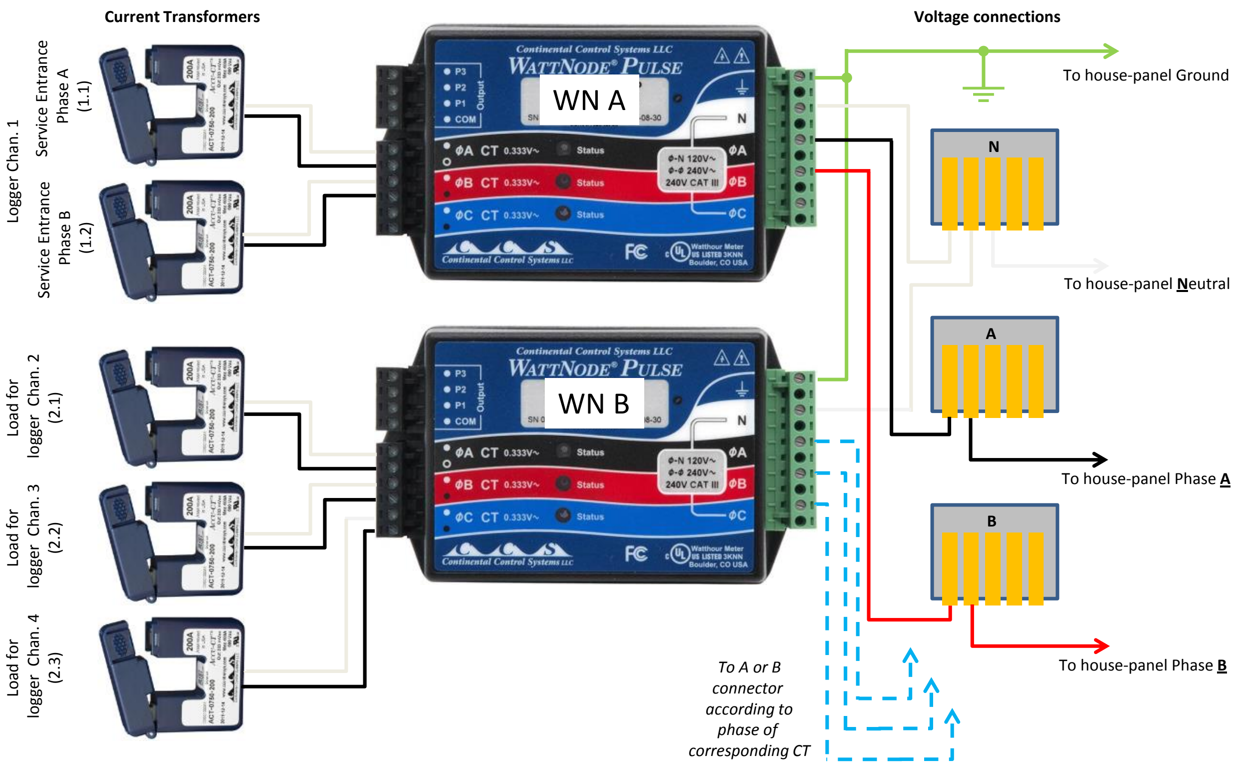

Fig. 1. Input wiring for panel-level electricity monitoring.

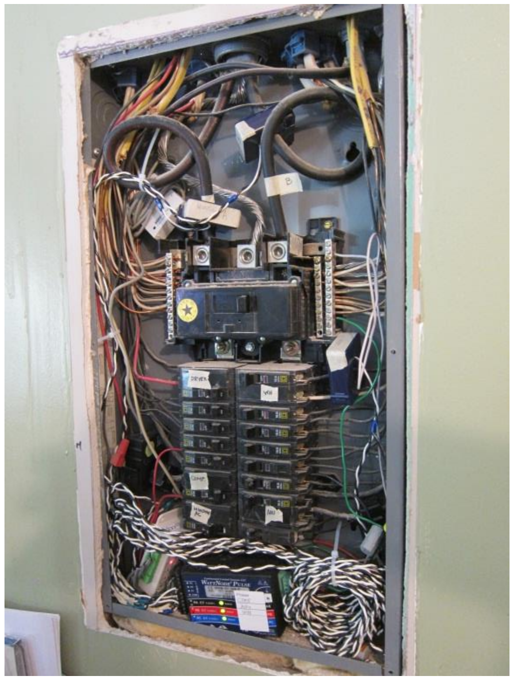

Fig. 2. Panel-level metering equipment located inside the home's main electric panel (Site 6).

Fig. 3. Panel-level metering equipment being installed exterior to the home's electrical panel (Site 7).

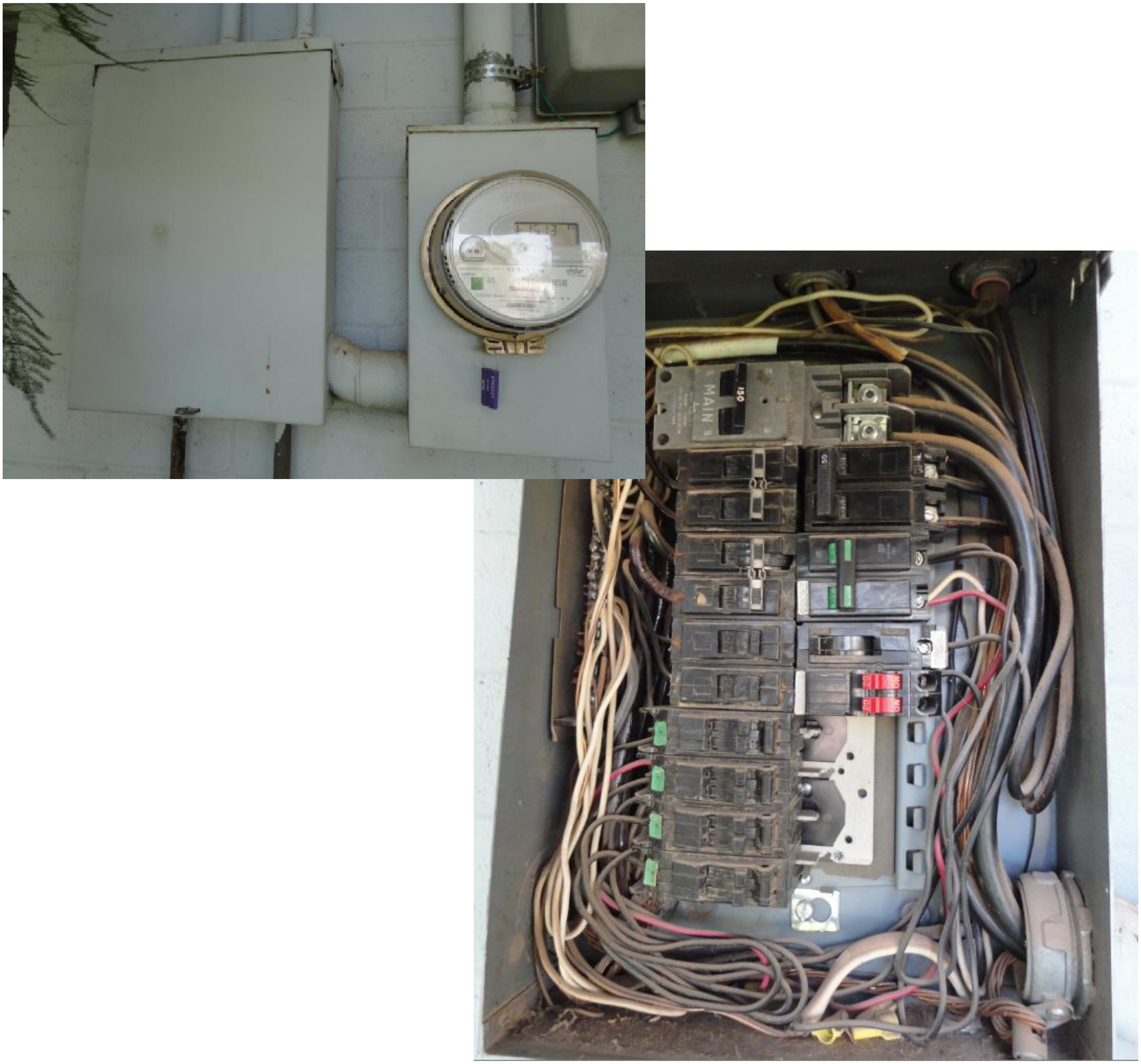

Fig. 4. Tight electrical panel for dropped site (Arizona).

Appendix A provides more detail about each of the 11 sites in the study, as well as graphical summaries of key monitoring parameters.   There were some issues with data recovery and how the cooling systems were used at more than half of the sites. These are also described in more detail in Appendix A, and summarized here as follows:

Site 3 – A loose wiring block led to the loss of electricity consumption data for the cooling-system over the entire monitoring period.

Site 4 — No panel-level monitoring data was recovered for this site (for unknown reasons); also, there were data quality issues with two of the three loggers tracking room air conditioner electricity use.

Site 7 — Most whole-house monitoring data was lost after an electrician apparently inadvertently disconnected a wiring harness about two weeks after installation. The central AC system at this site was not used much prior to weatherization.

Site 8 — This site had a non-functional package unit prior to weatherization, which was replaced by a ductless mini-split. The attempt to install panel-level monitoring for the mini-split prior to its installation was not successful.

Site 9 — The air handler for this site with a split central system was not monitored.

Site 10 — The panel level monitoring at this site was disconnected by someone at the time of weatherization.

3. RESULTS

3.1 COOLING-SYSTEM MONITORING RESULTS

The panel-level cooling-system monitoring data provides the most direct measurement of electricity use. Usable data for this parameter was obtained for eight of the 11 sites, though one site (Site 10) had only pre-weatherization data, and another site (Site 7) had minimal use of the cooling system prior to weatherization. For analysis, the data were collapsed down to daily sums and averages, and, for the sites with split systems, compressor and air handler daily kWh were combined. Days with no (or partial) cooling-system use were excluded from the analysis described below: the implications of occupants choosing not to use the system on some days are accounted for later in this report when monitoring results are compared to utility billing data.

With two notable exceptions that will be covered shortly, daily cooling-system electricity use was found to be reasonably linear with daily outdoor temperature (Fig. 5). For exploratory purposes, however, four models of daily electricity consumption were considered. These examined the impact of including or excluding outdoor humidity as an explanatory factor, as well as using the outdoor-indoor temperature difference instead of just outdoor temperature to model daily energy consumption:

Model	Temperature term	Humidity term
1	Outdoor temperature	Excluded
2	Outdoor-indoor temperature difference	Excluded
3	Outdoor temperature	Included
4	Outdoor-indoor temperature difference	Included

As noted above, days with no (or unusually low) cooling-system use were excluded from the model fits (these are shown as grey data points in Fig. 5). These clearly include some days when the household chose not to operate the system, and are shown separately as grey data points in Fig. 5. The fitted models were then translated into estimates of annual cooling-system kWh by applying them to long-term average weather conditions for the associated weather station. Details for this are provided in Appendix B.

The results of this exercise () show annual cooling energy estimates that range from about 1,000 kWh (Site 2) to more than 10,000 kWh (Site 9). Weatherization is associated with reductions of 20 to 40 percent for the six sites with adequate pre- and post-weatherization data (Fig. 7). Key weatherization measures for these sites included cooling system replacement (3 sites), ceiling insulation (4 sites), air sealing (5 sites) and duct repair (2 sites), as described in more detail in Appendix A.

For the most part, model choice does not have a strong impact on either the point estimate or the confidence interval for annual kWh and savings estimates. This suggests that simply regressing cooling-system electricity consumption against outdoor temperature provides a reasonable estimate of average annual consumption and savings in most cases.

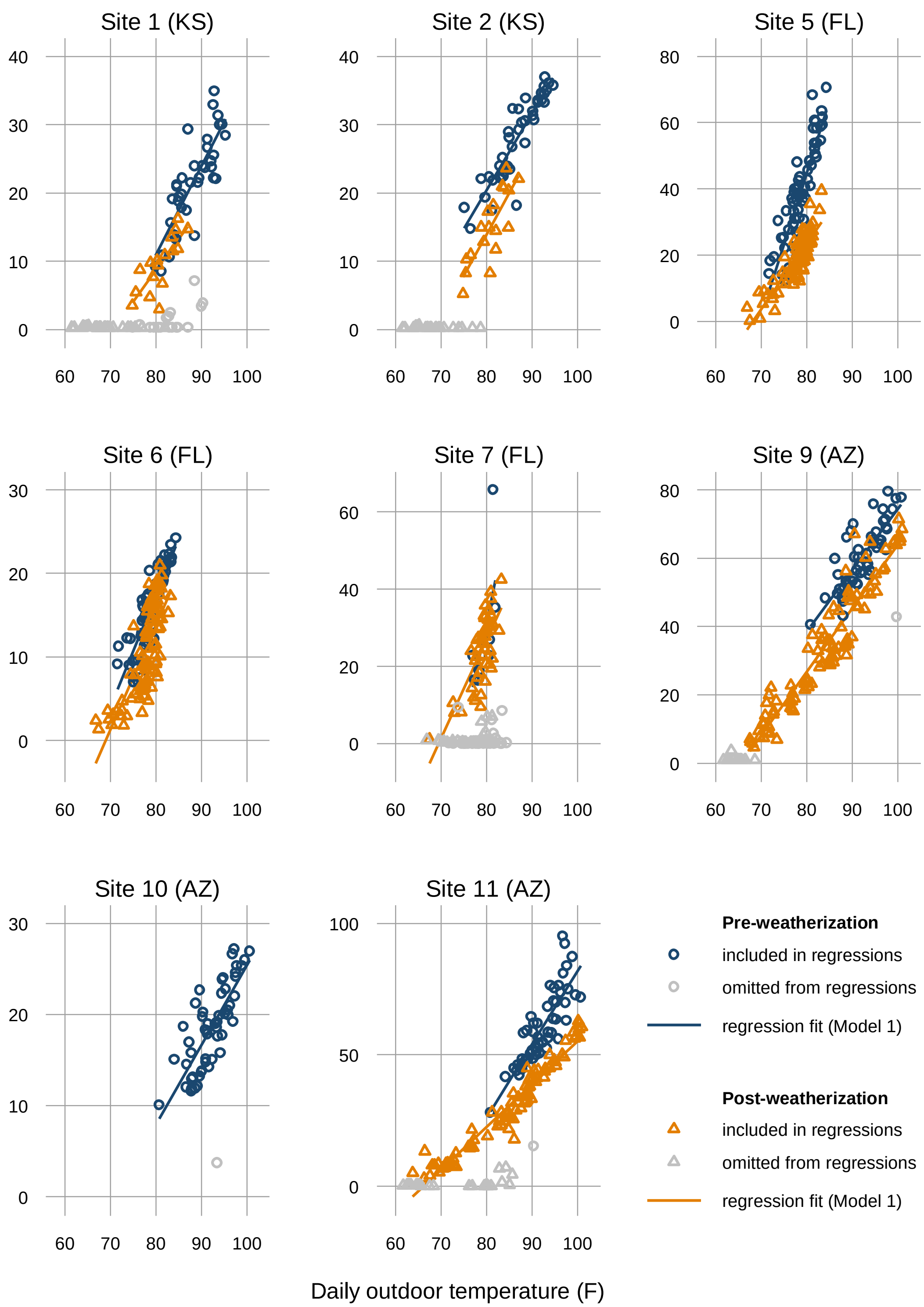

Fig. 5. Pre- and post-weatherization daily cooling-system kWh versus daily outdoor temperature.

