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BUILDING TECHNOLOGIES PROGRAM

Field Evaluation of Programmable Thermostats

O. Sachs, V. Tiefenbeck, C. Duvier, A. Qin, K. Cheney, C. Akers, and K. Roth
Fraunhofer CSE

December 2012

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U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Field Evaluation of Programmable Thermostats

Prepared for:

The National Renewable Energy Laboratory

On behalf of the U.S. Department of Energy's Building America Program

Office of Energy Efficiency and Renewable Energy

15013 Denver West Parkway

Golden, CO 80401

NREL Contract No. DE-AC36-08GO28308

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Prepared under Subcontract No. KNDJ-0-40345-00

December 2012

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Definitions

BA	Basic (low usability thermostat)
CSE	Center for Sustainable Energy Systems
DOE	U.S. Department of Energy
EIA	DOE Energy Information Administration
LBNL	Lawrence Berkeley National Laboratory
RH	Relative humidity
VP	VisionPro (high usability thermostat)

Executive Summary

In this study, a team from Fraunhofer Center for Sustainable Energy Systems (CSE) evaluated a low-cost and scalable way to reduce heating energy consumption using the energy-saving features of programmable thermostats (i.e., automatic daytime and nighttime setbacks). Even though these functions are available in most programmable thermostats, previous research at the Lawrence Berkeley National Laboratory (Meier et al. 2011) suggests that poor usability features of this product class could prevent their effective use, leaving their energy savings potential unrealized. We hypothesized that home occupants with high usability thermostats are more likely to use them to save energy than people with a basic thermostat.

To test this hypothesis, we collected field data from 77 apartments in an affordable housing complex in Revere, Massachusetts, and applied a novel data analysis approach to infer occupant interaction with thermostats from nonintrusive temperature and furnace on–off state sensors. Our analysis of the data collected from January through March 2012 focused on four types of occupant interactions with thermostats that can lead to energy savings: nighttime setbacks, daytime setbacks, vacation holds, and reprogramming. Surprisingly, usability did not influence the energy saving behaviors of study participants. We found no significant difference in temperature maintained in apartments that had either high or low usability thermostats. The minimum and mean nighttime and daytime setback temperature was 70°F–71°F in both thermostat conditions—considerably higher than the energy saving default of 62°F.

We also found that the proportion of households that used thermostat-enabled energy-saving settings was very low. Only 3% of households used default nighttime setbacks, regardless of the thermostat usability. No households with high usability thermostats and only 3% of households with low usability thermostats used daytime setbacks. Although many households used the permanent hold feature, it was used to maintain a high temperature and not to keep it at a constant low level when the apartment was unoccupied. The few cases of reprogramming that we found seem incidental and do not involve any meaningful lowering of the temperature to save energy.

Although our results are limited to the specific study sample that we used, they demonstrate that thermal comfort is much more important to people than energy efficiency. This is particularly striking for affordable housing residents who pay their own heating bills. It implies that only people with a strong motivation to save energy or money or both can benefit from energy saving features of programmable thermostats. The rest of the population is likely to use them to maintain a comfortable temperature in their houses.

The results of this project support previous research by Nevius and Pigg (2000), showing that installation of programmable thermostats alone does not lead to reliable energy savings. Effective use of energy saving features enabled by programmable thermostats depends on many factors besides usability. Our study demonstrates that home occupants strive to achieve thermal comfort in their homes regardless of what thermostat model they have. Without motivation to save energy, high usability alone is not enough to facilitate the use of energy saving features in programmable thermostats.

Acknowledgments

We would like to thank all the people and organizations that contributed to this project:

- Alan Meier (Lawrence Berkeley National Laboratory) and Marco Pritoni (University of California, Davis) for inspiration, thermostat usability research insights, and advice on selecting the thermostats for the study
- Darien Crimmin and Eli Herman from Winn Residential for finding and making the Broadway Towers property available for the study, supporting the deployment process, and supplying all relevant information about the building for the data analysis
- Marisa Cummings from the Broadway Towers for supporting the project daily and resolving any site and resident logistical issues
- Fraunhofer CSE interns and employees Tony Fontanini and Linda Mayer, who contributed to parts of the project
- Bryan Urban and Diana Elliott of Fraunhofer CSE for the building envelope analysis.

Finally, we are grateful to all residents of Broadway Towers for participating in the project, using their new thermostats, filling out surveys, and sharing their life philosophies and poetry with us on occasion.

1 Introduction

1.1 Background

Programmable thermostats have a high potential for saving energy. First, unlike several new categories of home energy management technologies, thermostats are already available to the majority of U.S. households. For example, 48% of U.S. households use a manual thermostat and 37% use a programmable thermostat for heating (Energy Information Administration [EIA] 2009). Second, programmable thermostats have been on the market for decades and have reached considerable technical maturity, which makes them a low-cost and low-risk investment for energy efficiency. Finally, and most important, building performance models developed in 1970s and 1980s suggest that each degree of reduction in daily nighttime temperature setback can result in approximately a 3% reduction in heating energy use, making a convincing case for the energy savings potential of programmable thermostats (Nelson and MacArthur 1978).

In 1995 the EPA established the ENERGY STAR programmable thermostat program to promote these devices as a way to save energy. EPA suggested that homeowners could save as much as $180 a year with a programmable thermostat that had default energy saving and comfort set point settings among its required features (EPA 2009). The mere availability of energy saving features, however, is not sufficient to achieve estimated energy savings. These are only possible if homeowners actively program thermostats and select settings that result in energy savings (e.g., daytime and nighttime setbacks). First anecdotal and then empirical evidence demonstrated that programming a thermostat is not a trivial task (Meier et al. 2011). A typical programmable thermostat has schedules for weekdays, weekends, and vacations, in addition to a hold or override option. Programming complexity is further exacerbated by buttons and fonts that are too small, abbreviations and terminology that are hard to understand, and lights and symbols that are confusing, as well as by illogical positioning of interface elements (Meier et al. 2011). On a more general conceptual level, people have many misconceptions about energy and thermostats. They may believe, for example, that heating all the time is more efficient than turning the heat off, that a thermostat is simply an on/off switch, that a thermostat is a dimmer switch for heat, or some combination (see, for example, Kempton 1986). Energy savings, then, ultimately depend on occupant behavior and whether home occupants are motivated to program their thermostats and capable of doing it when necessary.

Empirical studies of energy savings associated with programmable thermostats revealed conflicting results: some showed savings in heating energy consumption resulting from an upgrade from a manual to a programmable thermostat; others found no such savings, or even increases in energy consumption in homes that relied on programmable thermostats. On one hand, a survey and a gas bill analysis of 7,000 households that installed ENERGY STAR-rated programmable thermostats found a 6% reduction in total household annual gas consumption (RLW Analytics 2007). On the other hand, a study of 299 households in Wisconsin showed that installing programmable thermostats alone did not lead to energy savings (Nevius and Pigg 2000). Residents who practiced regular setbacks did it regardless of thermostat type—programmable or manual. Residents who did not use their manual thermostat for saving energy did not start doing so once their manual thermostat was replaced with a programmable model. This study has made a convincing argument that behavioral factors play a decisive role in effectiveness of thermostats for saving energy. Combined with the work of Meier and colleagues

(2011), all these findings suggest that people find programmable thermostats difficult to understand and use, calling into question the effectiveness of thermostats for saving energy.

1.2 Thermostat Usability

Since the end of 2009, the research focus has shifted toward usability of programmable thermostats. The ENERGY STAR Program started developing new specifications, focused on usability, for climate control devices. Program administrators began operating under one main assumption—that improved usability will facilitate energy saving behavior, enabling people to use the energy saving features of thermostats (EPA 2011).

Alan Meier and his colleagues at Lawrence Berkeley National Laboratory (LBNL), the University of California, Davis, and the University of California, Berkeley, have led the research to develop a reliable methodology to measure thermostat usability and to understand the variability in ease of use among currently available thermostats. In their laboratory, these researchers developed a testing protocol for evaluating the usability of thermostat interfaces and tested five thermostat models in a series of six tasks (Meier et al. 2011):

- Task 1: Turn the thermostat from "off" to "heat."
- Task 2: Set the correct time on the thermostat clock.
- Task 3: Identify the temperature the device is set to reach.
- Task 4: Identify what temperature the thermostat is set to reach on Thursday at 9:00 p.m.
- Task 5: Put the thermostat in "hold" or "vacation" mode to keep the same temperature during a human absence.
- Task 6: Program a schedule and temperature preferences for Monday through Friday.

Twenty-nine participants representing varied occupations and backgrounds (e.g., construction workers, business managers, nonprofit staffers, maintenance workers, and students) were asked to complete the tasks without any previous training. Notably, the majority of participants had "low" to "moderate" previous experience with programmable thermostats. Participants were videotaped and their behavior was measured using the following usability metrics:

- Success or failure in accomplishing the task
- Elapsed time to accomplish the task
- Number of times buttons were pushed (or other actions)
- Sequence of actions
- Hesitations and comments of users.

The results of the study revealed a wide range in the usability of tested programmable thermostats. All of the metrics used consistently produced sufficient ranges in results to demonstrate the robustness of the task-based approach to measuring usability. A wi-fi enabled thermostat with a Web interface and a touch-screen thermostat were clearly superior to other tested thermostats on Tasks 1, 3, and 4, from Meier et al. 2011.

Results of this research demonstrate that usability is an important factor affecting user experience with programmable thermostats (Meier et al. 2011). Significantly, it influences an individual's ability to operate the functions that are essential for achieving energy savings, suggesting that usability might play a key role in determining the effectiveness of programmable thermostats for saving energy. No existing research, though, has focused on testing this hypothesis and collecting field data to evaluate the impact of thermostat usability on encouraging energy saving behaviors of thermostat users. Closing this critical gap in existing knowledge is the main objective of this project.

1.3 Relevance to Building America's Goals

Evaluation of energy savings from high usability programmable thermostats is highly relevant to the goals of the U.S. Department of Energy's Building America Program. Energy savings resulting from automatic setbacks (~6%; RLW Analytics 2007) can substantially contribute to the program's overall 30%–50% energy reduction goal. Results of this project will contribute to development of usability specifications for programmable thermostats for the ENERGY STAR certification of this product class. More than 33 million of U.S. households in all climate zones have a programmable thermostat. Survey results suggest that 14.5 million of these households do not currently use their thermostat for daytime setbacks and 11.6 million do not use nighttime setbacks (DOE/EIA 2009). The successful outcome of this project, then, could be scaled quickly to millions of homes in the United States.

2 Experiment

2.1 Research Question

We designed this project to answer the following research question:

> Are people with a high usability thermostat more likely to use energy saving features than people with a low usability thermostat?

We have defined the following energy saving features in a programmable thermostat that can be used to reduce heating energy consumption: **nighttime setbacks**, **daytime setbacks**, **permanent vacation holds,** and **reprogramming** involving lowering of the temperature. In this project, we focused mainly on identifying how owners of high and low usability thermostats used these features.

In addition to investigating the impact of usability on these metrics, we explored users' subjective satisfaction with high and low usability thermostats to evaluate whether satisfaction is related to effective use of energy saving features.

2.2 Experimental Design

2.2.1 Thermostat Models Used

Selecting the thermostats to be tested was a key component of the experimental design. Based on LBNL thermostat usability research (Meier and Aragon 2010), we selected two programmable thermostats for testing. The high usability thermostat that we chose is the VisionPRO TH8000 by Honeywell; the low usability thermostat is the RTH221B – a basic programmable model by the same manufacturer. Both thermostats control the gas furnace and the central air conditioner, have identical program default settings and similar aesthetic qualities.

In this report, we refer to the high usability thermostat as VP (VisionPro) and the low usability thermostat as BA (basic).

2.2.2 Default Schedule and Possibilities for User Interventions

Importantly, both thermostats had identical default energy saving schedules (see Figure 1). New thermostats are shipped with these factory settings. During the heating season, the temperature set point is 70°F from 6:00 a.m. to 8:00 a.m. and from 6:00 to 10:00 p.m. During the other times of the day, the default set point is 62°F. This means that during those times, the furnace was active only when the temperature in the apartment fell below 62°F—unless it was manually overridden by the users.