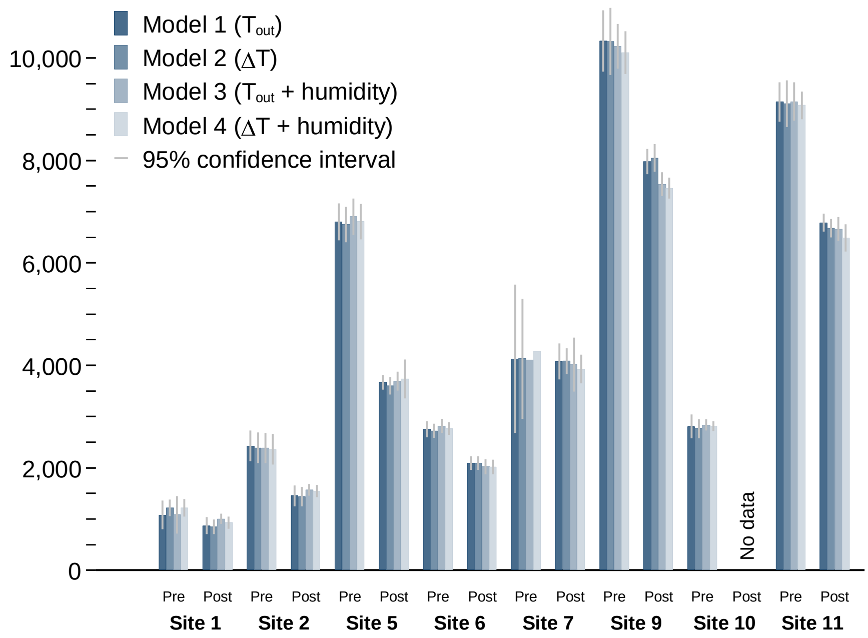

Fig. 6. Weather-normalized estimates of annual cooling-system electricity consumption from daily cooling-system monitoring data.

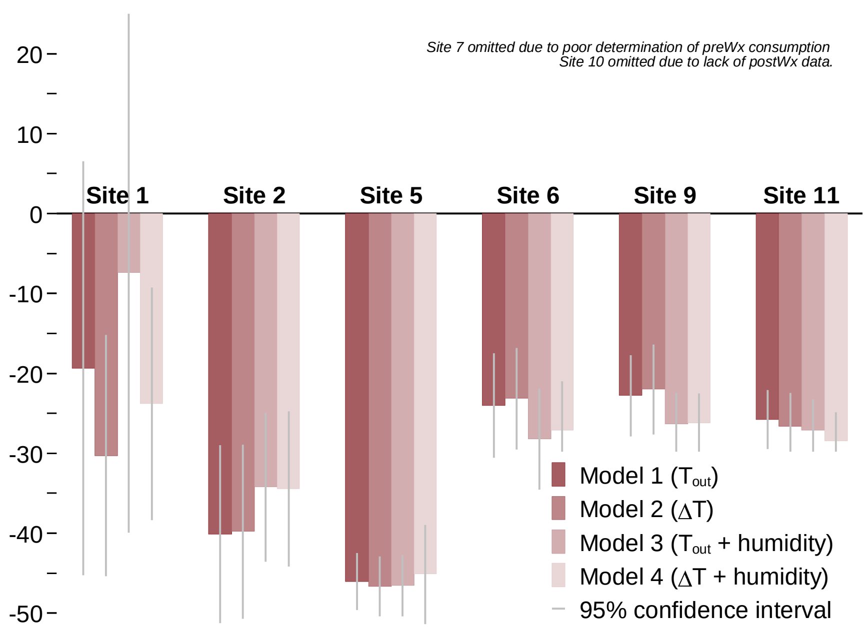

Fig. 7. Estimated percent change in normalized cooling-system electricity consumption.

As noted previously, two sites showed some non-linearity between daily cooling-system energy and outdoor temperature. Both of these were Florida sites, and both showed a tendency for a lower trend line between daily electricity consumption and outdoor temperature during October in the post-weatherization period (Fig. 8). Heat from solar gain can be an important factor in cooling-system energy use, and it is possible that the shorter days and different sun angle in October had a reduced impact on system load during this time. Because the monitoring was installed in mid-May at these sites, comparable pre-weatherization data were not available. This suggests that a seasonal bias could result if the pre-weatherization and post-weatherization periods cover different parts of the cooling season. From this standpoint, full pre- and post-weatherization seasons would be preferable to a split-season study like the one implemented here.

Note that re-analyzing the post-weatherization data for these two sites without the October data has a negligible impact for Site 5, but increases the estimate of annual cooling energy consumption by about 7 percent for Site 6, with an associated 5 percentage point decrease in estimated savings.

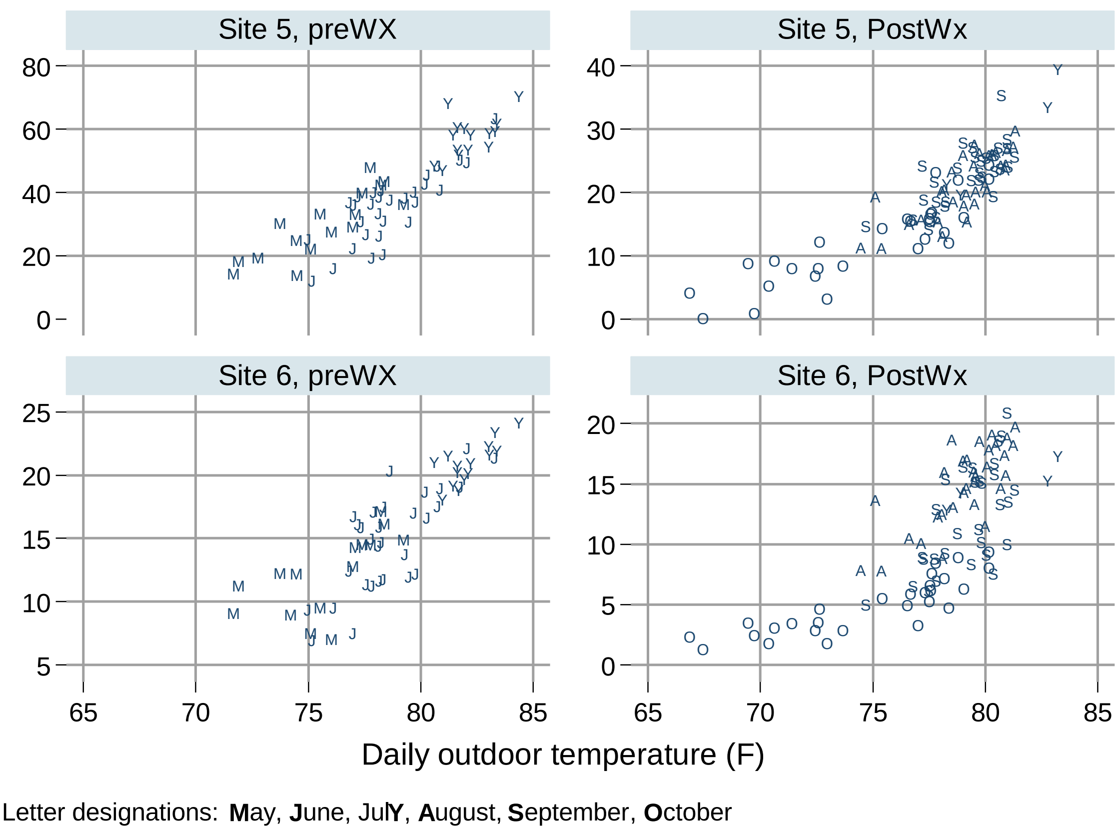

Fig. 8. Daily cooling-system electricity consumption versus outdoor temperature for two Florida sites.

Amperage Draw as a Proxy for Cooling System Electricity Consumption

In addition to direct monitoring of actual compressor electricity consumption, a separate data logger was installed at some sites to take snapshots of compressor current draw (amperage) every five minutes. The purpose of this was to test the efficacy of amperage data as a proxy measurement for actual electricity consumption, since it is somewhat easier and less expensive to monitor the former than the latter.[1]

In general, despite the fact that amperage draw was only measured once every five minutes (versus the continuous logging of actual electricity consumption), daily mean amps were found to be nearly perfectly correlated with daily compressor kWh (Fig. 9).

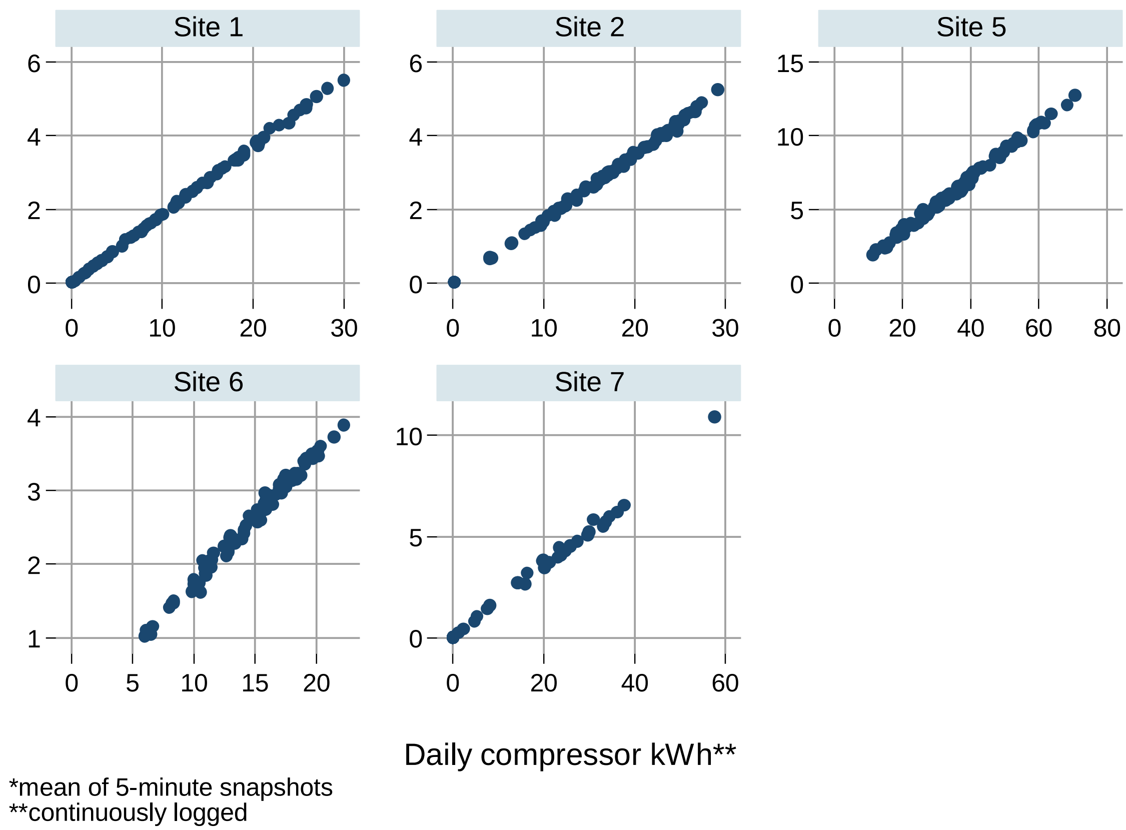

Fig. 9. Daily mean compressor amperage draw versus daily compressor electricity consumption.

[1] The equipment for monitoring actual cooling-system kWh for this project (one pulse data logger, one pulse-output kWh device and two current sensors) cost about $450 per site; the cost for tracking compressor amps (one data logger and one current sensor) was about $200. There would also be some labor savings in installing the less-complicated current-logging equipment.

While this is encouraging, in order to estimate daily cooling-system kWh from amperage monitoring data alone, the data must be combined with additional power-draw related spot measurements. Power draw and amperage for a cooling-system compressor (or any other AC electrical device) are related by the equation:

$$\text{Power} = \text{Amps} \times \text{Volts} \times \text{Power factor}$$

Power factor is a value between zero and unity that accounts for certain aspects of energy consumption by alternating-current devices. Because amperage draw is monitored, and voltage is generally kept within tight limits by electric utilities, power factor is the key remaining factor. Fortunately, for a device like an air conditioning compressor, the operating power factor does not vary significantly over time, and a spot measurement can be taken with a power analyzer at the time the monitoring is installed. Moreover, measured power factors ranged from 0.91 to 0.98 for the nine sites with working central-system compressors, suggesting that an assumed value of about 0.95 may be adequate for most purposes.

Another complication that arises for split systems is that air handler power consumption occurs on a separate circuit, and thus is not accounted for in compressor amperage draw monitoring. However, this can be addressed by taking a one-time measurement of air handler power, and then combining this with daily run-time information from the compressor amperage measurements.

Implementing this approach for the five sites with amp-draw data reveals a tight correlation between the amperage-only based estimates of daily cooling system kWh and actual monitored consumption (Fig. 10), suggesting that this approach is a viable one.

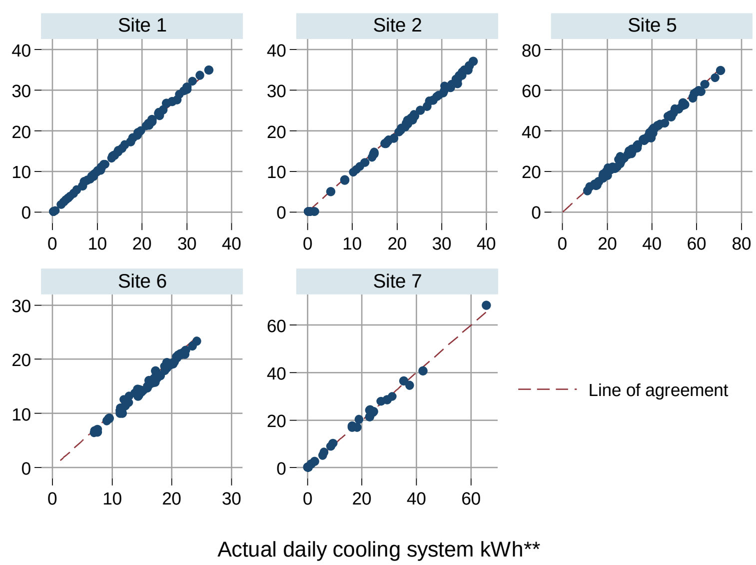

Fig. 10. Estimated daily cooling-system electricity consumption from amperage monitoring versus actual consumption.

3.2 WHOLE-HOUSE MONITORING RESULTS

Fig. 11 summarizes the daily whole-house monitoring data for sites with adequate data recovery for this parameter. Cooling-system operation is clearly evident for most sites as an upward trend in electricity consumption with increasing outdoor temperature, though variability in electricity consumption for other end-uses creates scatter in the data.[2]

Because whole-house metering data includes end uses other than the cooling system, isolating and normalizing cooling-system consumption from these data involves:

- identifying a base level of non-cooling electricity consumption (base use);
- finding the outdoor temperature at which cooling-system use begins (balance-point temperature); and,
- establishing the magnitude of the increase in daily cooling-system consumption per degree rise in outdoor temperature (cooling slope).

With adequate data over a wide span of outdoor temperatures, this can be readily accomplished using statistical procedures to find a best-fit model for these three parameters (as described in more detail in Appendix B). There are problems with the split-season data gathered for this study, though. In particular, the pre-weatherization data begin well after the start of the cooling season, so data are lacking for days without cooling system operation, making it impossible to empirically determine the balance-point temperature and level of base use for the pre-weatherization period. The post-weatherization data do not suffer this problem, because the post-weatherization monitoring extended well into cool fall weather for most of the sites.

Because of this, the analysis here focuses on estimates of post-weatherization cooling consumption from the whole-house data and how these compare with the cooling-system sub-metering data. As Fig. 12 shows, for four of the six sites with adequate sub-metering and whole-house data, there is a good correspondence between the two sets of estimates for seasonal cooling electricity consumption. The exceptions are Site 5 and Site 9. In both cases, it appears that confounding effects from other electric end-uses causes a misestimate in the cooling balance-point temperature for the site, resulting in a biased estimate of seasonal cooling consumption.

[2] Site 8 shows evidence of an increase in cooling electricity consumption. This site had a non-functional central package unit prior to weatherization, and although no other cooling equipment was present at the time of monitoring installation, several room air conditioners were found to be present later in the season, and were apparently used in the pre-weatherization period. In addition, weatherization services for the home included installation of a new mini-split system.

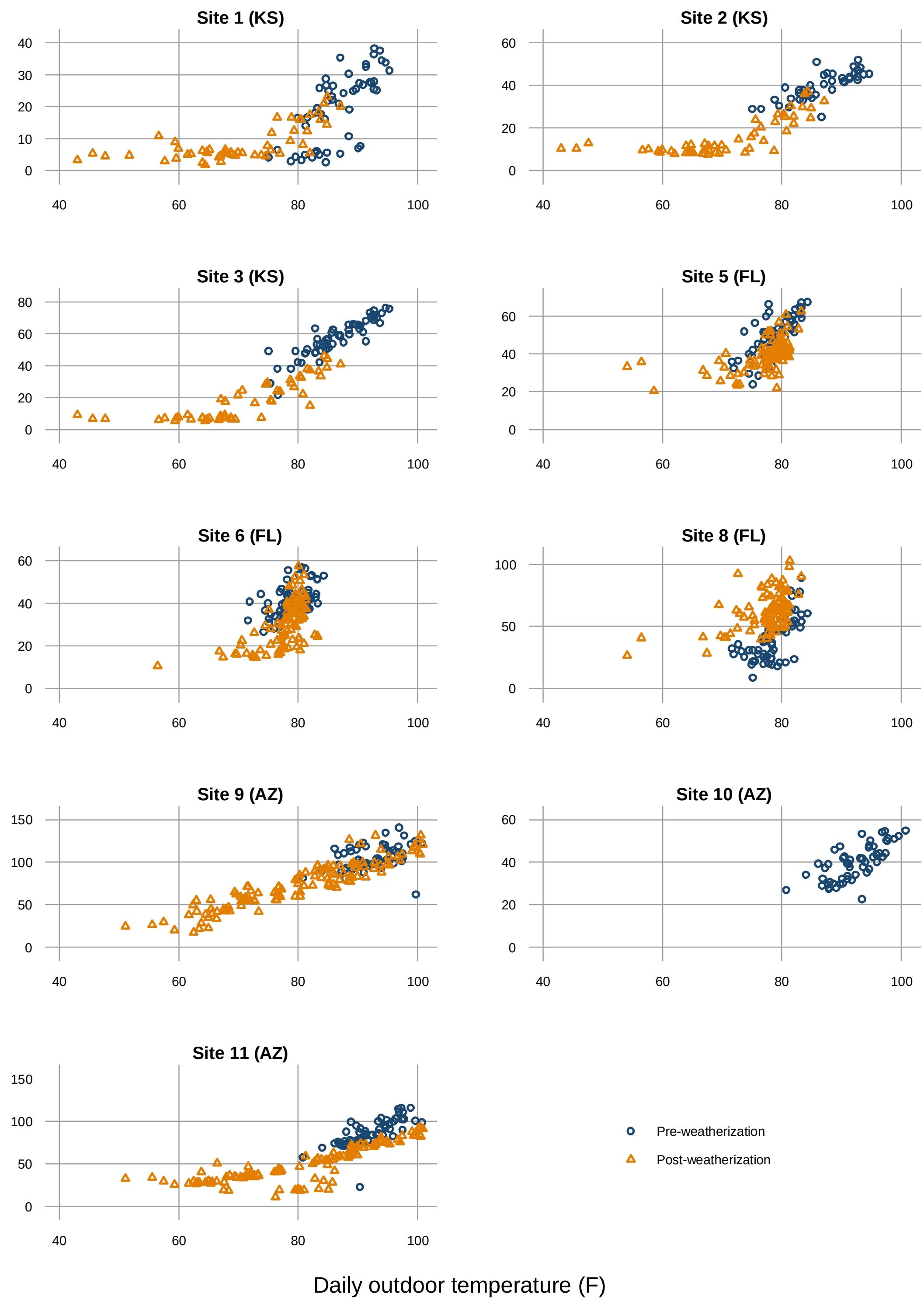

Fig. 11. Daily whole-house electricity consumption versus outdoor temperature.

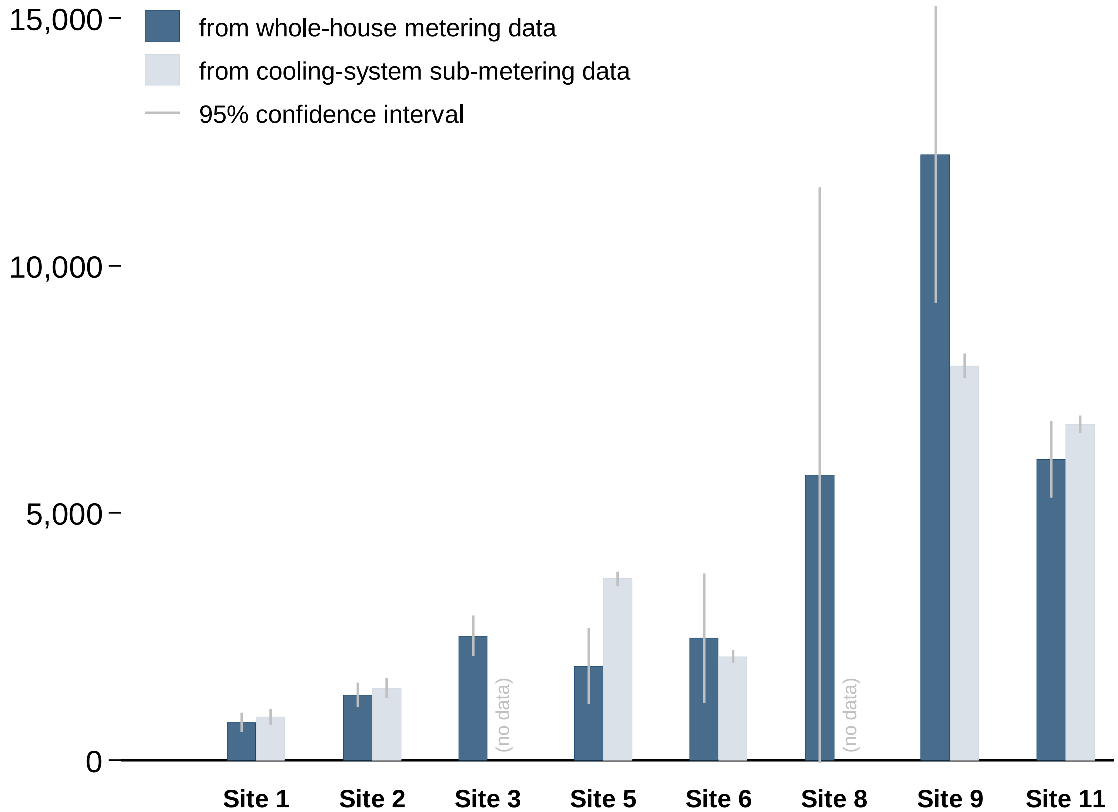

Fig. 12. Estimated post-weatherization seasonal cooling system electricity consumption from whole-house monitoring data and cooling-system sub-metering data.

3.3 UTILITY BILLING DATA

Utility billing histories were available for 10 of the sites. The histories comprised 20 to 44 months of pre-weatherization monthly electricity consumption, but only three to six months of post-weatherization usage. While the paucity of post-weatherization data preclude estimating weatherization savings from the utility data, it is possible to compare estimates of pre-weatherization cooling-energy consumption for the monthly utility histories and the daily monitoring data.

Analysis of the monthly utility data was implemented in the same manner as the whole-house monitoring data; namely by finding the best-fit cooling slope, base consumption and cooling reference temperature for each site's data. Because several of the sites also had some form of electric space heating, the models for these sites also included heating slope and heating reference temperature terms. (Appendix B provides additional detail regarding the analysis of the utility histories.)

The monitoring-based estimates of cooling energy use used here also take into account the fact that some households did not use their cooling systems on all days when outdoor conditions would suggest a need for cooling. The approach used to adjust the monitoring data for this discretionary use is described in Appendix B.

Despite the fact that the utility data embraces a longer time period than the monitoring data, there is a good correspondence between the two for most sites (Fig. 13), suggesting that analysis of monthly utility histories can provide a reasonable estimate of cooling system consumption.

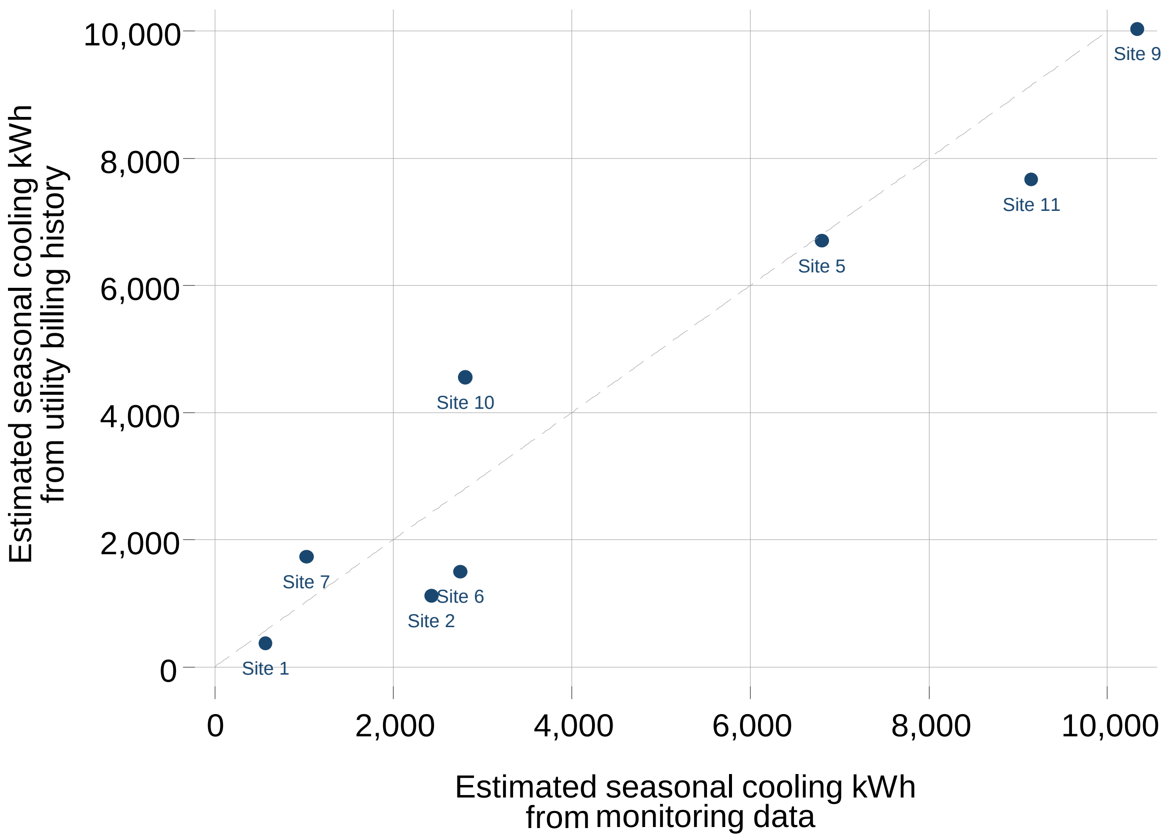

Fig. 13. Estimated seasonal pre-weatherization cooling electricity consumption from utility billing histories versus from direct monitoring of the cooling system.

4. CONCLUSIONS

The monitoring effort was successful at some sites, but not at others. Important issues related to unsuccessful data recovery included having a house electric panel that was too tightly packed to allow installation of monitoring equipment at all and interference with the monitoring equipment by electricians and other personnel associated with weatherization. The latter issue calls out the need for good communication and coordination when implementing monitoring in conjunction with weatherization activity.

The sub-metering data for sites suggest that in most cases daily cooling electricity consumption can be reasonably modeled as a function of outdoor temperature or cooling degree days, and that more complicated models involving indoor-outdoor temperature difference and outdoor humidity do not offer a significant advantage in estimating total seasonal consumption. However, two sites showed evidence of a seasonal difference in the relationship between daily cooling energy and outdoor temperature, perhaps reflective of varying solar gain due to differences in sun angles. This suggests that split-season studies of weatherization savings will be less reliable than approaches in which the pre- and post-weatherization periods each encompass a full cooling season.

From a monitoring-equipment standpoint, the data suggest that simply tracking compressor current draw—ideally combined with spot measurements of power factor and air handler power draw—is a viable approach to monitoring central cooling systems that can be implemented at somewhat less than half the equipment cost ($200 versus $450 per site) than tracking actual kWh consumption.

For the six sites where pre- and post-weatherization cooling-system consumption could be reasonably inferred from the monitoring data, all showed a significant reduction in electricity consumption following weatherization, ranging from about 20 percent to more than 40 percent.

The data from the pilot suggest that cooling-system consumption estimates derived from daily whole-house consumption and monthly utility histories generally compare favorably with actual cooling-system consumption from sub-metering, but also that, predictably, other end-uses can sometimes confound the analysis and lead to differences.