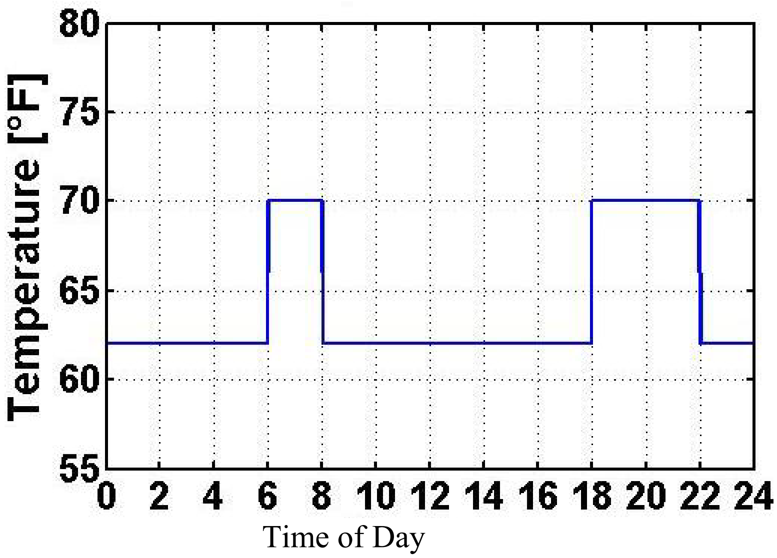

Figure 1. Default settings for the Honeywell VisionPro TH8000 and the Honeywell RTH221B

Users have several ways to make changes to this default schedule. These adjustments can be put into three categories:

- **Manual override** (one-time). The thermostat holds the temperature that the user puts in until the next set point change is scheduled. For example, for the default schedule, if a user manually sets the thermostat to 72° at 1:00 p.m., this temperature will be maintained until 6:00 p.m. when the set point changes to 70°F according to the default schedule.
- **Permanent hold** ("cruise control"). The current temperature set point is maintained until the permanent hold mode is suspended by pressing "Run" button.
- **Reprogramming.** Most users' daily schedules do not exactly match the preset times of the default program. Users can modify the automated schedule of the device to adjust set point temperatures and times to meet their daily schedule and comfort preferences. For instance, a household could program the thermostat to keep the apartment at 72°F at night between 5:00 p.m. and midnight or to set back the temperature to 64°F between 11:00 p.m. and 7:00 a.m. every day.

2.2.3 Design

In the study, households were randomly assigned to the high and low usability thermostat conditions. This ensured that any differences found in occupants' interaction with thermostats were attributable to the main factor—usability. The main dependent variable measured in the study was the percentage of households in each usability condition that used energy saving features of thermostats. Other dependent variables used were weekly gas consumption data and self-reported survey data. The surveys asked about home occupants' demographics, satisfaction with the previous thermostats, thermostat usage patterns, and comfort levels in their apartments.

2.3 Field Deployment

2.3.1 Test Site and Recruitment

We recruited households to participate in the study from a 96-unit multifamily building in Revere, Massachusetts (see Figure 2). Figure 3 shows one of the floors on the building plan. The building is heated with natural gas and residents pay for their heating consumption.

The project and all project materials were approved by the Central Department of Energy Institutional Review Board for human subject participation under the expedited review category 10 CFR 745.110(b)(1). Appendix A contains the approval letter.

We used an opt-out scheme to recruit residents for the study starting in October. All but ten residents agreed to participate in the study. Most residents in the building have low incomes and no Internet access (90% of residents without Internet). This precluded any possibility of using a wi-fi thermostat model.

Figure 2. 250 Broadway Tower, Revere, Massachusetts

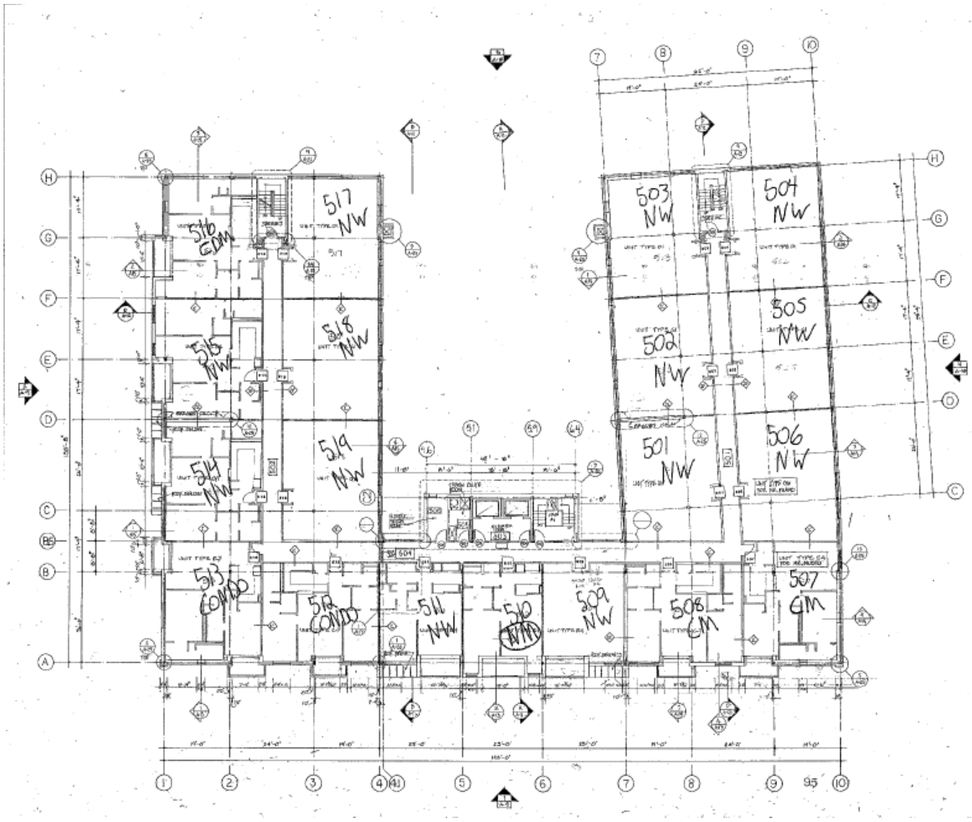

Figure 3. Floor 5 of the building where thermostats and data acquisition devices were installed. The two condo units were left out of the study.

2.3.2 Deployment Process

Thermostat installation began on December 15, 2011, and was completed on January 11, 2012. The data collection period ended in the last week of March 2012. The thermostats and data acquisition devices were installed at the same time as other energy efficiency upgrades (furnace/air-conditioner replacement and the insulation of the back wall in the utility closets). The Fraunhofer deployment team worked in parallel with the weatherization company team as they went into each apartment to complete their work. Weatherization work shifted the residents' attention away from thermostat installation, making it unlikely that thermostat behavior changes were observed just because something new was installed in the units.

The property managers gave access to each apartment; in most cases, the thermostat installations were coupled with other work undertaken in the apartments to minimize disruption to residents. Where residents were not present, all additional materials, namely the survey, the thermostat manual, and an informational flyer, were left in a highly visible place; otherwise residents received additional material personally. To collect energy consumption data, we read gas meters for all apartments once a week.

In addition to installing thermostats and the data acquisition devices, we collected subjective data via a standard survey instrument (see Appendix B). At the end of the study another survey was conducted that assessed self-reported use patterns, as well as residents' satisfaction with the thermostats (see Appendix C).

2.4 Data Acquisition

2.4.1 Data Acquisition Equipment Deployed

Besides thermostats, two types of data loggers were installed in every participating apartment: one to collect temperature and relative humidity (RH) data at 10-min intervals, and one to track the change of the furnace state (0 = on, 1 = off). Table 1 gives more details about the equipment used.

Table 1. Equipment Deployed for Sensing and Data Acquisition

Measurement	Equipment Used
First Zone Temperature	**HOBO U12-011 Temp/RH:** A two-channel electronic device that measures and logs temperature and RH. It features high-accuracy internal sensors and 12-bit resolution, and is capable of storing 43,000 samples. We programmed it to start at midnight on the day of installation and set the rate of sampling to 10 min.
HVAC State Data Logging	**CSV-A8 Current Switch:** A split-core inductance-based alternating current sensor with adjustable threshold switch. The switch outputs a signal when current flowing through the equipment reaches the desired threshold. The switch also outputs a different signal when the current flowing through the equipment falls below the desired threshold. **HOBO U9 State Data Logger:** A single-channel recording device that detects and logs on/off changes in the desired appliance. The device can store up to 43,000 state changes. The state data logger is attached to the current switch, and detects state changes from the current switch with 1-s resolution. We programmed it to start at midnight on the installation date of the thermostats for each apartment.

2.4.2 Participation and Attrition

Of the 96 apartments in the building, five were owner-occupied and did not participate in the study. Eight apartments opted out before the deployment started. One thermostat was used in the property management's office; three more apartments were empty during the study period. Residents of one apartment asked to have the old thermostat back and in another unit the old thermostat was never replaced. Fourteen apartments had sensor issues, with either the state data logger or the temperature data logger not working correctly (see Figure 4).

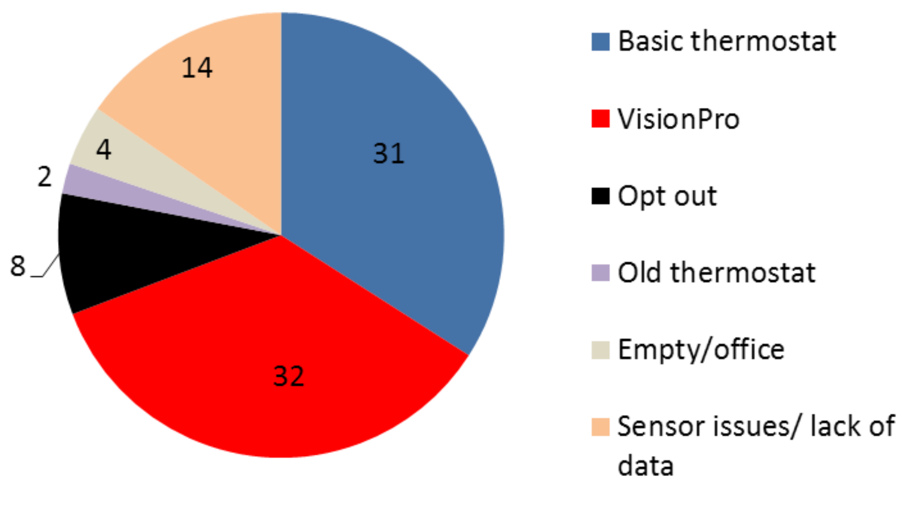

Figure 4. Participation and attrition rate in the study

We asked residents of all apartments where new thermostats were deployed to participate in a pen-and-paper survey. All those who filled out a survey took part in a raffle for gift cards at local supermarkets. There were two rounds of surveys. The first round took place when thermostats were first installed (December–January) and the second round occurred when thermostats had been in place for at least 3 months (March–April). In the first round, 33 residents filled out a survey, in the second round, 19 completed one. Of those, 13 residents filled out both surveys.

Both surveys consisted of demographic items, a five-point comfort scale (from very uncomfortable to very comfortable), and a short five-point behavioral scale (from never to very often). The second survey had additional yes/no format questions about the use of the thermostat, additional heating methods used, and an open-response segment asking about work and life schedule questions. Out of study participants who responded to the survey, 26 respondents were female and 7 were male. The average educational attainment of the sample was high school, with 46% of the sample having a high school education. Eighteen percent had received some schooling, and 36% had received professional certifications or higher education. Table 2 gives the rest of the demographic data.

Table 2. Demographics of Survey Participants

	Mean	Median	Range
Age	44	42	22–75
People in the Household	2	2	1–5
Children in the Household	0.6	0	1–5
People Older Than 60	0.2	0	0–2

To establish the comfort temperature range of the respondents, we asked them to indicate the range of temperature at which they feel the most comfortable in winter. Responses were elicited using an open-response format. Respondents from the first survey reported feeling comfortable at an average of 72°F (95% Confidence Interval = ±2.03). Respondents from the second survey indicated an average comfort level at 73°F (95% Confidence Interval = ±1.82).

2.4.3 Sensor Data Set Description

Two data sets were thus available from each participating apartment: 10-min data on temperature and RH from the HOBO U12-011 Temp/RH data logger (with time stamp), and event-based data from the state data logger that logged an entry (with time stamp) every time the furnace switched on or off.

In the first step of the analysis, we joined these two data sets. Figure 5 illustrates the results of this step in simplified form.

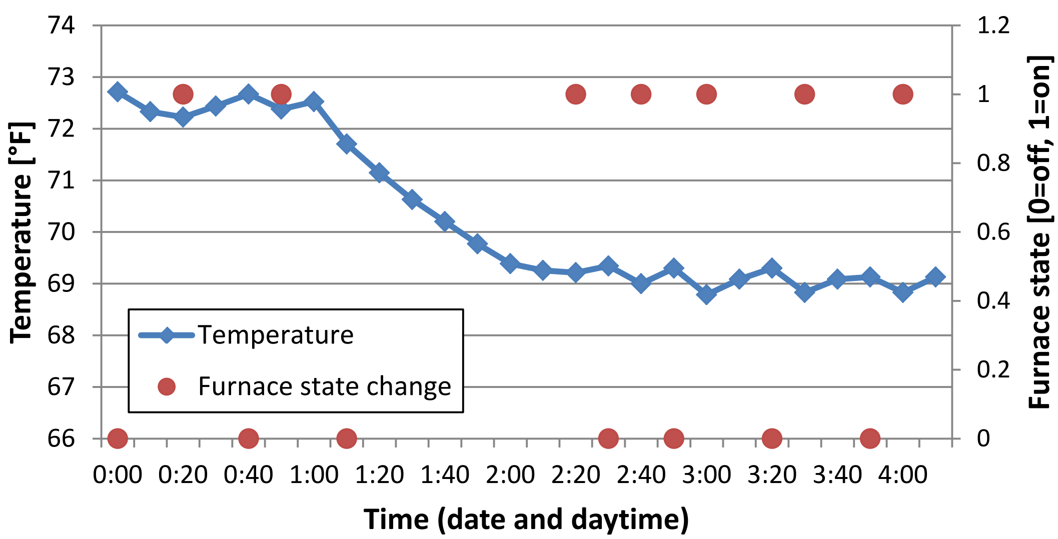

Figure 5. Simplified example of joint sensor data sets

Figure 6 shows an actual apartment's combined data set. We can identify periods where the furnace is cycling to maintain a certain temperature level (orange and red circles around temperature data in black, underlain by green vertical lines where the furnace switches on and off). We can also detect set point changes, where the temperature falls (no furnace activity) until the new set point is reached (light blue circles for examples of set point changes toward the default temperature of 62°F).

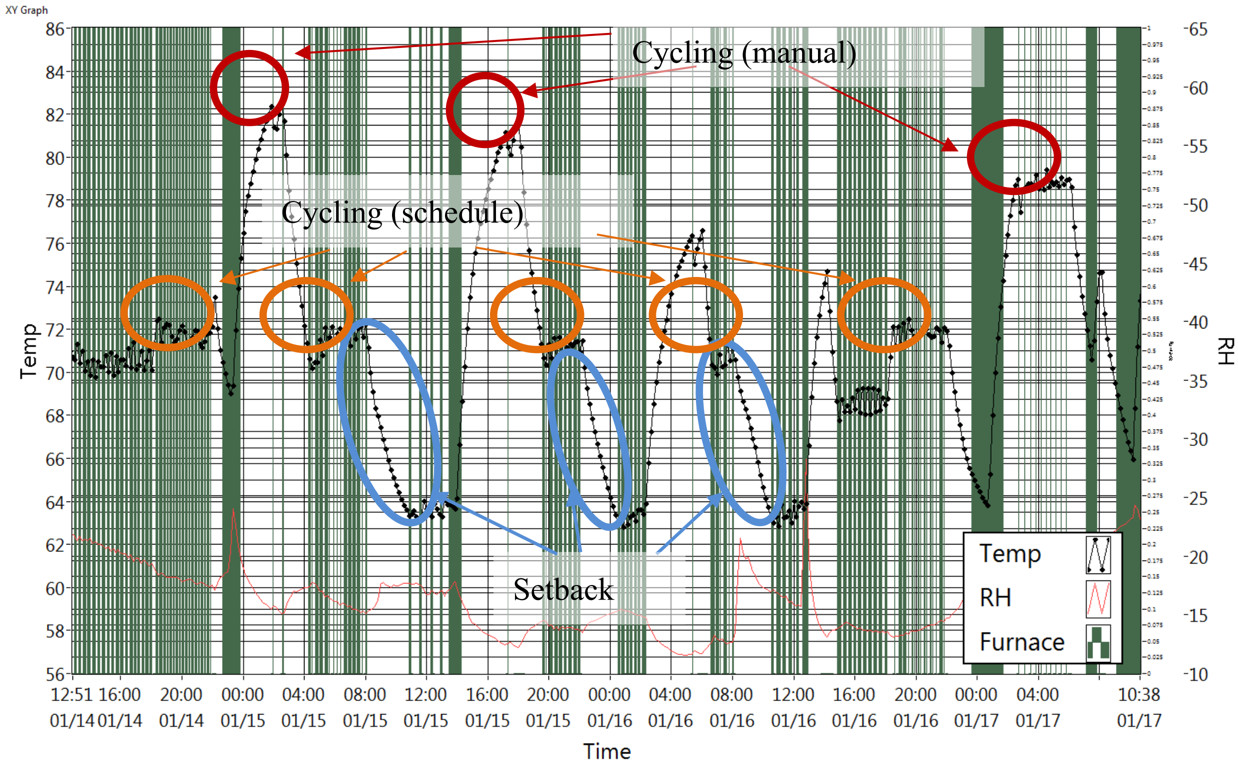

Figure 6. Example of apartment dataset and interpretation: Furnace activity (green lines) and temperature (black curve)

2.4.4 Sensor Data Retrieval

To download data from each individual HOBO sensor, we used the Hoboware Pro software from Onset Computer Corporation. After that, all further analyses were carried out in Matlab. We used three main files, with each calling several functions. The first main file generated a matrix for each apartment that contained information for each time stamp, furnace state, and temperature. These were saved into separate mat-files.

3 Results

3.1 Setback Analysis

One of the main arguments for using programmable thermostats is that they can meet occupant comfort preferences while they are present and awake, yet allow at the same time for energy savings while they are gone or asleep. By default, the thermostats were set up to allow colder temperatures (62°F) during night hours (10:00 p.m. to 6:00 a.m.) and during the day (8:00 a.m. to 6:00 p.m.). In the following analyses we define setback periods as the times when the temperature was at or below 62°F. We chose this definition to be consistent with the EPA-recommended factory settings for programmable thermostats (most programmable thermostats are sold with such settings).

3.1.1 Methodology

We decided to narrow the time windows for nighttime setback analysis to midnight to 4:00 a.m., and for daytime setback to 10:00 a.m. to 2:00 p.m. These hours are most representative for nighttime and daytime behavior. We left a 2-h buffer for a nighttime setback and a larger buffer (4 h) for a daytime setback because daytime schedules are more variable. We needed the buffer because VP thermostats show anticipation behavior: in heating mode (winter), they start to heat the space in advance to ensure that it *has reached* the desired higher temperature level at the time indicated for a higher temperature set point (in contrast, BA thermostats *start* heating at the time of the scheduled set point change). In addition, data between 10:00 p.m. and midnight can be affected by occupants staying up late; temperatures after midnight are more likely to be representative of nighttime settings. We applied the same 2-h buffer to the time window for daytime setback analysis.

Figure 7 illustrates the methodology used for setback analysis. The raw 10-min data from the temperature/RH files were filtered for the dates and buffered setback time windows (Step 2). For each apartment, we calculated the minimum and the mean temperature of this time window for every night (Step 3) and put these values into a list (Step 4). Thereafter, these mean and minimum values by apartment and by night could be averaged either by apartment for **cross-section analyses** or by dates for **time-series analyses** (Step 5).

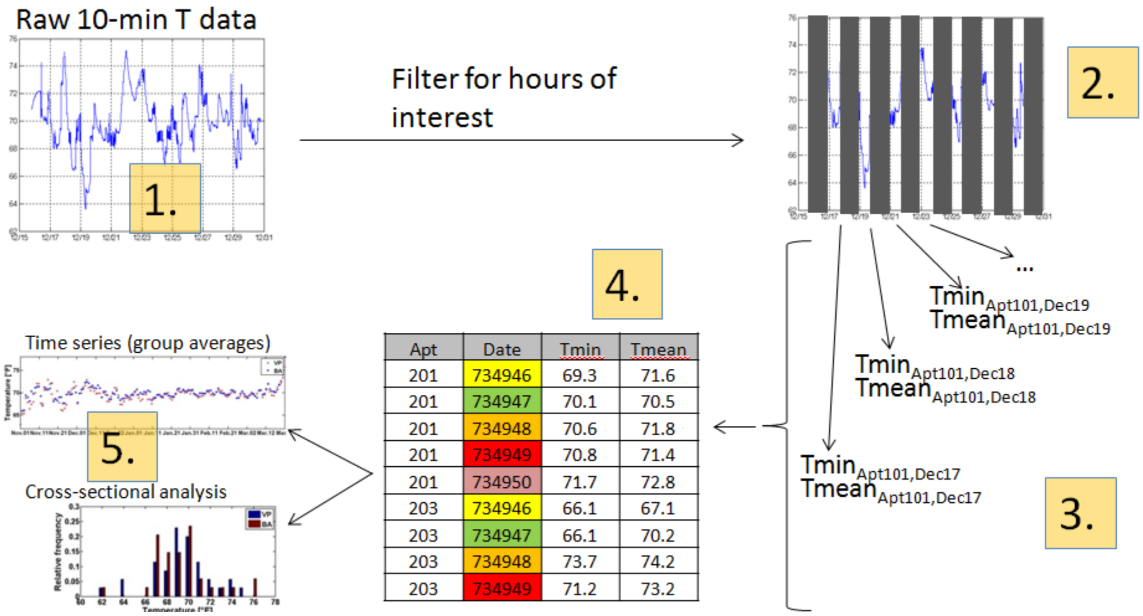

Figure 7. Illustration of setback analysis process. In Step 5 the data were clustered by date (time-series analysis) or by apartment (cross-sectional analysis).

Because outdoor temperatures increased considerably after March 6 (see Figure 8), we limited the data set to the period from January 12 to March 6, 2012. Temperatures were relatively mild for this time of the year in the Boston area. Consequently, on many days many apartments were able to maintain temperatures above 68°F or 70°F all night without any furnace activity. This, however, makes setback analyses more challenging because it is not possible to determine the temperature set point of these apartments for those nights without furnace activity.

As a result, more meaningful results can be obtained from nights/days where the mean temperature was below the freezing point (32°F). For the study period starting on January 12, this was the case for 22 nights. We calculated the minimum and mean apartment temperature for each of these nights (between midnight and 4:00 a.m.). Then we took the 22 minimum and mean values of each apartment and calculated the mean of these minimum and mean values, respectively, for each apartment.