APPENDIX A – SITE DETAILS

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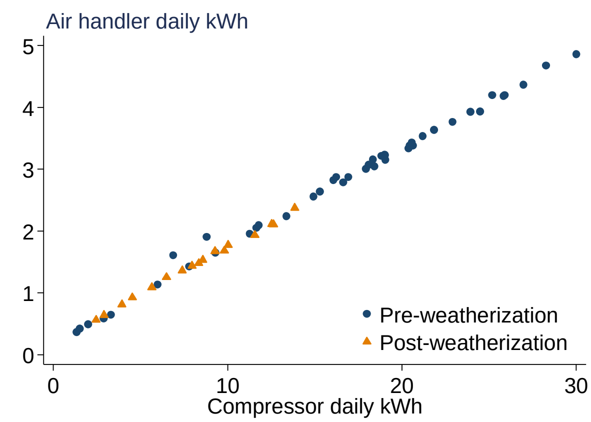
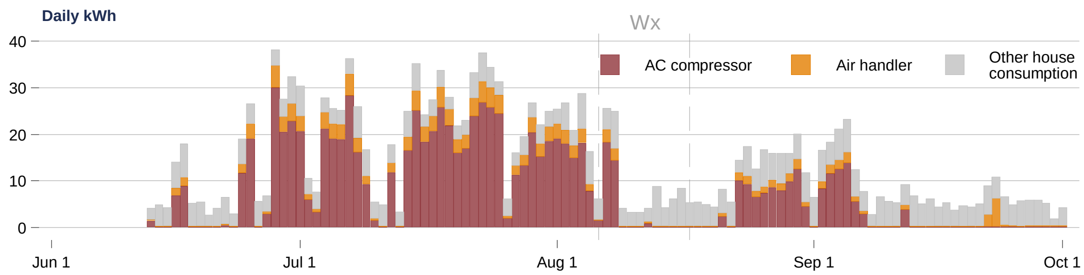
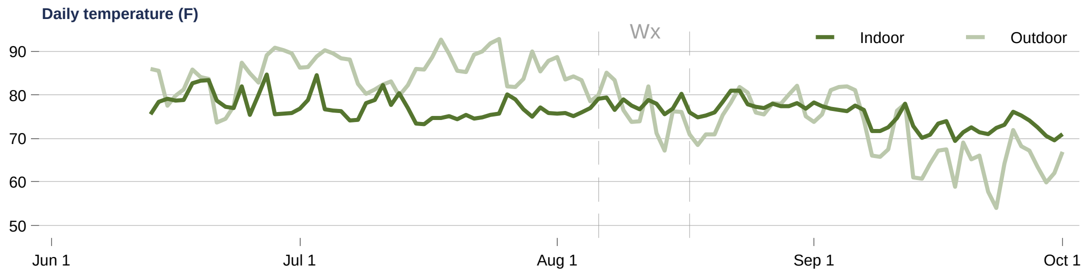
Site 1 – Kansas

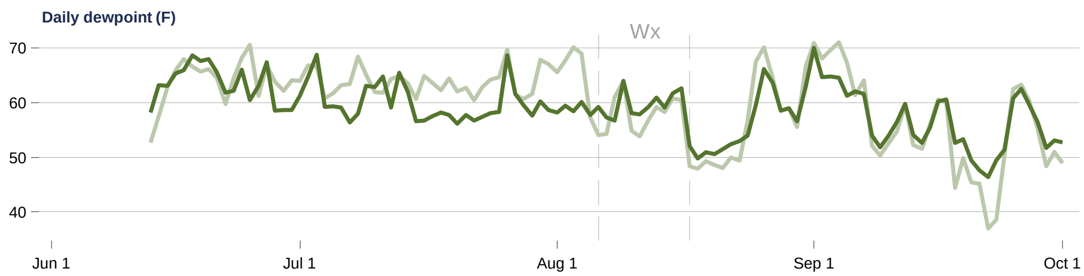
Home description	single-family, detached home with basement Square footage: 792	
Cooling system description	Older, 2-ton, SEER-10, split-system with gas, forced-air furnace (air handler). Duct work is in basement.	

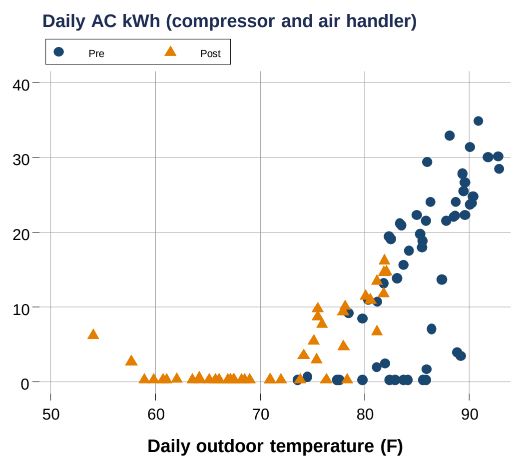
Weatherization measures	Furnace replacement, programmable thermostat, attic insulation, air sealing, CFLs and refrigerator replacement. Total job cost: $5,272.	
Monitoring and analysis notes	There was no change in air handler electricity consumption following furnace replacement	

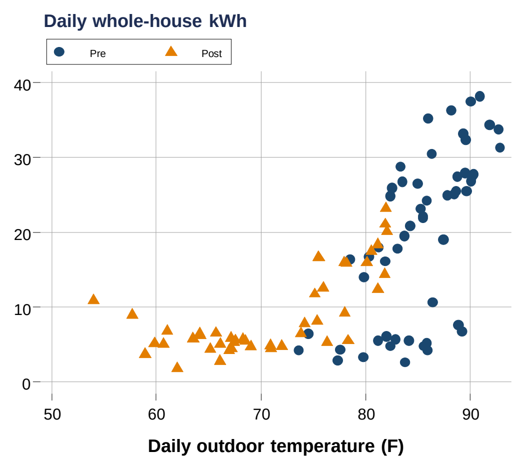
Site 1


Daily kWh
Wx
AC compressor
Air handler
Other house consumption
40
30
20
10
0
Jun 1
Jul 1
Aug 1
Sep 1
Oct 1


Daily temperature (F)
Wx
Indoor
Outdoor
90
80
70
60
50
Jun 1
Jul 1
Aug 1
Sep 1
Oct 1


Daily dewpoint (F)
Wx
70
60
50
40
Jun 1
Jul 1
Aug 1
Sep 1
Oct 1

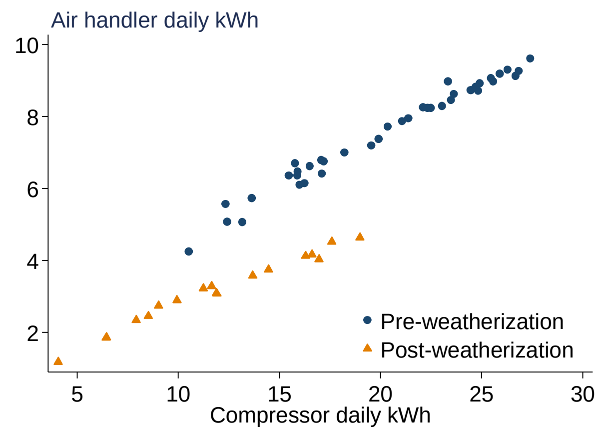

Daily AC kWh (compressor and air handler)
Pre
Post
40
30
20
10
0
50
60
70
80
90
Daily outdoor temperature (F)


Daily whole-house kWh
Pre
Post
40
30
20
10
0
50
60
70
80
90
Daily outdoor temperature (F)

Site 2 – Kansas

Home description	Single-family, detached home with walkout basement. Square footage: 1,003	
Cooling system description	Newer, 2-ton, SEER-13 split system with gas, forced-air furnace (air handler). Duct work is in basement.	 

<table>
<tr><td>Weatherization measures</td><td>Furnace replacement, programmable thermostat, attic insulation, air sealing, CFLs and refrigerator replacement.

Total job cost: $5,713.</td><td></td></tr>
<tr><td>Monitoring and analysis notes</td><td>Air handler electricity consumption decreased by about 27 percent following furnace replacement</td><td>
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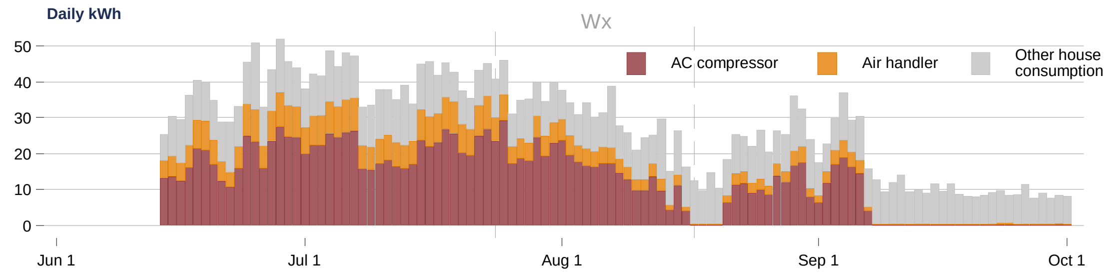
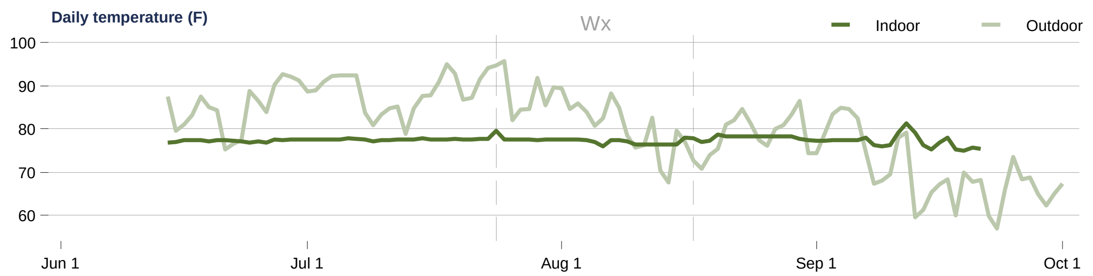
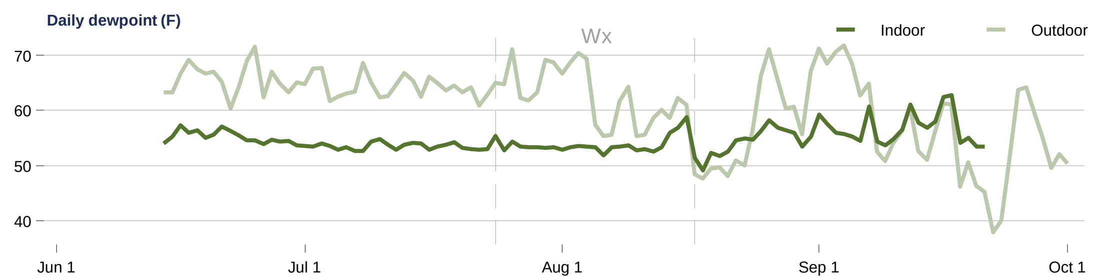
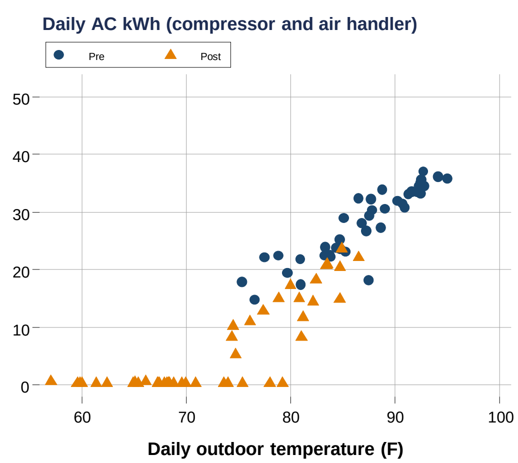
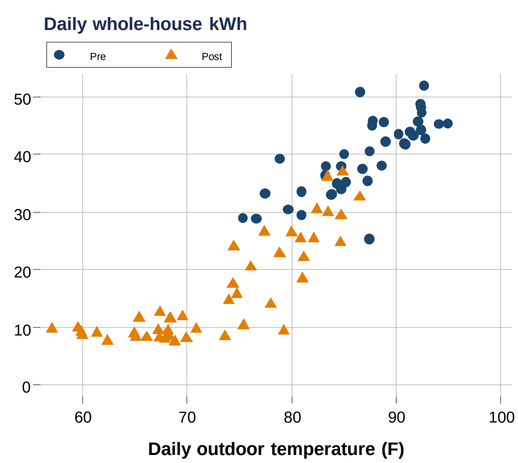
Site 2


Daily kWh
Wx
AC compressor
Air handler
Other house consumption
50
40
30
20
10
0
Jun 1
Jul 1
Aug 1
Sep 1
Oct 1


Daily temperature (F)
Wx
Indoor
Outdoor
100
90
80
70
60
Jun 1
Jul 1
Aug 1
Sep 1
Oct 1

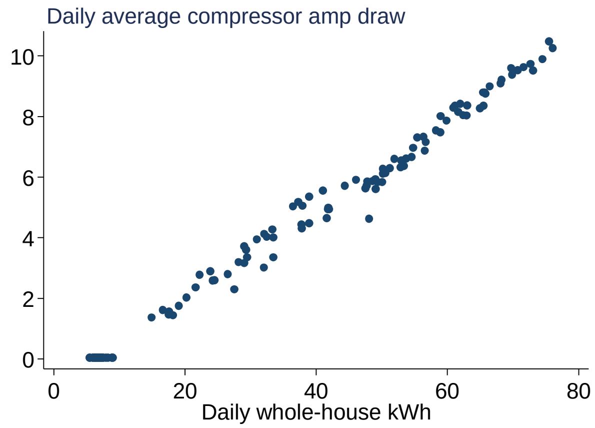

Daily dewpoint (F)
Wx
Indoor
Outdoor
70
60
50
40
Jun 1
Jul 1
Aug 1
Sep 1
Oct 1


Daily AC kWh (compressor and air handler)
Pre
Post
50
40
30
20
10
0
60
70
80
90
100
Daily outdoor temperature (F)

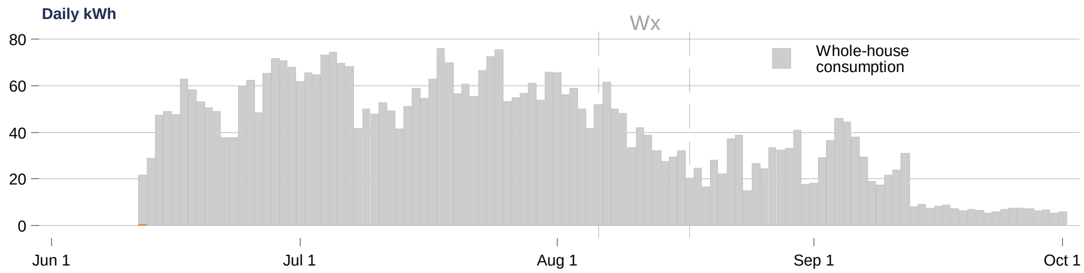

Daily whole-house kWh
Pre
Post
50
40
30
20
10
0
60
70
80
90
100
Daily outdoor temperature (F)

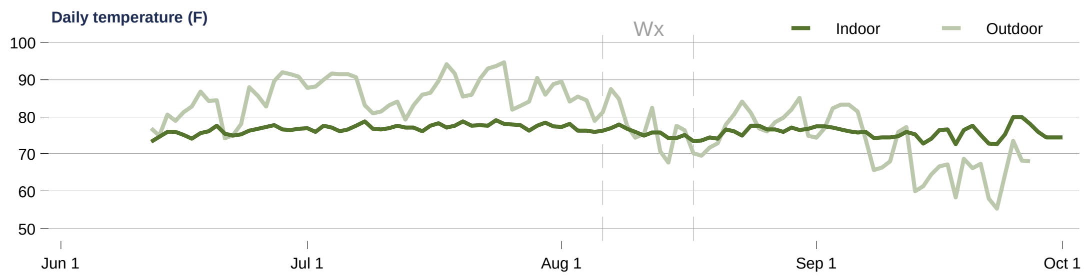
Site 3 – Kansas

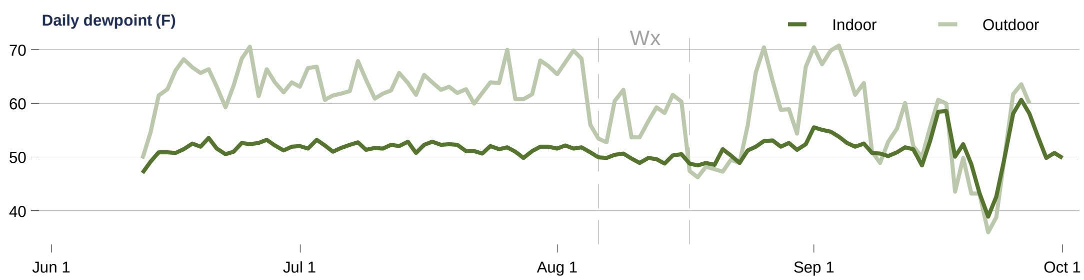
Home description	Single-family, detached home with basement Square footage: 1,181	
Cooling system description	Older, 3-ton split system with gas, forced-air furnace (air handler).	 