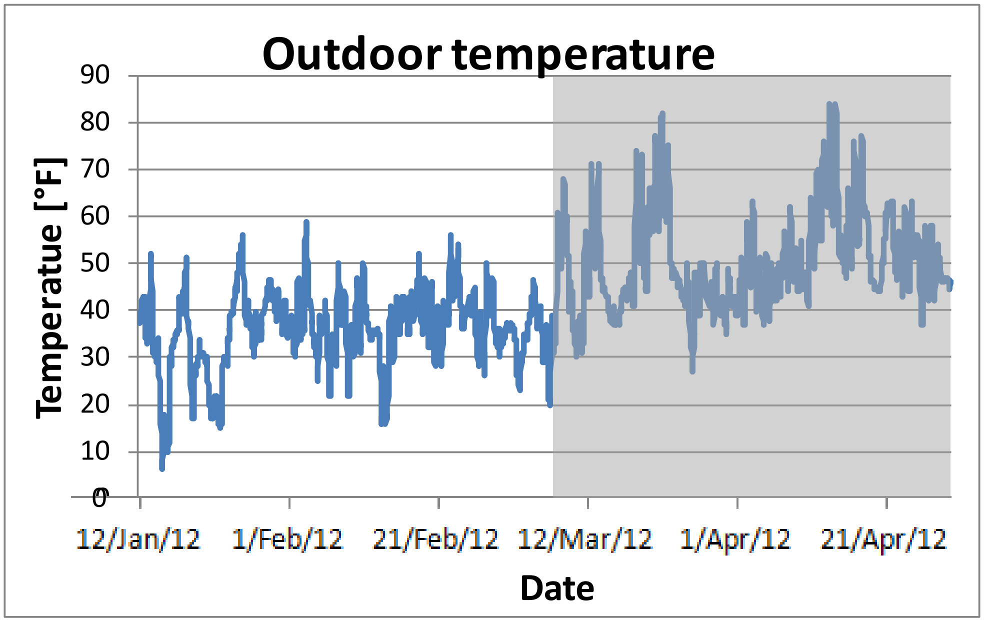

Figure 8. Outdoor temperature during the study.
The shaded area marks the period after the heating season.

As a first step in the analysis, we investigated how many apartments used thermostats effectively and had temperature setbacks similar to the default schedule and what percentage did not. We distinguished four different cases for this (Table 3).

Table 3. Setback Analysis Criteria

No Furnace Activity All Day and Night	Disregarded ("vacation")
Furnace on During Designated Hours, $T>T_{threshold (62°F)}$	No Setback
Furnace on During Designated Hours, $T<T_{threshold (62°F)}$	Setback
Furnace off During Setback Hours, but on at Other Times of the Day	Uncertain

We only analyzed cases where the furnace was active at least at some point during the day, to avoid the days when residents were gone.

Figure 9 shows the evolution of the temperature in the apartments over the course of the day. Data from all nights between January 12 and March 6 (the end of the heating period) were averaged on an hourly basis per apartment. Based on these hourly averages per apartment, we calculated the hourly group mean temperature. The graph also shows the confidence interval for each group (a standard deviation of the mean). The group mean temperature profile is very flat and the two groups show a very similar temperature profile, especially when compared with the default temperature profile.

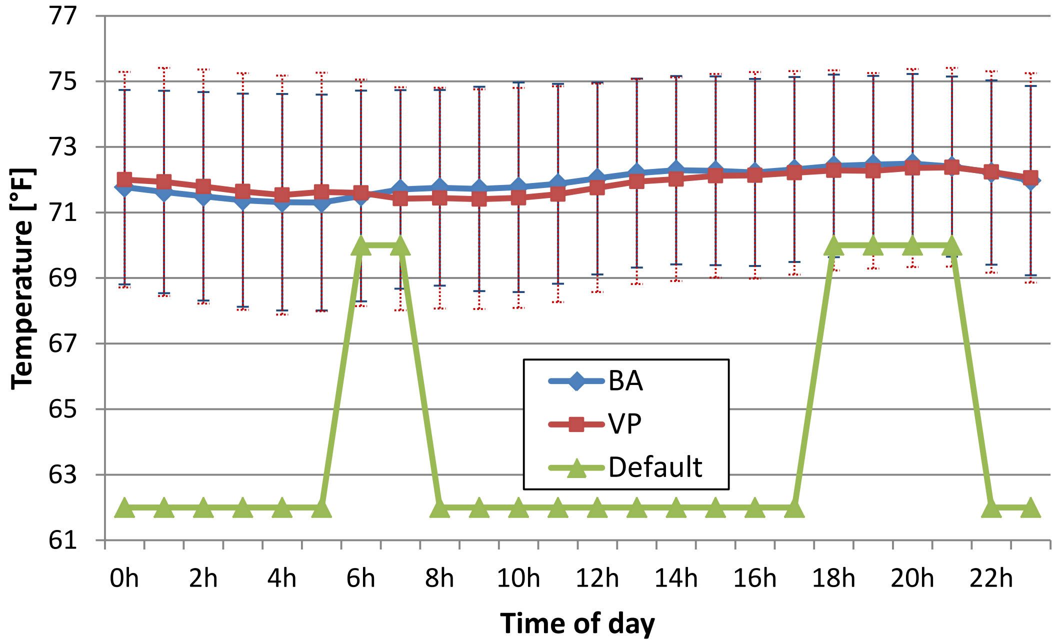

Figure 9. Hourly group mean temperature over the course of the day (averaged over all nights between January 12 and March 6)

3.2 Nighttime Setbacks

This section focuses on the results for nighttime temperature setbacks: what temperature was maintained in apartments overnight, how close it was to the energy saving default temperature, and what proportion of households used nighttime setbacks during the study. Nighttime setbacks represent the easiest opportunity to save energy because people would likely either be asleep or working a nighttime shift during that period.

3.2.1 Temperature: Time-Series Analysis

The goal of this analysis was to understand what temperature, on average, apartments in each thermostat condition had at night during the project period.

We conducted a time series analysis on the daily group averages of the minimum and mean apartment nighttime temperature (between midnight and 4:00 a.m.) over the study duration (Figure 10 and Figure 11, respectively). In contrast to the large oscillations of the outdoor temperature (Figure 9), we can see that the group means stay quite stable during heating season (ending around March 6) for both the minimum and the mean temperature. Both groups show very similar behaviors and trends and the mean temperature of both groups is clearly above 62°F on a day-by-day analysis.

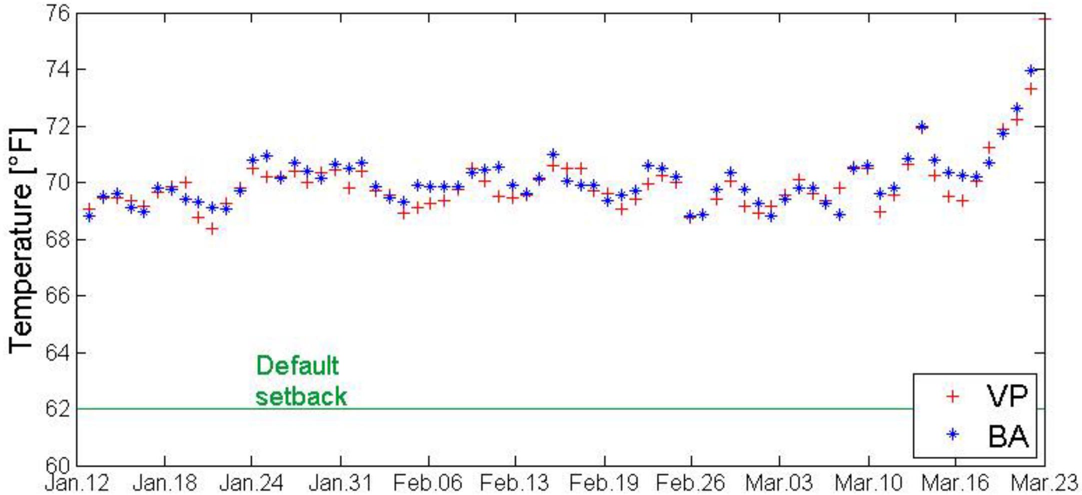

Figure 10. Minimum apartment temperature at night averaged by thermostat condition

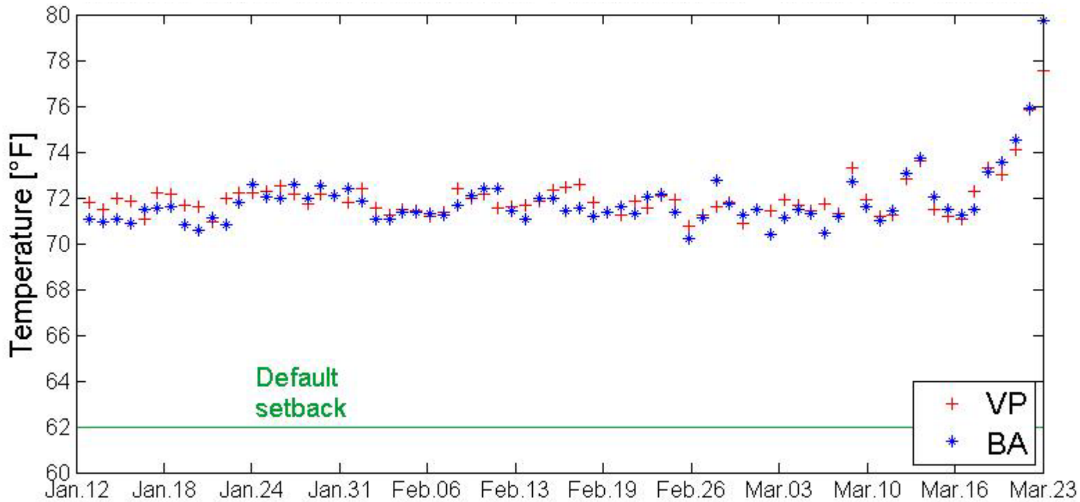

Figure 11. Mean apartment temperature at night averaged by thermostat condition

3.2.2 Temperature Cross-Sectional Analysis

The goal of this analysis was to understand how many apartments in each thermostat condition lowered the temperature for the night. As stated earlier, this analysis was limited to the 22 coldest nights of the heating season when the outside nighttime temperature fell below the freezing point. Figure 12 shows the percentage of all apartments that retained a low setback temperature on cold nights (as their average across all cold nights). It also shows what temperatures were kept by other apartments and illustrates the most common nighttime temperature. Figure 13 does the same for the minimum temperatures recorded inside the apartments on the coldest nights.

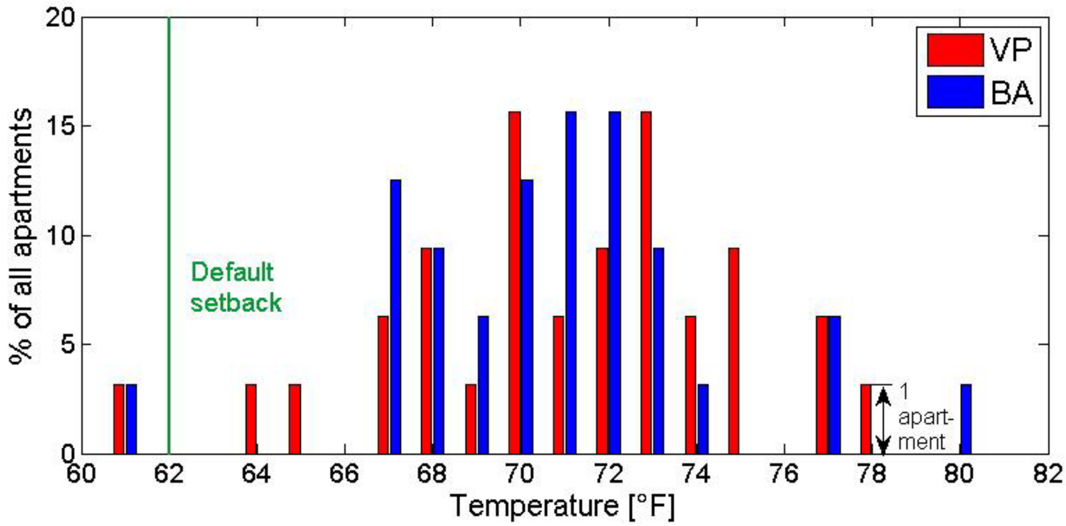

Figure 12. Mean apartment temperature for the nights below freezing point

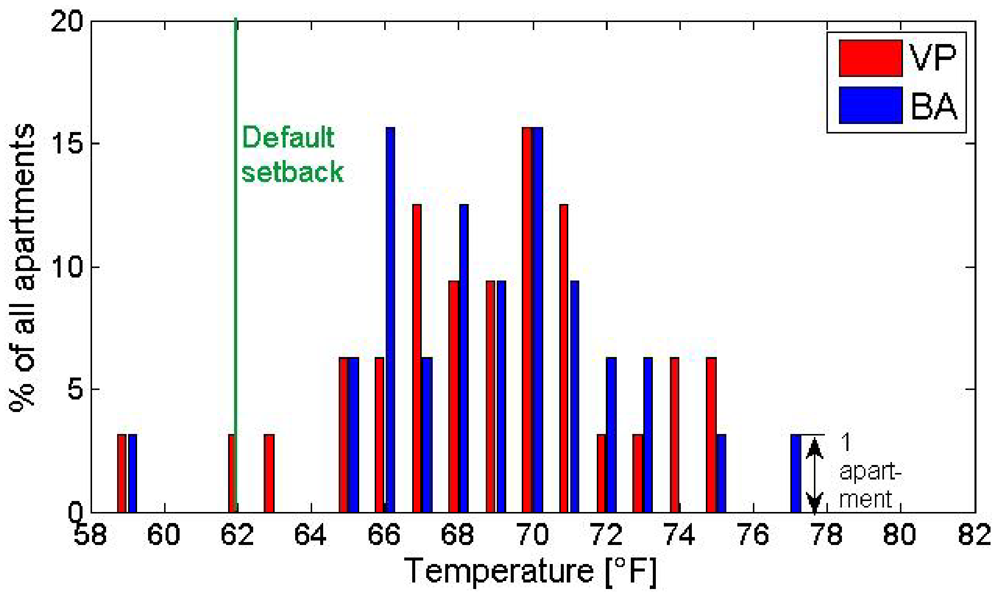

Figure 13. Minimum apartment temperature for the nights below the freezing point

Figures 12 and 13 illustrate two main findings: (1) there is no significant difference between the two thermostat conditions and (2) the vast majority of apartments did not use the default setback temperature.

Table 4 shows the mean and minimum apartment temperature during the nights below freezing point in two thermostat conditions. Both thermostat groups have similar values well above the default setback value of 62°F.

Table 4. Mean and Minimum Temperature Maintained in Low and High Usability Apartments at Nighttime (Midnight to 4:00 a.m.)

	Low Usability (BA)	High Usability (VP)
T_{mean} (°F)	71.6	71.2
T_{min} (°F)	69.4	69.5

Table 5 shows the compliance rate with the default settings. Only 3.1% of the high usability thermostat apartments had an average nighttime setback temperature at or below 62°F. This number was higher—6.25%—when only minimum nighttime temperatures were averaged across all cold nights. For the low usability group, the proportion of households who kept their apartments at or below 62°F remained the same—3.2%—whether the average or minimum temperature was considered.

Table 5. Percentage of Apartments in Low and High Usability Conditions That Used the Default Nighttime Temperature (62°F)

	Low Usability (BA)	High Usability (VP)
T_{mean} (°F)	3.2% (1 of 31)	3.1% (1 of 32)
T_{min} (°F)	3.2% (1 of 31)	6.25% (2 of 32)

3.2.3 Self-Reported Nighttime Setbacks

The observable data on the percentage of households who practiced nighttime setback are in stark contrast to self-reported data. In both in the initial and follow-up survey, more than 50% of survey respondents indicated that they practice nighttime setbacks occasionally, often, or very often (see Figure 14).

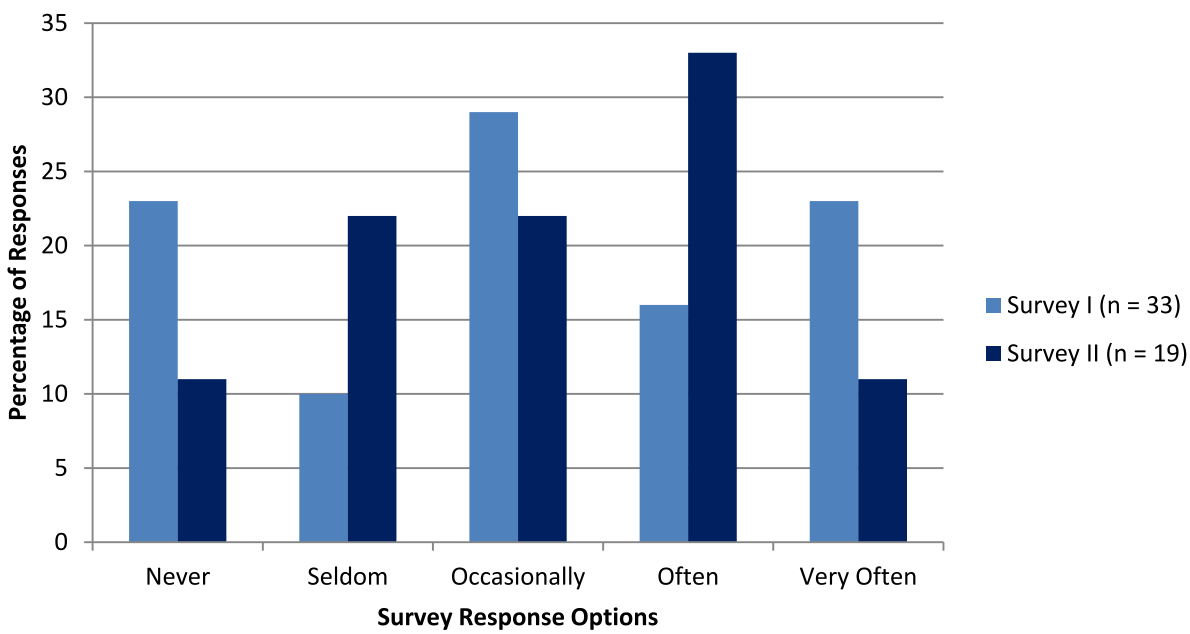

Figure 14. Percentage of households who reported nighttime setbacks

3.3 Daytime Setbacks

We also analyzed setback behavior during the daytime (10:00 a.m. to 2:00 p.m.) for the entire study period and for the coldest days (below the freezing point). The goal was to identify both the temperature that was maintained in the apartments during the setback period and how many households used daytime setbacks during the study. In this period the average outdoor air temperature was 35.8°F, or 5.5°F warmer than the typical Boston average of 30.2°F.

3.3.1 Temperature: Time-Series Analysis

As in the nighttime setback section, the goal of this analysis was to understand what temperature, on average, apartments in each thermostat condition had during the day throughout the project period. Again, the vast majority of apartments do not use default temperature settings.

Figure 15 shows the daily group means of the minimum temperature between 10:00 a.m. and 4:00 p.m. in each apartment over time. Figure 16 shows the group means of the average apartment temperature. Similar to nighttime behavior, temperatures are quite stable. Both group means are well above the 62°F default setback temperature.

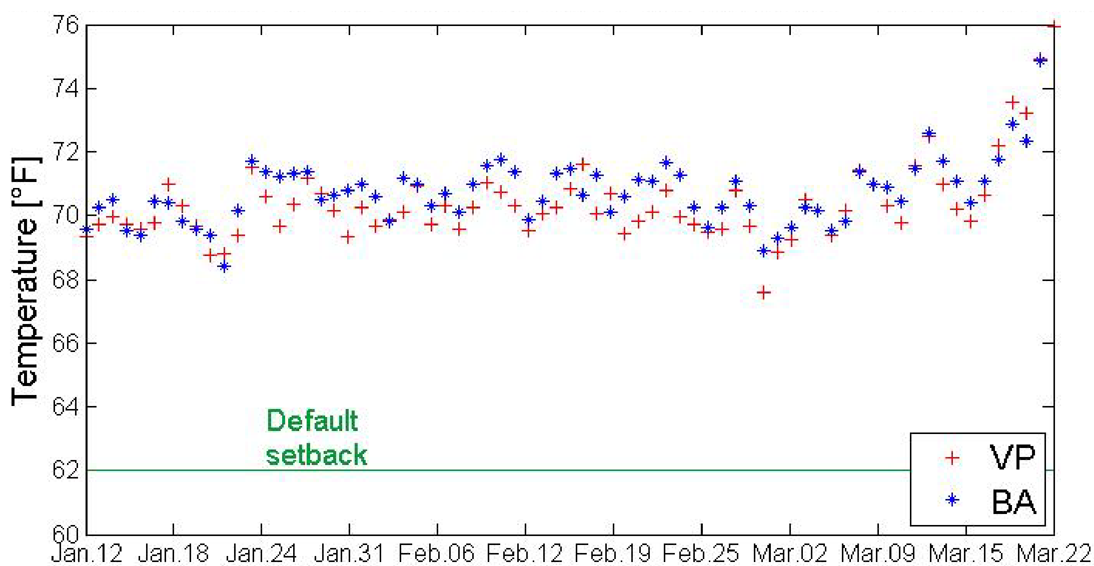

Figure 15. Minimum apartment temperature during the day, averaged by thermostat condition

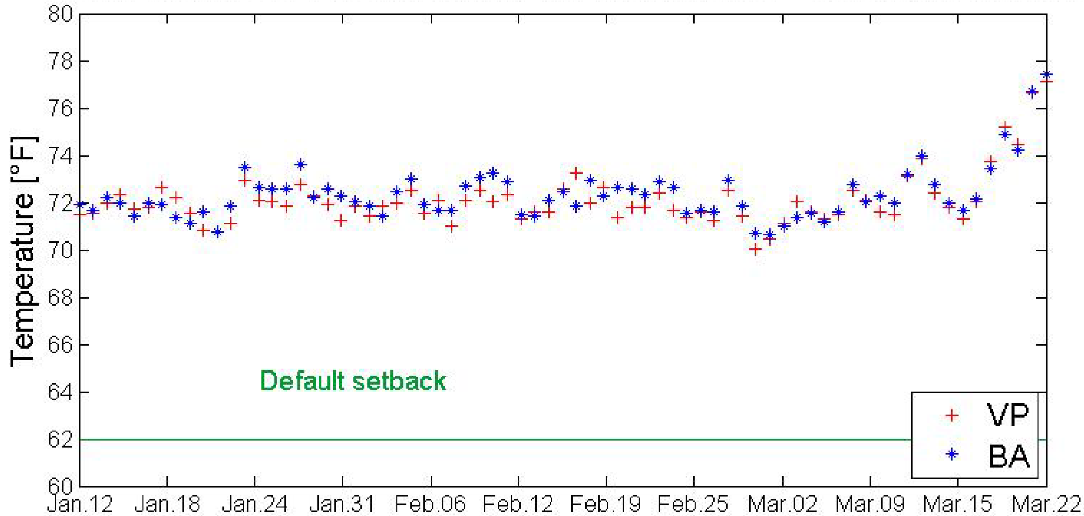

Figure 16. Mean apartment temperature during the day, averaged by thermostat condition

3.3.2 Temperature Cross-Sectional Analysis

The goal of this analysis was to understand how many apartments in each thermostat condition lowered the temperature during the day. Figure 17 shows the percentage of all apartments that retained a low setback temperature on days below the freezing point (as their average across all cold days). It also shows what temperatures were kept by other apartments, along with the most common daytime temperature. Figure 18 does the same for the minimum temperatures recorded inside the apartments on the coldest days.