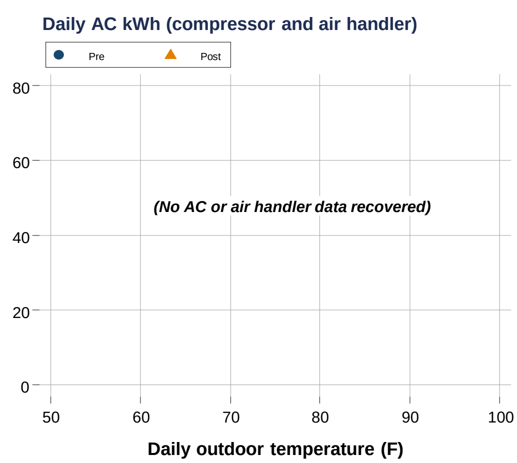
Weatherization measures	Furnace replacement, attic insulation, air sealing, CFLs and refrigerator replacement. Total job cost: $4,709.	
Monitoring and analysis notes	Terminal block connection for AC kWh monitoring was inadvertently disconnected during installation final assembly: no kWh data recovery for air conditioner compressor or air handler, though amp draw data were obtained for the compressor, and these are highly correlated with whole-house kWh.	

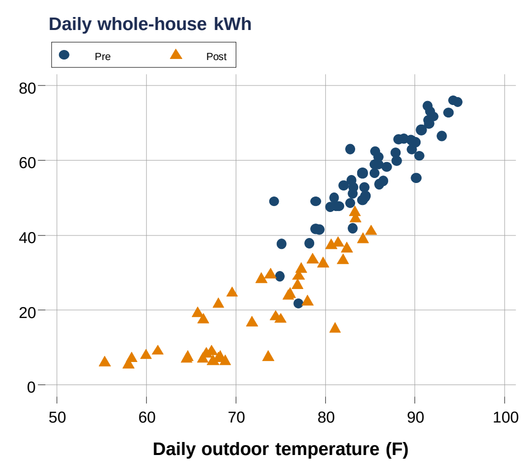
Site 3


Daily kWh
Wx
Whole-house consumption
80
60
40
20
0
Jun 1
Jul 1
Aug 1
Sep 1
Oct 1


Daily temperature (F)
Wx
Indoor
Outdoor
100
90
80
70
60
50
Jun 1
Jul 1
Aug 1
Sep 1
Oct 1


Daily dewpoint (F)
Wx
Indoor
Outdoor
70
60
50
40
Jun 1
Jul 1
Aug 1
Sep 1
Oct 1


Daily AC kWh (compressor and air handler)
Pre
Post
80
60
40
20
0
(No AC or air handler data recovered)
50
60
70
80
90
100
Daily outdoor temperature (F)


Daily whole-house kWh
Pre
Post
80
60
40
20
0
50
60
70
80
90
100
Daily outdoor temperature (F)

Site 4 – Kansas

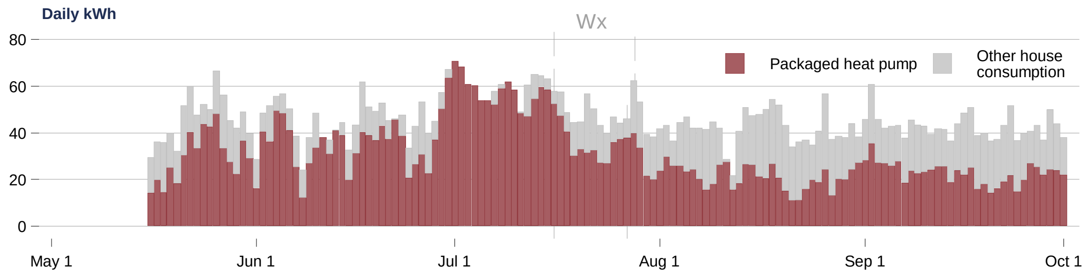
Home description	Single-family, detached, slab-on-grade. Square footage: 1,144	
Cooling system description	Pre-weatherization: 3 room air conditioners (1 per bedroom) and non-functional central heat pump. Post-weatherization: central heat pump	  
Weatherization measures	Replacement of non-functional heat pump, air sealing, refrigerator replacement and CFLs. Total job cost: $4,124.	
Monitoring and analysis notes	For unknown reasons, no data recovery from panel-level metering. Also, there were data issues with monitoring two of the three room air conditioners.	

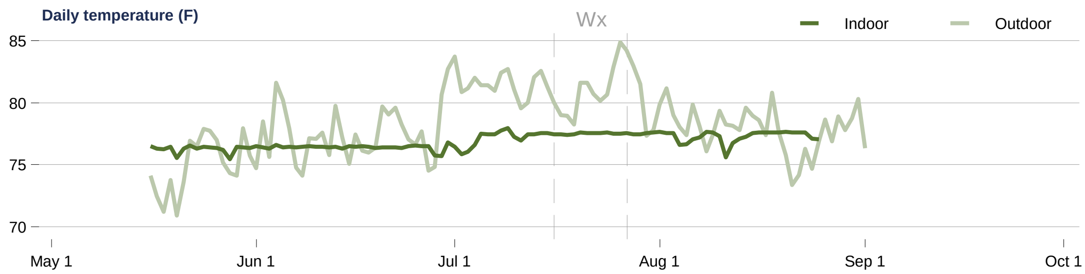
Site 5 – Florida

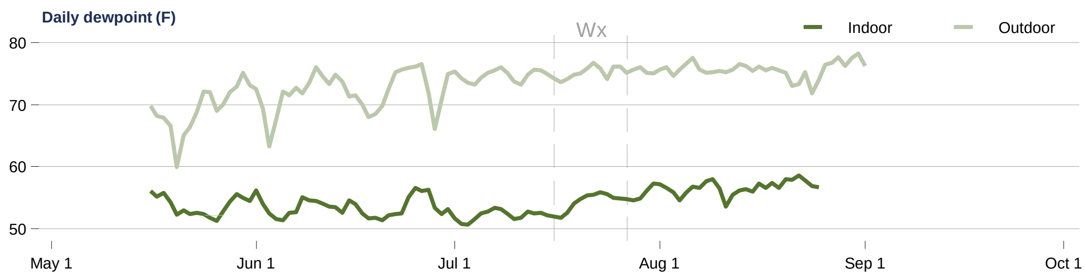
Home description	Single-family, detached with crawlspace. Home has two parallel sections, one of which was originally a mobile home. Square footage: 1,904	 
Cooling system description	Older, 4-ton packaged heat pump	

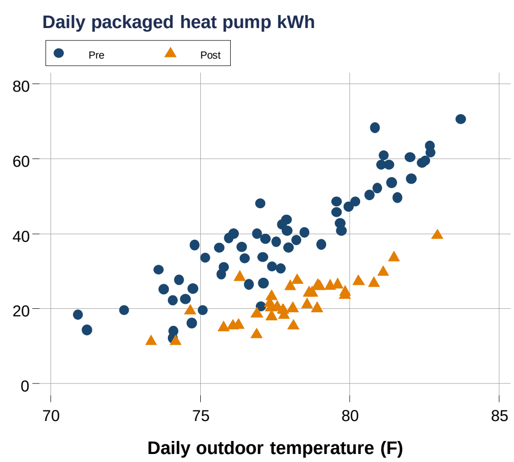
Weatherization measures	Heat pump replacement, duct repair, attic insulation, air sealing, new refrigerator and CFLs Total job cost: $5,877	
Monitoring and analysis notes		

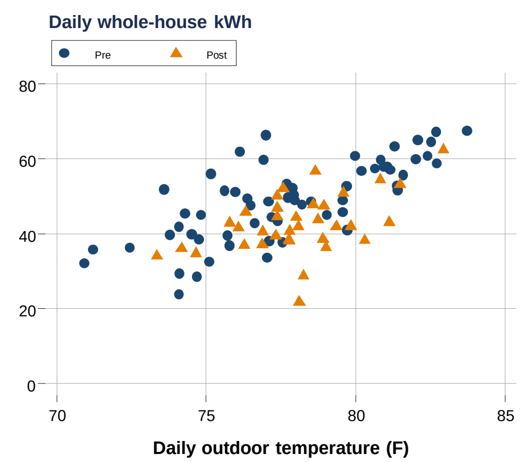
Site 5


Daily kWh
Wx
80
60
40
20
0
Packaged heat pump
Other house consumption
May 1
Jun 1
Jul 1
Aug 1
Sep 1
Oct 1


Daily temperature (F)
Wx
Indoor
Outdoor
85
80
75
70
May 1
Jun 1
Jul 1
Aug 1
Sep 1
Oct 1


Daily dewpoint (F)
Wx
Indoor
Outdoor
80
70
60
50
May 1
Jun 1
Jul 1
Aug 1
Sep 1
Oct 1

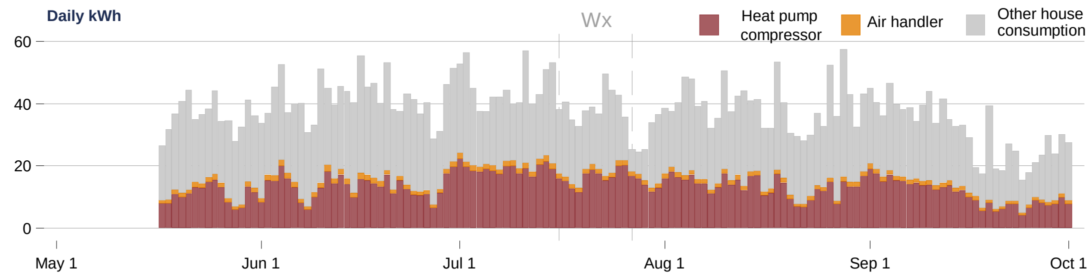

Daily packaged heat pump kWh
Pre
Post
80
60
40
20
0
70
75
80
85
Daily outdoor temperature (F)

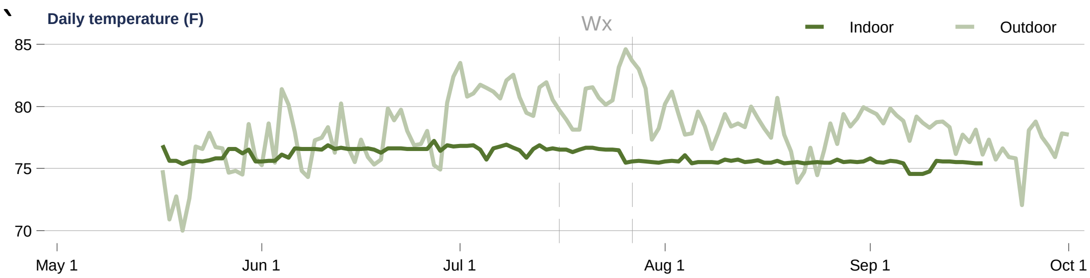

Daily whole-house kWh
Pre
Post
80
60
40
20
0
70
75
80
85
Daily outdoor temperature (F)

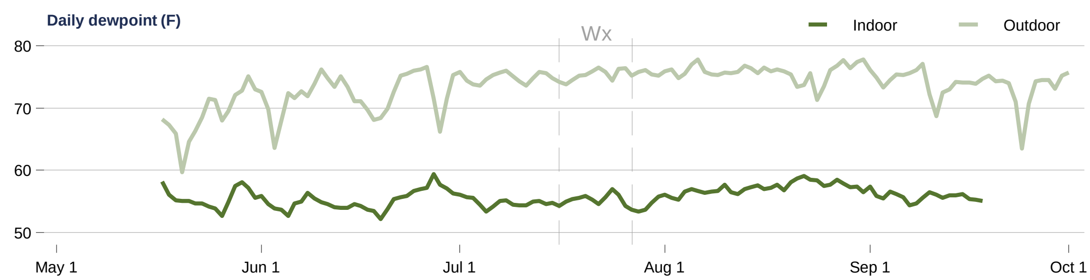
Site 6 – Florida

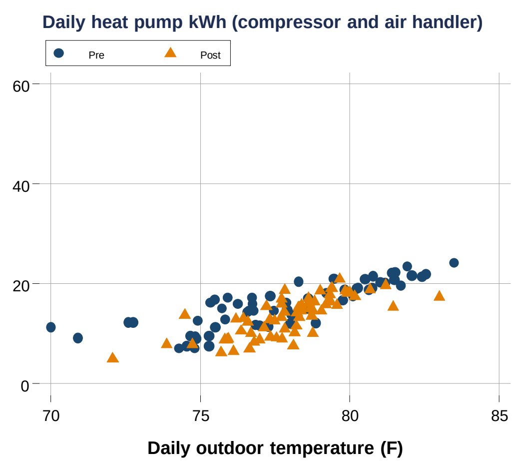
Home description	Single-family, detached, slab-on-grade foundation. Square footage: 1,120	
Cooling system description	New, SEER 14, 2-ton heat pump.	
Weatherization measures	Air sealing, attic access insulation, new refrigerator and CFLs. Total job cost: $2,648	
Monitoring and analysis notes		

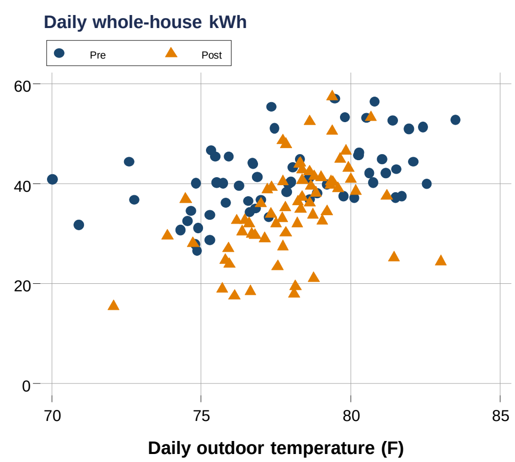
Site 6


Daily kWh
Wx
Heat pump compressor
Air handler
Other house consumption
60
40
20
0
May 1
Jun 1
Jul 1
Aug 1
Sep 1
Oct 1


Daily temperature (F)
Wx
Indoor
Outdoor
85
80
75
70
May 1
Jun 1
Jul 1
Aug 1
Sep 1
Oct 1


Daily dewpoint (F)
Wx
Indoor
Outdoor
80
70
60
50
May 1
Jun 1
Jul 1
Aug 1
Sep 1
Oct 1

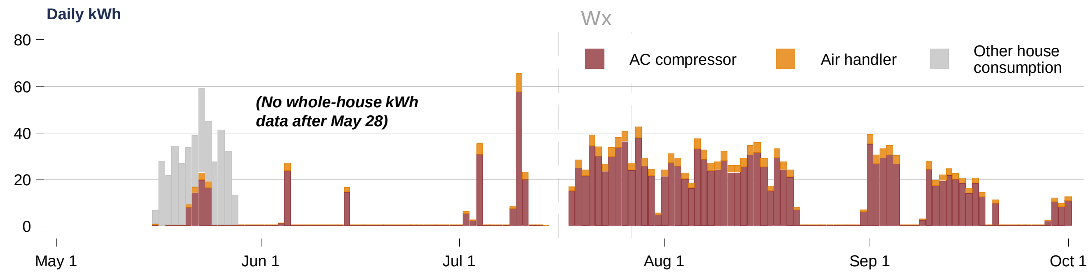

Daily heat pump kWh (compressor and air handler)
Pre
Post
60
40
20
0
70
75
80
85
Daily outdoor temperature (F)

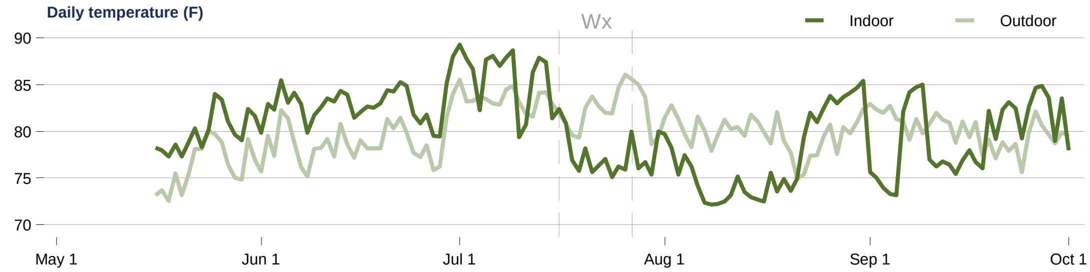

Daily whole-house kWh
Pre
Post
60
40
20
0
70
75
80
85
Daily outdoor temperature (F)

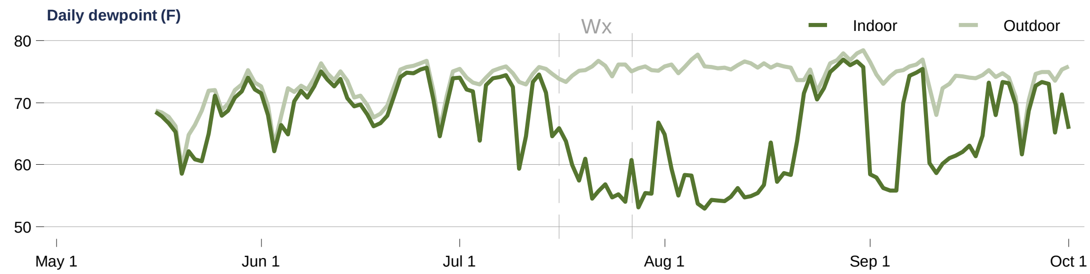
Site 7 – Florida

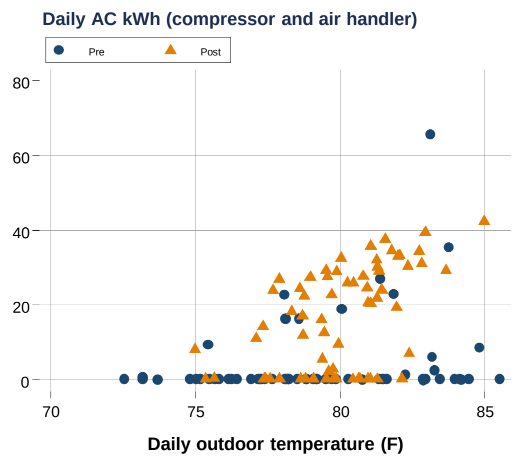
Home description	Single-family, detached on crawlspace foundation. Square footage: 1,300	
Cooling system description	Older, 10-SEER, 2.5-ton heat pump.	
Weatherization measures	SEER 14 heat pump and replacement air handler, programmable thermostat, attic insulation, air sealing and CFLs.	
Monitoring and analysis notes	No whole-house kWh data after May 28th, which corresponds with electrician visit to check wiring. Cooling system not used often prior to weatherization.	

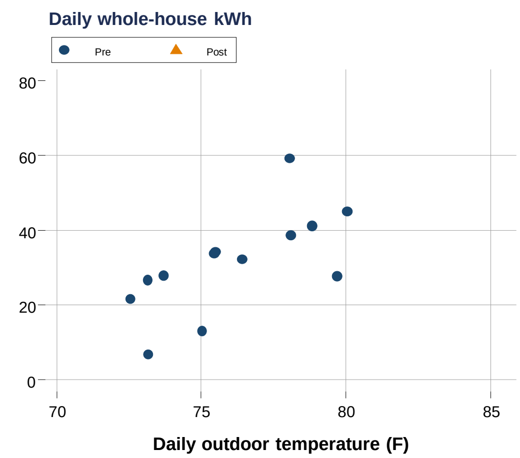
Site 7


Daily kWh
Wx
AC compressor
Air handler
Other house consumption
(No whole-house kWh data after May 28)
80
60
40
20
0
May 1
Jun 1
Jul 1
Aug 1
Sep 1
Oct 1


Daily temperature (F)
Wx
Indoor
Outdoor
90
85
80
75
70
May 1
Jun 1
Jul 1
Aug 1
Sep 1
Oct 1


Daily dewpoint (F)
Wx
Indoor
Outdoor
80
70
60
50
May 1
Jun 1
Jul 1
Aug 1
Sep 1
Oct 1

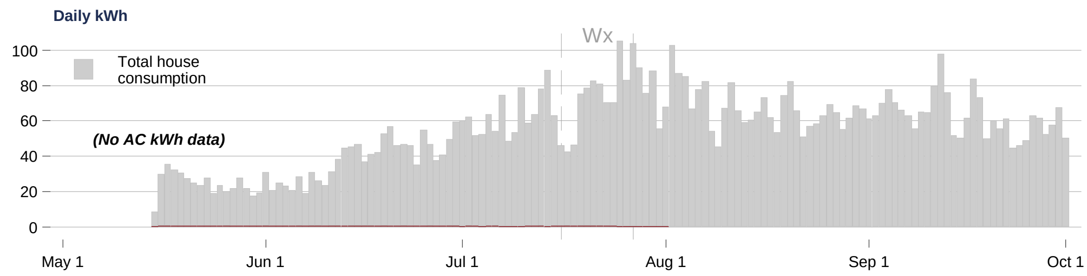

Daily AC kWh (compressor and air handler)
Pre
Post
80
60
40
20
0
70
75
80
85
Daily outdoor temperature (F)

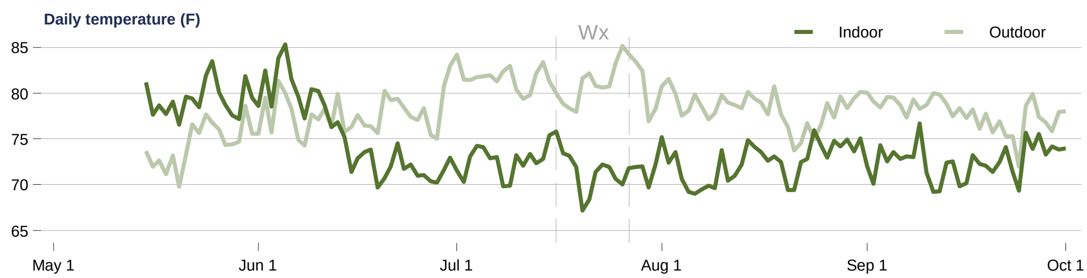

Daily whole-house kWh
Pre
Post
80
60
40
20
0
70
75
80
85
Daily outdoor temperature (F)

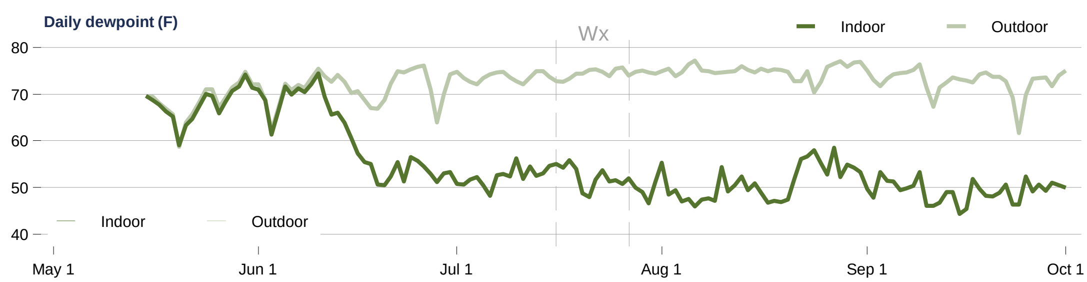
Site 8 – Florida

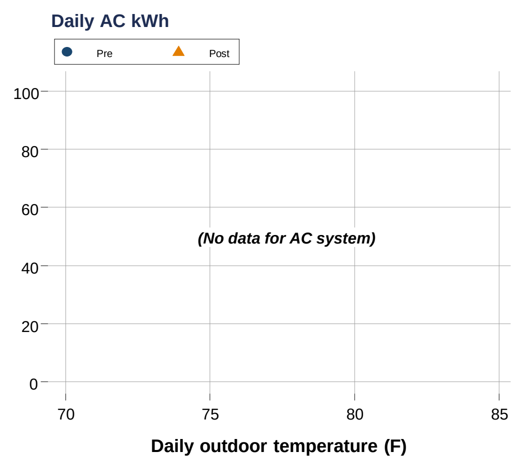
Home description	Double-wide mobile home (in poor condition) Square footage: 1,239	 
Cooling system description	Pre-weatherization: non-functional packaged heat pump. Later evidence of room AC use, though not present at time of installation. Post-weatherization: ductless minisplit system.	
Weatherization measures	Installation of 2-ton, 2-head ductless minisplit system, air sealing and CFLs Total job cost: $5,735	
Monitoring and analysis notes	No kWh or amp data recovered for minisplit system. Indoor temperature data are for a bedroom, due to thermostat logger removal by occupants.	

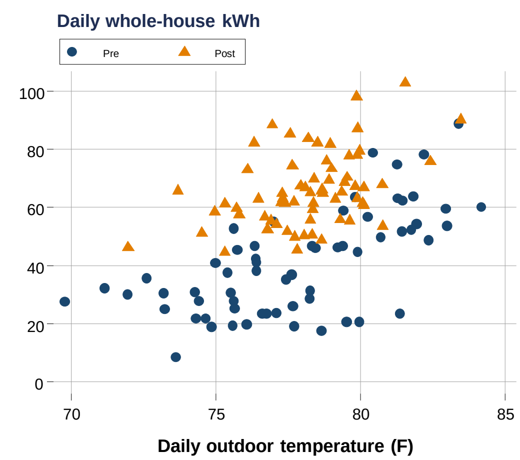
Site 8


Daily kWh
Wx
100
80
60
40
20
0
Total house consumption
(No AC kWh data)
May 1
Jun 1
Jul 1
Aug 1
Sep 1
Oct 1

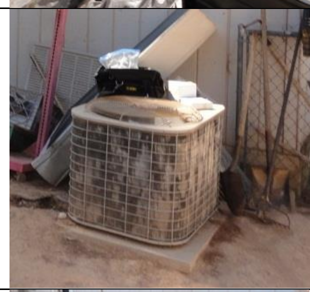

Daily temperature (F)
Wx
Indoor
Outdoor
85
80
75
70
65
May 1
Jun 1
Jul 1
Aug 1
Sep 1
Oct 1


Daily dewpoint (F)
Wx
Indoor
Outdoor
80
70
60
50
40
Indoor
Outdoor
May 1
Jun 1
Jul 1
Aug 1
Sep 1
Oct 1

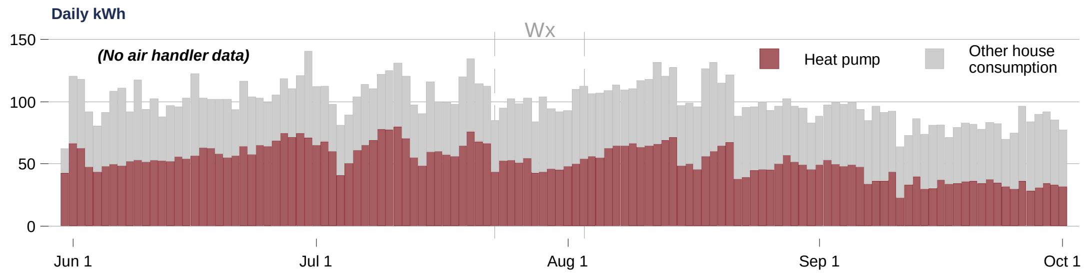

Daily AC kWh
Pre
Post
100
80
60
40
20
0
(No data for AC system)
70
75
80
85
Daily outdoor temperature (F)

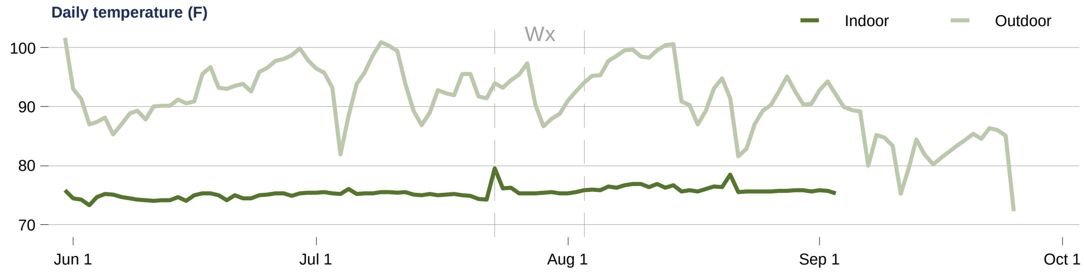

Daily whole-house kWh
Pre
Post
100
80
60
40
20
0
70
75
80
85
Daily outdoor temperature (F)

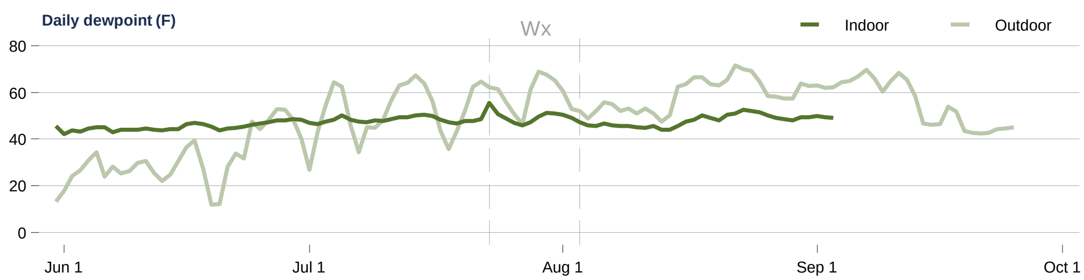
Site 9 – Arizona

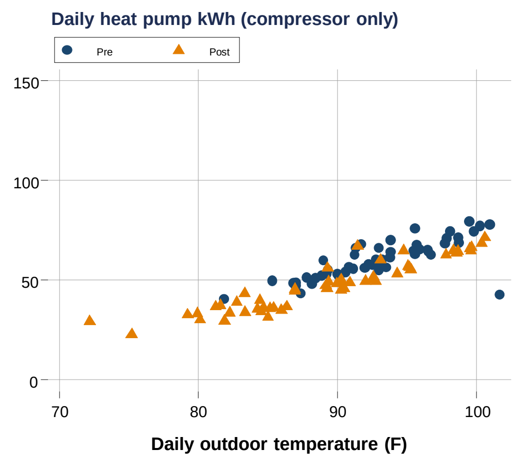
Home description	Double-wide mobile home. Square footage: 1,715	
Cooling system description	Pre-weatherization: older, SEER-10, 4-ton heat pump. Post-weatherization: new SEER 13, 4-ton heat pump	
Weatherization measures	Heat pump and air handler replacement; refrigerator replacement. Total job cost: $7,240	
Monitoring and analysis notes	Air handler kWh not monitored	

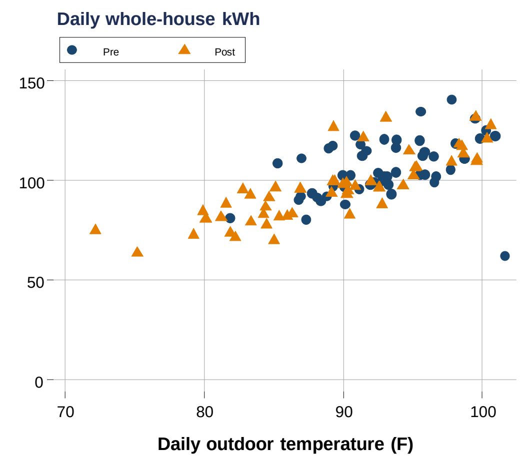
Site 9


Daily kWh
(No air handler data)
Wx
Heat pump
Other house consumption
150
100
50
0
Jun 1
Jul 1
Aug 1
Sep 1
Oct 1