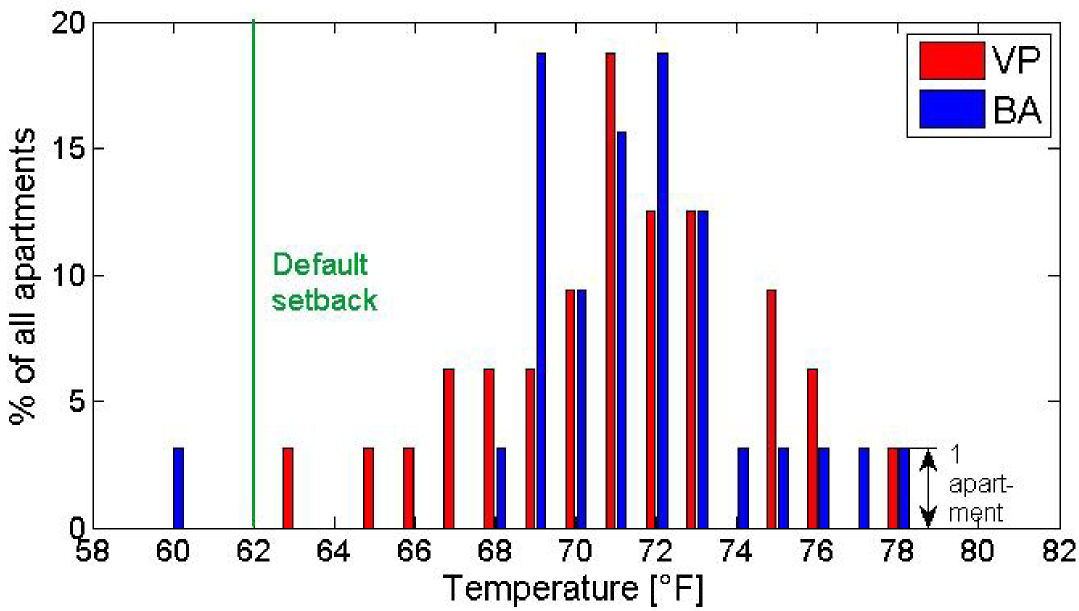

Figure 17. Mean apartment temperature for the days below the freezing point

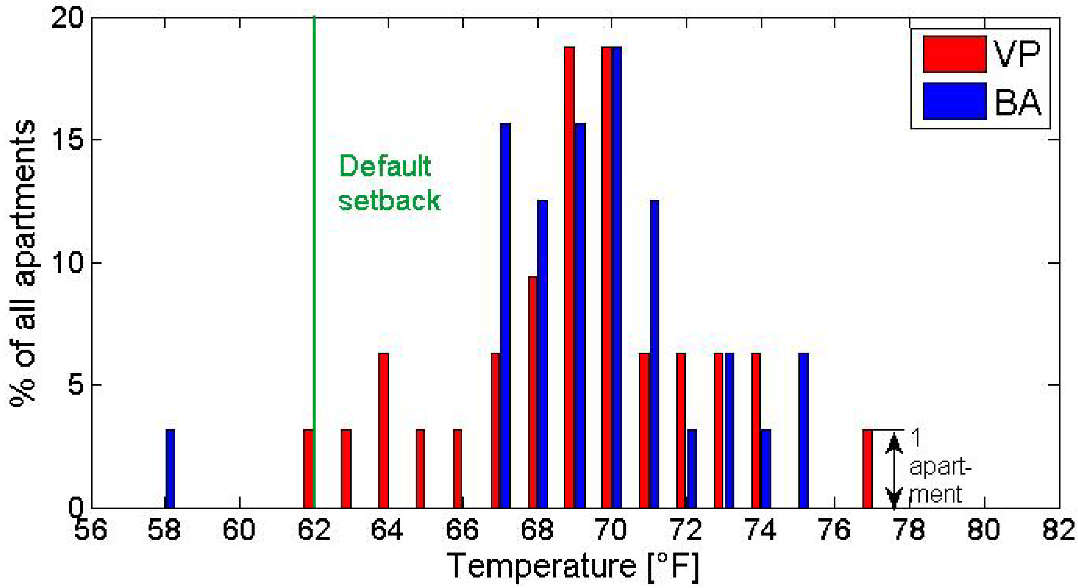

Figure 18. Minimum apartment temperature for the days below the freezing point

The group average of the mean daytime temperature (10:00 a.m. to 4:00 p.m.) during those days was very similar for both groups and far above the default setback temperature: 71.8°F for low usability apartments and 71.6°F for high usability apartments (Table 6). The use of the default settings in the course of the day was even lower than with default night setbacks (Table 7).

Table 6. Mean and Minimum Temperature Maintained in Low and High Usability Apartments during the Day (10:00 a.m. to 4:00 p.m.)

	Low Usability (BA)	High Usability (VP)
T_{mean} (°F)	71.8	71.6
T_{min} (°F)	70.1	69.7

Table 7. Percentage of Apartments in Low and High Usability Conditions That Used the Default Daytime Temperature (62°F)

	Low Usability (BA)	High Usability (VP)
T_{mean} (°F)	3.2% (1 of 31)	0%
T_{min} (°F)	3.2% (1 of 31)	3.1% (1 of 32)

3.3.3 Self-Reported Daytime Setbacks

As with nighttime setbacks, there is a gap between observable and self-reported data. More than 60% of respondents to the first survey indicated that they set back the temperature during the day either often or very often. This pattern changed slightly in the second survey, where just over 50% of respondents indicated that they use daytime setbacks, with more respondents reporting that they do so often instead of very often (see Figure 19).

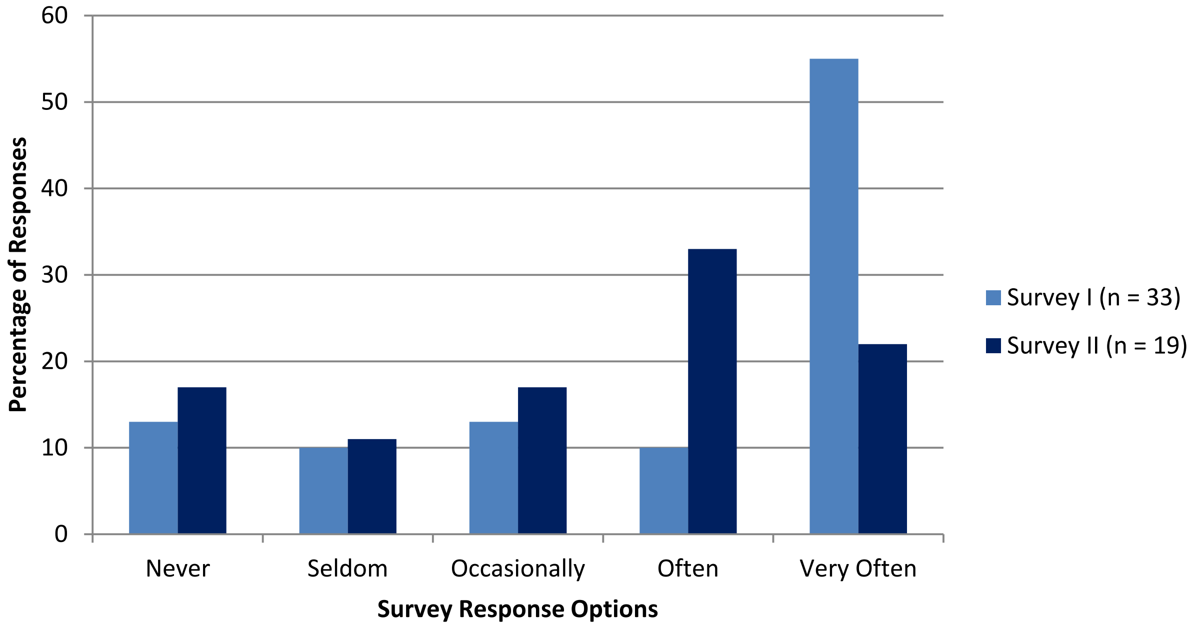

Figure 19. Percentage of households who reported daytime setbacks

3.4 Permanent Hold Events

The permanent hold function is another way users can override default settings. The intended use for this mode is to maintain a certain minimum temperature in the apartment over longer periods of absence (e.g., vacation). This mode, however, can also be used as a "set and forget" feature that disables temperature setbacks permanently (until the hold mode is manually canceled).

Forty-nine percent of BA apartments and 25% of VP apartments used the hold functionality at some point. Most hold events were of rather short duration: 87% of BA hold events and 75% of hold events in the VP group were up to 2 days and a single apartment in the BA group maintained hold events of 1 week or more (duration of 7 or 10 days, respectively). Summing the time on hold of all hold events by apartment, we found that two apartments in the BA group and five apartments in the VP group had the temperature on hold for a week or more. These findings are illustrated in Figure 20, Figure 21, and Figure 22.

Figure 20 shows the duration of the longest hold event per apartment by group. With the exception of one apartment (in the BA group) that maintained the temperature on hold for 10 consecutive days, all other apartments limited the duration of individual hold events to less than 6 days.

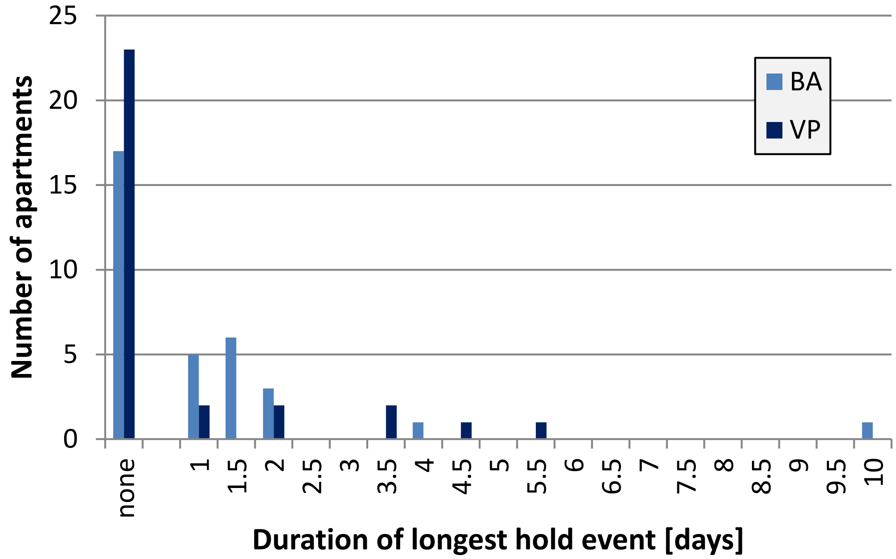

Figure 20. Duration of the longest hold event per apartment

Figure 21 shows the total time on hold by apartment for all apartments that had used the hold functionality at some point. Although more apartments in the BA group used the hold functionality at all, among those who used it, more VP apartments kept the temperature on hold for more than 1 week during the study.

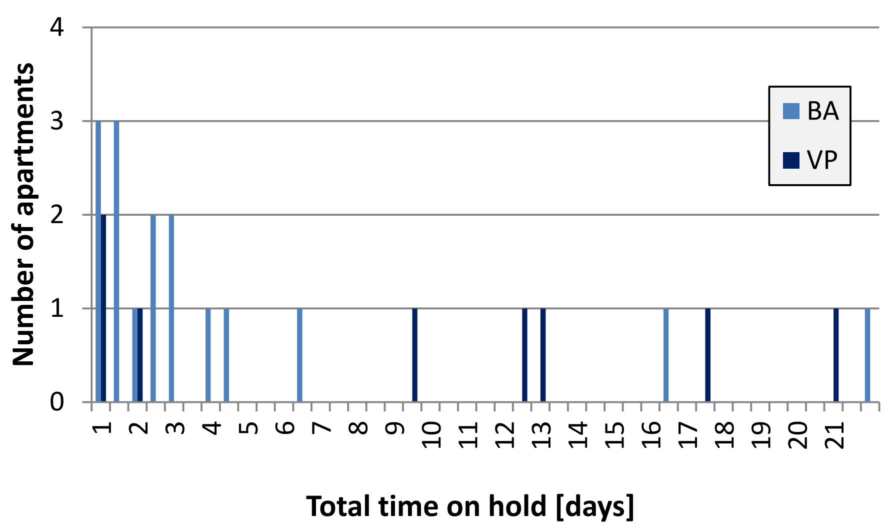

Figure 21. Total time on hold by apartment

Figure 22 shows at what temperature and for how long the temperature was kept on hold in the two groups. The five events with the longest duration in the BA group (≥4 days) all come from the same apartment. In both groups, we can see the general tendency to use the hold function for increased comfort, not to maintain the apartment at a minimum temperature while occupants are on vacation or otherwise gone as foreseen by thermostat manufacturers. Instead, most apartments used this feature as a set-and-forget autopilot that keeps the temperature at a level perceived as comfortable all day long, saving them the hassle of repetitive overrides of default setbacks or reprogramming.

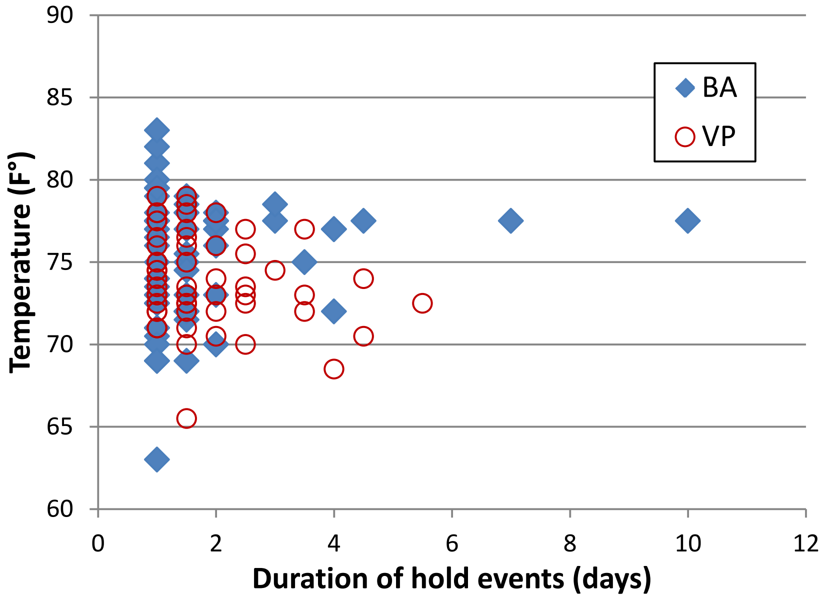

Figure 22. Temperature and duration of individual hold events.
All hold events of the apartments within the same group were pooled.

Table 8 presents an overview of these findings.

Table 8. Overview of Permanent Hold Results

	Low Usability (BA)	High Usability (VP)
% of Apartments Using Hold Feature	49	25
Average Hold Temperature (°F)	75.3	74.4
Average Duration per Hold Event	1.8 days	1.9 days
Mean of Maximum Hold Event Duration[a]	2.1 days	2.9 days
[a] Among all apartment who used the hold functionality in each group		

3.4.1 Self-Reported Permanent Hold Events

Even though a high percentage of households used a permanent hold function, they did not do so to reduce the temperature while they were gone, but to retain high temperature for longer periods of time. It is particularly striking that the self-reported vacation setbacks deviate so much from observable data.

In the first survey, more than 70% of respondents indicated that they set back the temperature either very often or often when they are on vacation, and nobody reports that they do not set back the temperature when they are on vacation. In the second survey, more than 20% of respondents indicated that they never set back the temperature when they go on vacation, and just over 50%

reported that they set back the temperature either often or very often when they go on vacation (see Figure 23). A potential confound in these data is that when talking about vacation, survey respondents could be thinking about an occasional event that may or may not have coincided with the test period, and they might overestimate their behavior related to that event.

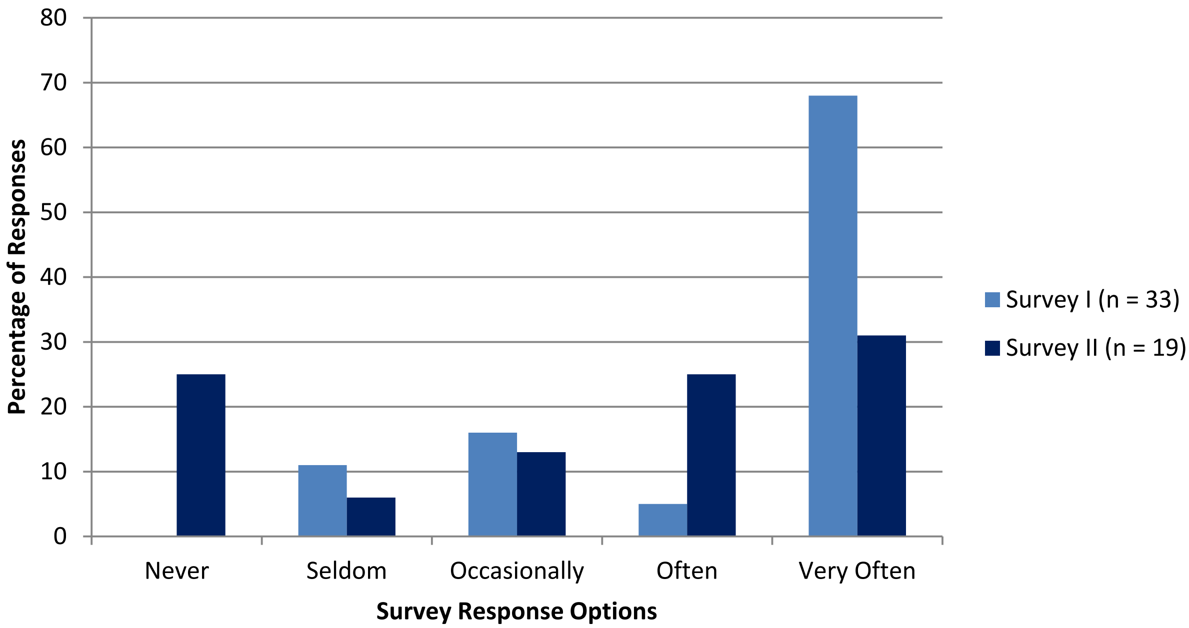

Figure 23. Percentage of households who reported vacation setbacks/holds

3.5 Regular Reprogramming Patterns

3.5.1 Methodology: Development of the Algorithm

We used Matlab to analyze the data for reprogrammed schedules versus manual overrides. As we mentioned in the data retrieval section, it consisted of two main files. The first one created a matrix for each apartment (saved as a mat-file), which was the starting point for all further analyses. Based on this matrix, classification procedures could be easily rerun with different parameters and thresholds (e.g., to test the sensitivity of the results on the exact temperature cut-off values).

3.5.2 Reprogramming Results

Very few apartments showed patterns that fit reprogramming criteria. After additional visual analysis of the eight reprogramming candidates, we determined that the four apartments described in Table 9 actually reprogrammed their thermostats.

Table 9. List of Apartments in Which Residents Reprogrammed Their Thermostats Based on Algorithm Data and Visual Inspection

Apt	Group	Temperature and schedule	Detection
B02	Low usability (BA)	78°F from 7:00 p.m. to 11:30 a.m.	Algorithm
B03	Low Usability (BA)	70°F from 6:00 a.m. to noon, 72°F from noon to 1:30 p.m., (default 70°F from 6:00 p.m. to 10:00 p.m., 72°F from 11:00 p.m. to 1:00 a.m., 72°F from 2:00 a.m. to 3:00 a.m.)	Algorithm
B04	Low Usability (BA)	70.5°F from 10:00 p.m. to 4:00 a.m., 73°F from 4:00 a.m. to 6:00 p.m., 72°F from 6:00 p.m. to 10:00 p.m.	Visual inspection
B26	Low Usability (BA)	74°F from 3:00 p.m. to 6:00 a.m., and to 75°F from 6:00 a.m. to 3:00 p.m.	Visual inspection

This list is striking for several reasons. First, very few apartment occupants reprogrammed their thermostats. Somewhat surprisingly, all four apartments that do show reprogramming patterns had a BA thermostat. None of the VP apartments successfully reprogrammed their thermostats. Also, none of the four apartments that show reprogramming patterns allowed the temperature to fall back anywhere close to the default setback temperature. Although one apartment actually set a schedule that held 78°F for 16.5 hours of the day, the three remaining apartments chose set points between 70°F and 75°F. The set points programmed by these three apartments are very close to each other. Overall, just as the manual override data show, most residents seem to have a preference for much higher temperature in the winter than the default schedule of current programmable thermostats.

3.5.3 Self-Reported Adjustments of Thermostats

About 3 months after the new thermostats were installed, we asked respondents a range of questions about the use of the new devices. These questions were designed to find out whether respondents relied primarily on the set schedule or engaged in frequent manual interaction. We found that 56% of households indicated that they adjust their thermostats two or more than two times a day. In 13% of households, the thermostat was adjusted once a day. These responses show a lack of understanding of a programmable schedule that should theoretically be adjusted rarely. Thirty-one percent of respondents reported that they adjust their thermostats either very rarely or not at all. Compared to the results of the first survey, where we asked respondents to indicate whether they adjust their thermostat either daily, weekly, or monthly, there is no large difference. In the first survey, 68% of respondents indicated that they adjusted their thermostats at least daily.

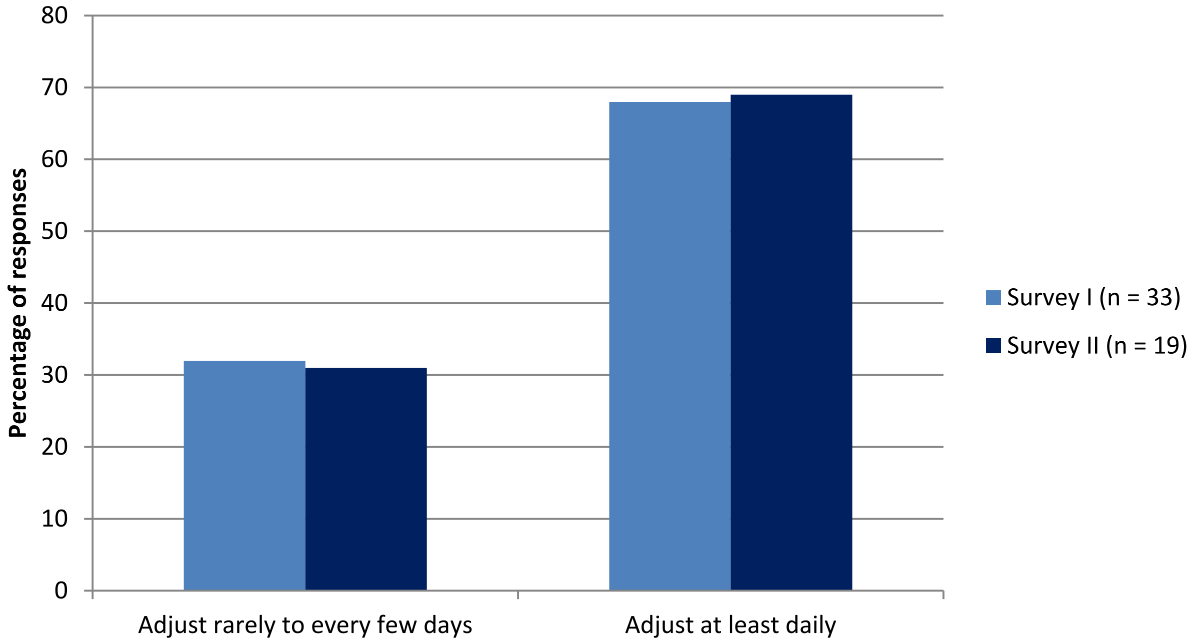

Figure 24. Percentage of households who reported adjustment of thermostats before and at the end of the study

3.6 Satisfaction with Thermostats and Comfort Ratings

When the thermostats were installed, the residents were given a user manual. In the second survey, we asked respondents if they had read the manual, and 83% reported that they had. We also questioned which household occupant primarily adjusted the thermostat. We found that 61% of those filling out the survey were the only ones in the household who adjusted the thermostat, 39% also had a family member or other person apart from the respondent who adjusted the thermostat.