Daily temperature (F)
Wx
Indoor
Outdoor
100
90
80
70
Jun 1
Jul 1
Aug 1
Sep 1
Oct 1


Daily dewpoint (F)
Wx
Indoor
Outdoor
80
60
40
20
0
Jun 1
Jul 1
Aug 1
Sep 1
Oct 1

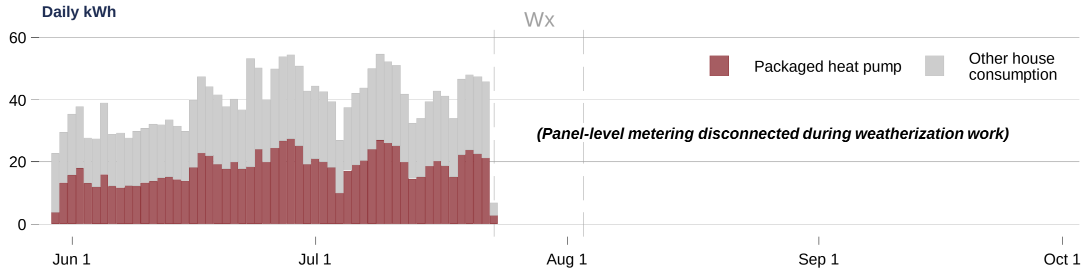

Daily heat pump kWh (compressor only)
Pre
Post
150
100
50
0
70
80
90
100
Daily outdoor temperature (F)

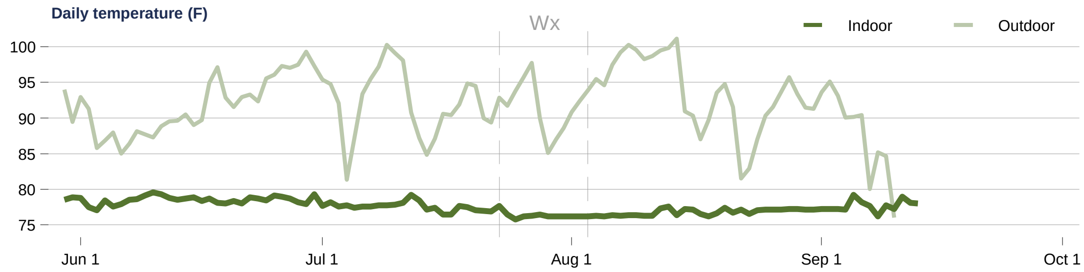

Daily whole-house kWh
Pre
Post
150
100
50
0
70
80
90
100
Daily outdoor temperature (F)

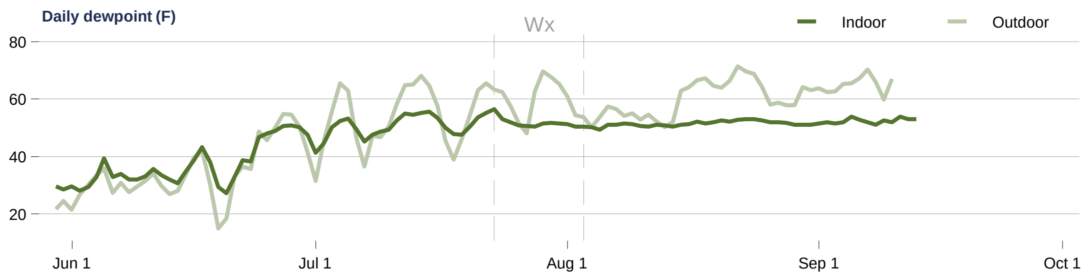
Site 10 – Arizona

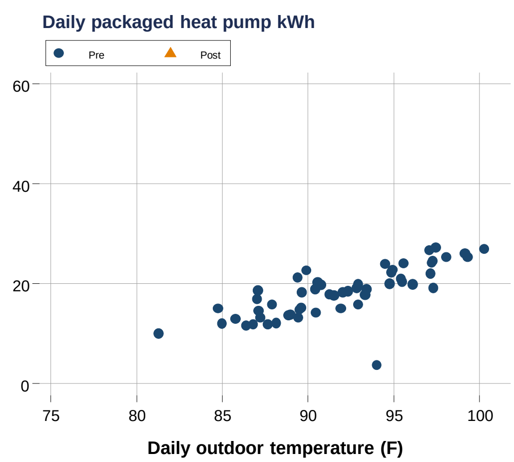
Home description	Single-family, detached home on slab foundation. Square footage: 840	
Cooling system description	Pre-weatherization: older roof-mounted, 2.5 ton packaged heat pump Post-weatherization: new, SEER 13, 2-ton packaged heat pump	
Weatherization measures	Heat pump replacement, attic insulation and duct sealing.	
Monitoring and analysis notes	Panel-level monitoring disconnected at time of weatherization.	

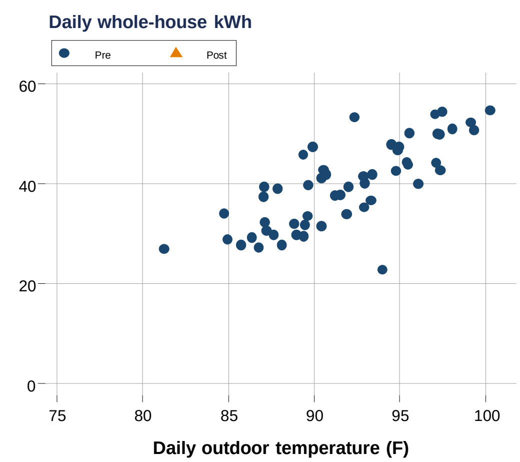
Site 10


Daily kWh
Wx
Packaged heat pump
Other house consumption
(Panel-level metering disconnected during weatherization work)
60
40
20
0
Jun 1
Jul 1
Aug 1
Sep 1
Oct 1


Daily temperature (F)
Wx
Indoor
Outdoor
100
95
90
85
80
75
Jun 1
Jul 1
Aug 1
Sep 1
Oct 1


Daily dewpoint (F)
Wx
Indoor
Outdoor
80
60
40
20
Jun 1
Jul 1
Aug 1
Sep 1
Oct 1

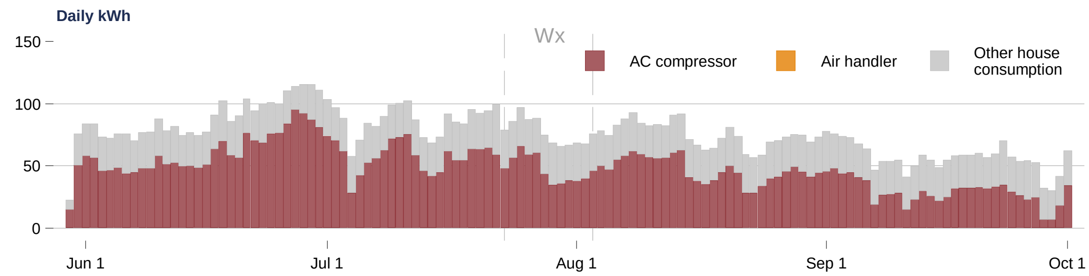

Daily packaged heat pump kWh
Pre
Post
60
40
20
0
75
80
85
90
95
100
Daily outdoor temperature (F)

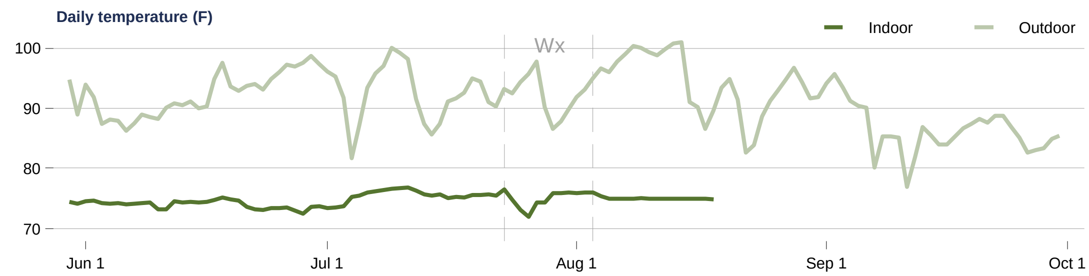

Daily whole-house kWh
Pre
Post
60
40
20
0
75
80
85
90
95
100
Daily outdoor temperature (F)

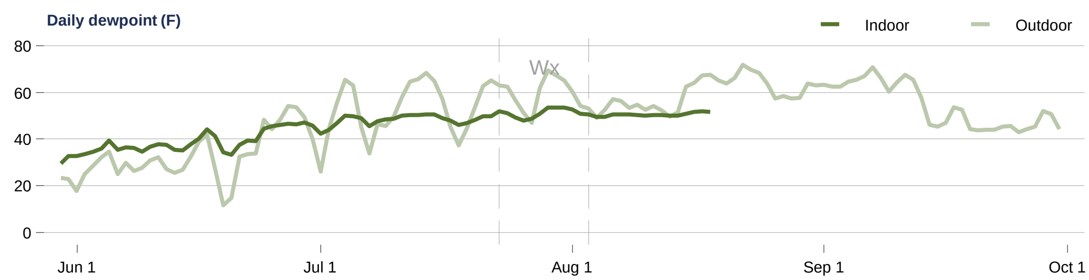
Site 11 – Arizona

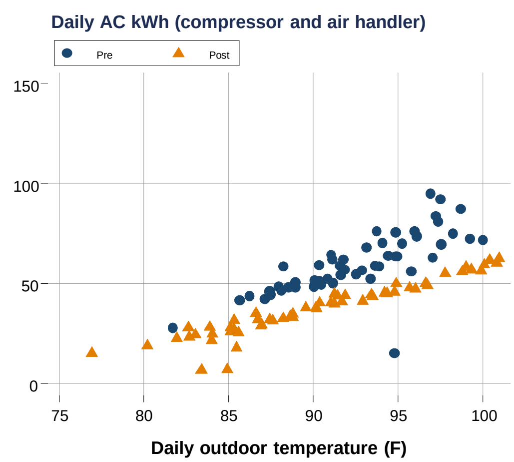
Home description	Single-family, detached, one-story home on slab foundation. Square footage: 1,846	
Cooling system description	Older, roof-mounted, SEER 12, 5-ton, packaged AC and gas heating system.	
Weatherization measures	Replaced package unit with new SEER-13, 5-ton system; air sealing; duct sealing; solar screens; redistribution of existing attic insulation. Total job cost: $11,760	
Monitoring and analysis notes		

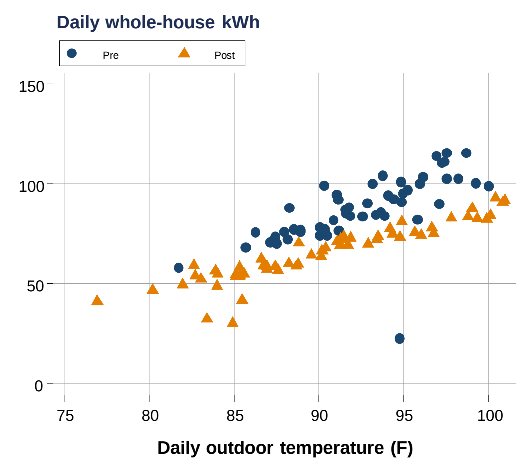
Site 11


Daily kWh
150
100
50
0
Wx
AC compressor
Air handler
Other house consumption
Jun 1
Jul 1
Aug 1
Sep 1
Oct 1


Daily temperature (F)
Indoor
Outdoor
100
90
80
70
Wx
Jun 1
Jul 1
Aug 1
Sep 1
Oct 1


Daily dewpoint (F)
Indoor
Outdoor
80
60
40
20
0
Wx
Jun 1
Jul 1
Aug 1
Sep 1
Oct 1


Daily AC kWh (compressor and air handler)
Pre
Post
150
100
50
0
75
80
85
90
95
100
Daily outdoor temperature (F)


Daily whole-house kWh
Pre
Post
150
100
50
0
75
80
85
90
95
100
Daily outdoor temperature (F)

APPENDIX B. MODELING DETAILS

APPENDIX B – MODELING DETAILS

This appendix provides additional detail about the modeling used for the analysis of daily cooling-system electricity consumption, daily whole-house electricity consumption and utility billing data.

Daily Cooling-System Electricity Consumption

Four models were considered for the analysis of daily cooling-system electricity consumption:

Model 1 – temperature; no humidity term:

daily AC kWh = $\beta_1 * T_o + \beta_0 + \varepsilon$

Model 2 – temperature difference; no humidity term:

daily AC kWh = $\beta_1 * \Delta T_{oi} + \beta_0 + \varepsilon$

Model 3 – temperature; includes humidity term:

daily AC kWh = $\beta_1 * T_o + \beta_2 D_o + \beta_0 + \varepsilon$

Model 4 – temperature difference; includes humidity term:

daily AC kWh = $\beta_1 * \Delta T_{oi} + \beta_2 D_o + \beta_0 + \varepsilon$

where

$T_o \equiv$ daily average outdoor temperature (F)

$\Delta T_{oi} \equiv$ daily difference between outdoor (T_o) and indoor (T_i) temperature (F)

$D_o \equiv$ daily average outdoor dewpoint temperature (F)

$\varepsilon \equiv$ random error

Each of these models was fit separately to the pre- and post-weatherization periods for each site with available daily cooling-system electricity consumption data, excluding days with no cooling-system use and some days with clearly-limited operation.

The tables that follow provide the fitted results for each site and time period for the four models.

Table B1. Fitted results for Model 1

Model: daily kWh = $\beta_1 * T_o + \beta_0 + \varepsilon$								
Site	**Period**	**Days**	**β_1**	**Std. error**	**β_0**	**Std. error**	**Implied balance-point temperature***	**Adjusted r^2**
1	pre	37	1.31	0.13	-93.6	11.3	71.7	0.694
	post	17	0.91	0.15	-64.1	12.4	70.5	0.601
2	pre	40	1.12	0.06	-69.1	5.6	61.7	0.825
	post	18	1.21	0.17	-83.0	13.6	68.5	0.652
5	pre	61	4.31	0.29	-299.5	23.1	69.5	0.770
	post	93	1.98	0.14	-134.6	11.0	68.1	0.760
6	pre	60	1.35	0.11	-90.7	9.2	67.1	0.728
	post	93	1.25	0.11	-86.3	8.2	69.0	0.580
7	pre	8	5.72	2.87	-426.1	225.3	74.5	0.356
	post	46	2.55	0.37	-177.0	29.1	69.4	0.552
9	pre	52	1.80	0.16	-105.5	15.0	58.6	0.673
	post	98	1.87	0.05	-122.5	3.9	65.7	0.909
10	pre	53	0.87	0.09	-62.0	8.2	71.0	0.636
	post	0	–	–	–	–	–	–
11	pre	53	2.79	0.26	-197.6	23.4	70.7	0.712
	post	86	1.63	0.05	-108.0	3.9	66.2	0.947

*Lowest outdoor temperature at which cooling system is used. Calculated as $-\beta_0 / \beta_1$

Table B2. Fitted results for Model 2.

Model: daily kWh = $\beta_1 * \Delta T_{oi} + \beta_0 + \varepsilon$								
Site	**Period**	**Days**	**β_1**	**Std. error**	**β_0**	**Std. error**	**Implied balance-point ΔT***	**Adjusted r^2**
1	pre	37	1.17	0.08	7.3	0.8	-6.3	0.830
	post	17	1.02	0.13	6.0	0.8	-5.9	0.696
2	pre	40	1.14	0.07	17.4	0.8	-15.3	0.818
	post	18	1.25	0.16	11.3	0.7	-9.0	0.707
5	pre	61	4.73	0.34	29.2	1.3	-6.2	0.768
	post	93	2.46	0.26	17.8	0.6	-7.3	0.596
6	pre	60	1.47	0.11	12.2	0.5	-8.3	0.766
	post	93	1.29	0.11	7.9	0.4	-6.1	0.565
7	pre	8	5.53	2.89	36.8	6.3	-6.7	0.536
	post	46	2.52	0.20	15.2	0.9	-6.0	0.781
9	pre	52	1.81	0.18	29.1	3.4	-16.1	0.632
	post	98	2.18	0.06	13.7	0.8	-6.3	0.876
10	pre	53	0.93	0.07	5.4	1.2	-5.8	0.712
	post	0	–	–	–	–	–	–
11	pre	53	2.84	0.22	10.2	3.8	-3.6	0.793
	post	86	1.80	0.06	11.6	1.0	-6.4	0.938

*Lowest outdoor-indoor temperature difference at which cooling system is used. Calculated as $-\beta_0/\beta_1$

Table B3. Fitted results for Model 3.

Model: daily kWh = $\beta_1 * T_o + \beta_2 D_o + \beta_0 + \varepsilon$										
Site	**Period**	**Days**	β_1	**Std. err.**	β_2	**Std. err.**	β_0	**Std. error**	**Implied balance-point temperature***	**Adjusted r^2**
1	pre	37	1.31	0.14	0.01	0.21	-94.0	19.3	72.0	0.685
	post	17	1.11	0.10	0.29	0.07	-98.1	10.7	88.5	0.844
2	pre	40	1.13	0.07	0.21	0.18	-83.1	13.6	73.8	0.828
	post	18	1.54	0.13	0.38	0.06	-132.7	12.6	85.9	0.892
5	pre	61	4.94	0.37	-0.87	0.29	-287.8	21.1	58.3	0.796
	post	93	2.05	0.23	-0.06	0.14	-136.0	11.7	66.2	0.758
6	pre	60	1.64	0.11	-0.39	0.08	-86.1	7.3	52.4	0.785
	post	93	0.97	0.17	0.24	0.12	-81.4	9.1	84.0	0.593
7	pre	8	6.03	5.64	-0.37	9.76	-425.0	711.2	70.5	0.230
	post	46	2.36	0.57	0.19	0.51	-175.6	44.8	74.5	0.545
9	pre	52	1.87	0.12	0.30	0.05	-124.9	11.3	66.8	0.847
	post	98	1.62	0.06	0.31	0.05	-116.8	4.2	72.2	0.937
10	pre	53	0.91	0.05	0.17	0.02	-72.5	4.5	80.0	0.877
	post	0	–	–	–	–	–	–	–	
11	pre	53	2.84	0.27	0.22	0.06	-211.1	25.4	74.4	0.752
	post	86	1.31	0.14	0.07	0.04	-106.6	4.3	67.8	0.948

*Lowest outdoor temperature at which cooling system is used. Calculated as $-\beta_0/\beta_1$

Table B4. Fitted results for Model 4.

Model: daily kWh = $\beta_1 * \Delta T_{oi} + \beta_2 D_o + \beta_0 + \varepsilon$										
Site	**Period**	**Days**	β_1	**Std. err.**	β_2	**Std. err.**	β_0	**Std. error**	**Implied balance-point ΔT***	**Adjusted r^2**
1	pre	37	1.18	0.08	0.05	0.13	4.0	8.6	-3.4	0.826
	post	17	1.05	0.11	0.16	0.10	-3.6	6.3	3.4	0.761
2	pre	40	1.14	0.07	0.20	0.18	5.0	11.5	-4.3	0.820
	post	18	1.48	0.13	0.31	0.07	-8.5	4.3	5.7	0.883
5	pre	61	5.20	0.44	-0.63	0.30	72.4	20.4	-13.9	0.780
	post	93	2.58	0.29	-0.25	0.24	35.5	17.4	-13.8	0.602
6	pre	60	1.69	0.11	-0.30	0.08	32.5	5.6	-19.2	0.800
	post	93	0.96	0.17	0.28	0.12	-10.9	8.0	11.3	0.584
7	pre	8	5.15	4.32	1.42	15.94	-64.2	1150	12.5	0.508
	post	46	2.27	0.22	0.42	0.25	-14.4	17.5	6.3	0.798
9	pre	52	1.96	0.13	0.34	0.05	11.5	3.0	-5.9	0.858
	post	98	1.83	0.07	0.42	0.05	-3.4	2.1	1.8	0.935
10	pre	53	0.92	0.04	0.15	0.02	-1.1	0.8	1.2	0.901
	post	0								
11	pre	53	2.99	0.16	0.32	0.05	-6.3	3.9	2.1	0.882

post	86	1.74	0.06	0.10	0.04	6.8	2.6	-3.9	0.942

*Lowest outdoor-indoor temperature difference at which cooling system is used. Calculated as $-\beta_0/\beta_1$

These model fits were translated into normalized estimates of annual consumption by combining them with long-term average weather data for the respective local weather stations. Specifically, daily data for April through October over the 20-year time span from 1993 through 2012 were used to determine the long-term average joint distributions (1F bins) of daily outdoor dry-bulb and dewpoint temperature. Weather-normalized consumption was estimated by first using the fitted model to estimate daily cooling-system kWh in each temperature/dewpoint bin, then multiplying these values by the empirical average incidence (days per year) of that bin, and finally summing the results across all bins.[3] For the models involving the outdoor-indoor temperature difference, the overall average indoor temperature for the period in question was used for normalization procedure.

Standard errors for the seasonal cooling-system consumption estimates were developed using a bootstrap technique: the daily data for each run were repeatedly re-sampled with replacement, the regression model was re-fit, and annual kWh consumption was re-calculated. Ten thousand iterations were performed for each estimate. The standard deviation of the resulting distribution of estimates was taken as the standard error for seasonal cooling consumption.

Site- and period-specific estimates, with standard errors, are shown in the table below.

Table B5. Weather-normalized estimates of April-October cooling-system energy consumption from daily cooling-system data

		Model 1		Model 2		Model 3		Model 4		Mean
Site	Period	kWh	std. error	kWh	std. error	kWh	std. error	kWh	std. error	T_i (F)
1	Pre	1,082	137	1,220	81	1,083	179	1,222	85	76.0
	Post	872	79	850	68	1,002	46	931	56	77.5
2	Pre	2,428	149	2,392	148	2,389	145	2,361	147	77.5
	Post	1,453	95	1,439	89	1,571	52	1,547	56	77.9
5	Pre	6,801	180	6,751	173	6,904	177	6,807	173	76.5
	Post	3,669	73	3,603	87	3,690	94	3,734	190	77.4
6	Pre	2,752	79	2,723	69	2,819	71	2,766	63	76.4
	Post	2,091	67	2,091	68	2,023	74	2,014	73	75.4
7	Pre	4,127	592	4,133	479	4,101	2,629	4,280	4,471	81.0
	Post	4,079	175	4,083	124	4,018	261	3,929	140	75.3
9	Pre	10,333	299	10,322	326	10,226	218	10,105	208	74.9
	Post	7,975	124	8,049	137	7,537	115	7,458	103	74.8
10	Pre	2,807	116	2,763	93	2,836	56	2,815	46	78.1
	Post									
11	Pre	9,144	193	9,105	227	9,149	188	9,075	134	74.6
	Post	6,786	89	6,681	91	6,663	117	6,490	134	74.9

[3] Daily kWh was set to zero for bins where the model would otherwise predict negative electricity consumption.

Adjustment for discretionary use of cooling system

Several sites (notably, Sites 1 and 7) showed evidence of discretionary use of the cooling system: i.e. there were some days where the system was used, and other days at comparable outdoor temperatures where the system was not used at all—presumably because the household chose not to operate it. In order to estimate as-used cooling electricity consumption, it is necessary to account for this phenomenon.

To accomplish this, a logistic model of cooling system use as a function of outdoor temperature was employed. Specifically, a binary variable was created with a value of zero if the daily cooling system electricity consumption was less than 2 kWh, and a value of unity if it was 2 or more kWh. A logistic model of the probability of using the cooling system as a function of outdoor temperature was then fit to the data:

$$\Pr(\text{AC use}) = 1/(1+e^{-(\beta 0+\ \beta 1T)})$$

where

Pr(AC use) ≡ probability that the cooling system will be used on a given day

T ≡ average daily outdoor temperature

The model provides an estimate of the proportion of days at any given outdoor temperature where the cooling system will be operated. This can be combined with the site-specific model of daily cooling kWh when the system is operated and the distribution of daily outdoor temperature to yield an adjusted estimate of seasonal cooling energy taking into account the fact that the system is not always operated.

Table B below shows the results of this analysis for sites and periods where there was a mix of days with and without cooling-system operation.

Table B6. Logistic model fits of cooling-system use, with unadjusted and adjusted estimates of seasonal electricity consumption.

			Logistic model fit				Estimated Apr-Oct cooling kWh		
Site	**Period**	**n**	**β_1**	**s.e. β_1**	**β_0**	**s.e. β_0**	**No adjustment**	**Adjusted**	**Ratio**
1	Pre	37	0.492	0.276	-40.5	23.0	1,082	570	0.53
	Post	17	0.540	0.446	-41.2	33.6	872	726	0.83
2	Post	18	0.648	0.202	-49.0	15.3	1,453	1,197	0.82
5	Post	93	0.749	0.724	-50.7	50.9	3,669	3,656	1.00
6	Post	93	0.511	0.287	-34.6	20.3	2,091	2,071	0.99
7	Pre	8	0.151	0.126	-13.3	10.0	4,127	1,030	0.25
	Post	46	0.398	0.141	-30.9	11.1	4,079	2,594	0.64
9	Post	98	0.961	0.442	-64.4	30.1	7,975	7,964	1.00
11	Post	86	0.131	0.028	-8.8	2.1	6,786	6,331	0.93

Note: sites and periods not shown had cooling-system use for all observed days, which precludes fitting a logistic model of use.

Whole-House Electricity Consumption

Although in theory the whole-house monitoring data could include electric space heating consumption as well as cooling consumption, in the monitoring period for the study was such that only non space-conditioning and cooling loads were present. Further, as noted previously the pre-weatherization data were inadequate for distinguishing cooling loads from non space-conditioning loads due to a lack of days without cooling consumption. The model for whole-house, post-weatherization electricity consumption used here is thus:

$$\text{daily whole-house kWh} = \beta_1 * CDD_\tau + \beta_0 + \varepsilon$$

where

$CDD_\tau \equiv$ cooling degree days to reference temperature, τ, or

$T_o - \tau$ (for $T_o > \tau$)

0 ($T_o \leq \tau$)

Here, τ represents the cooling-system balance point temperature, β_1 is the cooling slope term (kWh of cooling per degree of outdoor temperature, and β_0 is the estimated base (or non-cooling) electricity consumption.

The model was fit by iteratively stepping through integer values of τ from 50F through 85F, and selecting the fit with the highest r^2. Seasonal cooling consumption was then estimated by applying β_1 to long-term (1993-2012) April-October cooling-degree days for the associated local weather station. Standard errors were estimated using the bootstrap procedure described above.

Results are shown in the table below.

Table B7. Model fits and estimated seasonal cooling consumption for daily, post-weatherization whole-house electricity consumption.

	Weather normalization model								Estimated PostWx seasonal cooling electricity	
Site	**n**	**τ**	**s.e.**	**β_1**	**s.e.**	**β_0**	**s.e.**	**r^2**	**kWh**	**s.e.**
1	52	73	1.86	1.10	0.37	5.2	0.3	0.720	760	96
2	51	72	1.69	1.66	0.37	9.8	0.3	0.833	1,319	125
3	51	66	1.85	1.64	0.25	7.1	0.6	0.824	2,512	205
5	96	73	1.90	1.98	0.46	29.6	2.1	0.424	1,901	386
6	94	73	3.06	2.56	0.75	17.3	3.3	0.378	2,468	661
8	95	63	9.98	2.00	15.6	33.2	14.7	0.268	5,761	2,931
9	118	59	3.44	2.16	0.09	28.0	7.1	0.857	12,247	1,514
11	100	70	1.89	1.79	0.10	31.2	1.7	0.950	6,084	390

Utility Billing data

The model for pre-weatherization electricity consumption from utility billing data is:

monthly whole-house kWh = β_1*$CDD_{\tau c}$ + β_2*$HDD_{\tau h}$ + β_0 + ε

where

$CDD_{\tau c}$ ≡ cooling degree days to reference temperature, τ_c, or

$T_o - \tau_c$ (for $T_o > \tau_c$)

1 ($T_o \leq \tau_c$)

$HDD_{\tau h}$ ≡ heating degree days to reference temperature, τ_h, or

$\tau_h - T_o$ (for $T_o < \tau_h$)

0 ($T_o \geq \tau_h$)

Note that the HDD term—which models heating consumption—is only implemented if the home has some form of electric heat. The model is fit by iteratively fitting linear regressions over a range of τ_c and τ_h (subject to the constraint $\tau_c \geq \tau_h$), and choosing the value with the highest r^2 statistic. Seasonal normalized cooling energy consumption is then estimated by multiplying the β_1 term by long-term average cooling degree days (April-October) for the associated weather station.

Two sets of estimates were developed for each site: the first looked at only the most recent 12-month period prior to weatherization; the second used all available data. Scatter plots of the monthly consumption histories are shown in Figure B1. Normalization results for the sites with are provided in Table B8.

Table B

Table B8. Weather-normalization fitted parameters for pre-weatherization monthly utility billing histories, with estimated normalized April-October cooling kWh.

		Weather-normalization model							Estimated PreWx seasonal cooling kWh
Site	Run	n	τ_c	β_1	τ_h	β_2	β_0	r^2	
1	1yr	13	80	1.88			5.74	0.899	369
	All	39	77	1.38			7.14	0.537	498
2	1yr	13	76	2.59			16.72	0.900	1,118
	All	22	72	1.93			16.88	0.731	1,521
3	1yr	12	69	2.60			13.90	0.983	2,941
	All	44	69	2.57			14.28	0.963	2,903
4	1yr	13	63	1.83	63	1.65	20.31	0.725	3,589
	All	42	72	1.98	55	1.97	33.40	0.853	1,565
5	1yr	12	68	3.60			37.54	0.916	6,699
	All	20	65	3.96	65	2.63	21.42	0.920	9,742
6	1yr	12	75	2.33	53	19.94	35.61	0.884	1,496
	All	20	65	1.61	65	4.83	24.57	0.899	3,972
7	1yr	12	80	15.98	66	2.84	30.23	0.949	1,729
	All	21	80	14.43	58	7.70	31.79	0.944	1,561
9	1yr	13	64	2.18	52	13.14	49.65	0.959	10,032
	All	34	69	2.63	57	1.87	51.80	0.961	9,459
10	1yr	13	75	1.84			8.39	0.990	4,548
	All	34	75	1.68			10.86	0.968	4,136
11	1yr	13	74	2.89			36.70	0.973	7,661
	All	29	74	3.11			31.37	0.943	8,224