Finally, respondents to the second survey were asked to indicate their satisfaction with the thermostat—whether they found it easy to use, liked the look, enjoyed using it, would recommend it to others, and thought the thermostat helped to save money. Figure 25 shows the responses to all five items, with satisfaction, dissatisfaction, and "do not care" answers. The majority of respondents are overall satisfied with the new thermostat, with over 70% positive responses for each item. We further analyzed these results by comparing satisfaction with all five items for respondents with high usability thermostats to those with low usability thermostats (see Figure 26). Results show a trend towards higher satisfaction with the high usability thermostats in terms of aesthetics, enjoyment of using it, recommending it to others, and its ability to save money. Respondents with low usability thermostats were much less convinced that the thermostat helps them to save money than respondents with high usability thermostats.

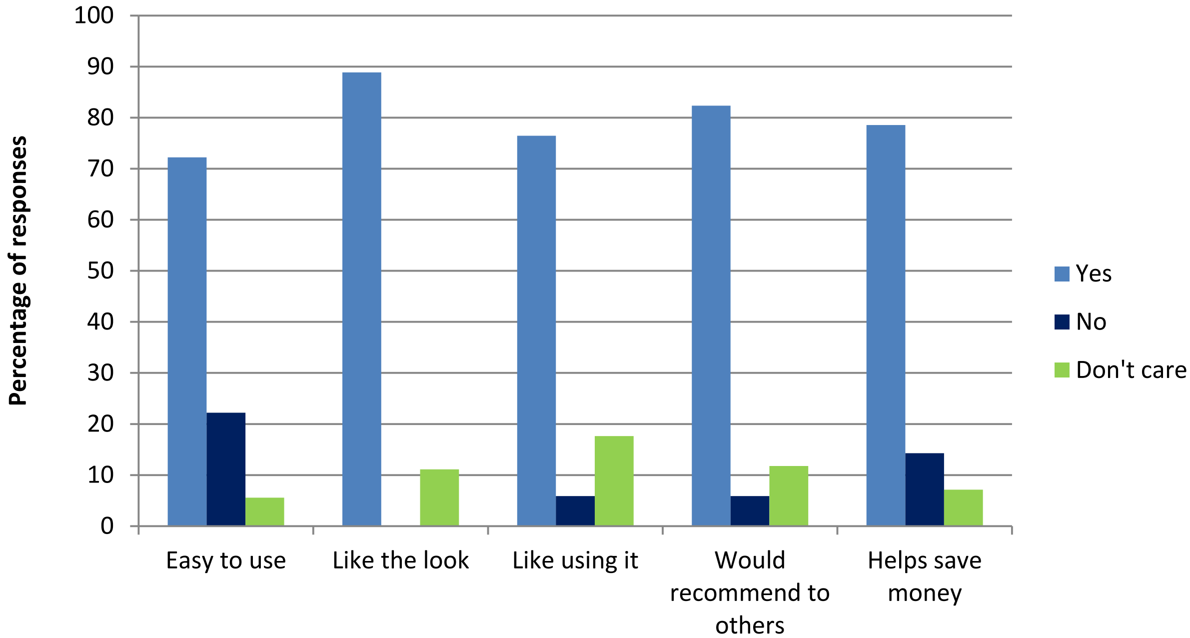

Figure 25. Survey 2: Self-reported opinions about new thermostats

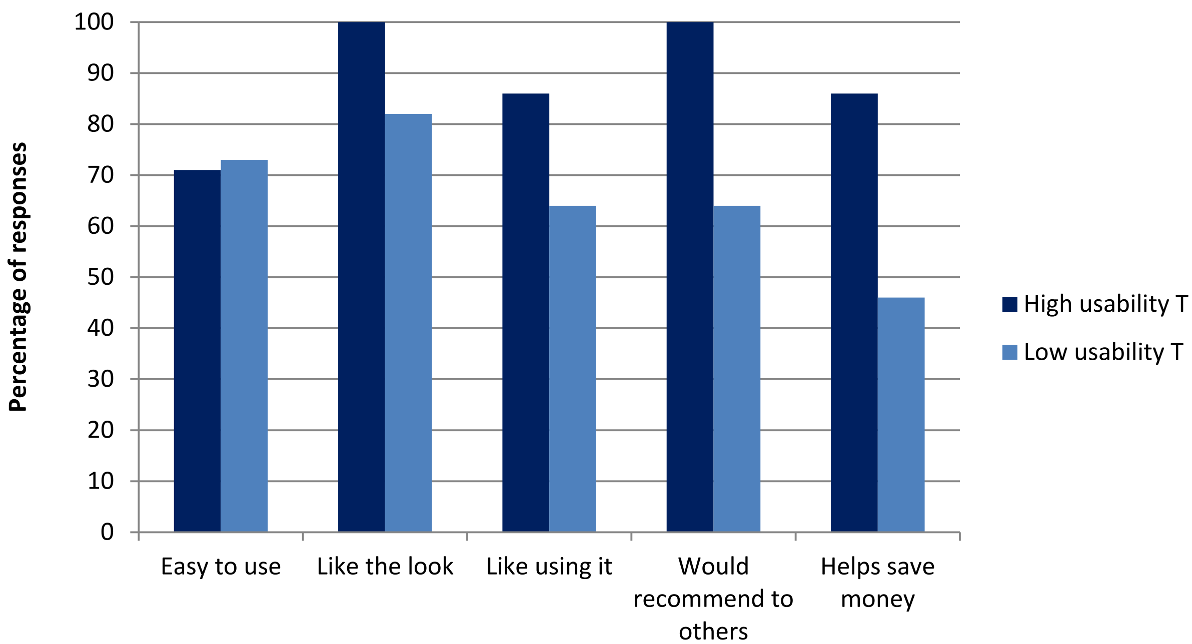

Figure 26. Survey 2: Self-reported satisfaction with high and low usability thermostats

Perceived thermal comfort in the apartment is another self-report measure that we used in the survey. This measure can indicate whether high and low usability thermostats had a different impact on occupant satisfaction.

We surveyed comfort levels in the morning, afternoon, and evening to see if there were noticeable dips in comfort during setback periods. Few respondents indicated that they were uncomfortable or very uncomfortable at any part of the day, with the majority falling in the neutral or comfortable category. One trend that is obvious for all time periods is that the low usability thermostat received more "regular" or neutral ratings, whereas the high usability thermostat received more ratings on the extreme sides of the scale—"very uncomfortable" or "very comfortable."

Because of a low sample size (19 respondents to the second survey), we could not run any meaningful statistical analyses on the difference in comfort levels between high and low usability thermostats. We can, however, discuss the trends for comfort in the morning, afternoon, evening, and nighttime. In the morning, similar numbers of respondents were comfortable with both high and low usability thermostats (see Figure 27).

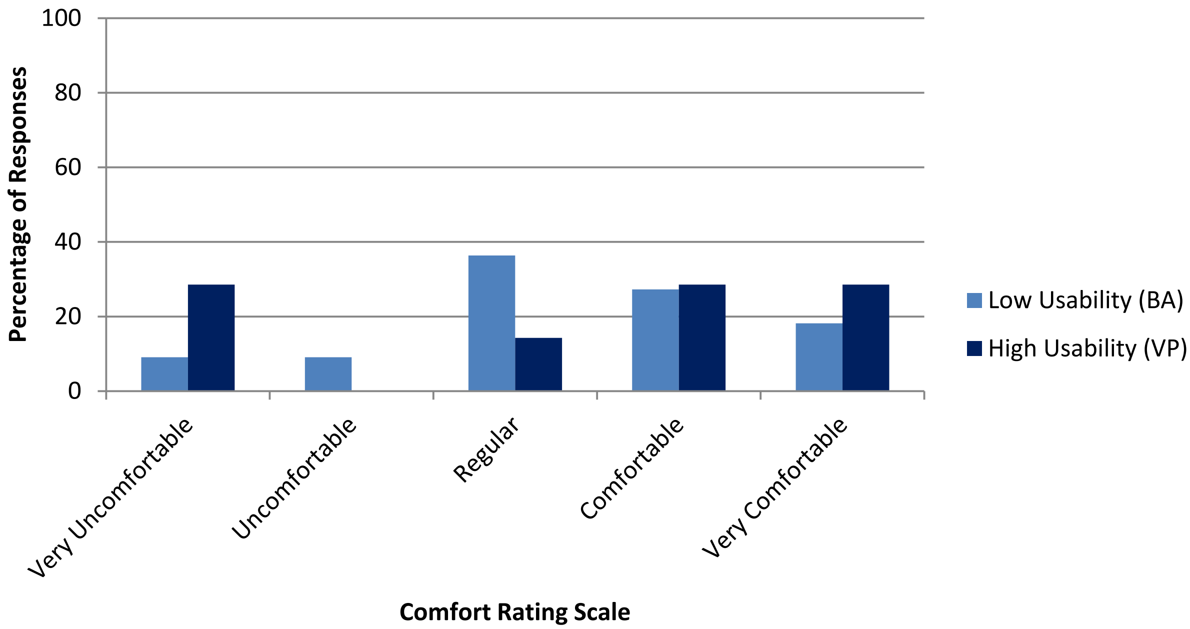

Figure 27. Self-reported comfort levels with high and low usability thermostats in the morning

In the afternoon, more high usability thermostat owners were more comfortable than owners of low usability thermostats (see Figure 28). Similar trends were also observed for the evening and nighttime periods (see Figure 29 and Figure 30, respectively).

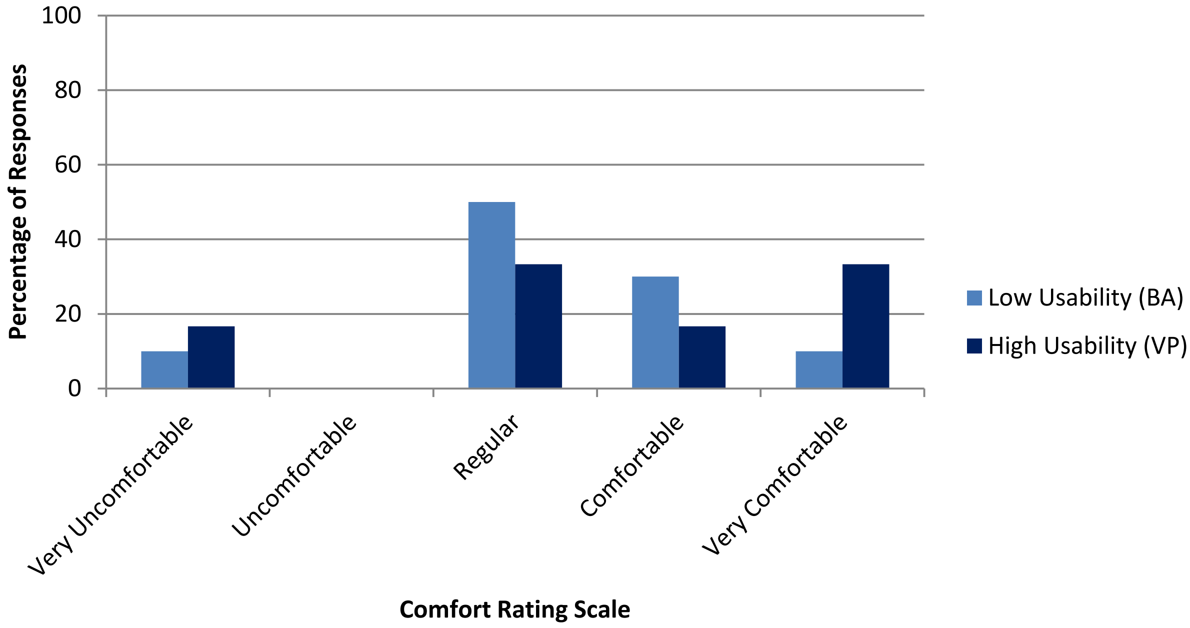

Figure 28. Self-reported comfort levels with high and low usability thermostats in the afternoon

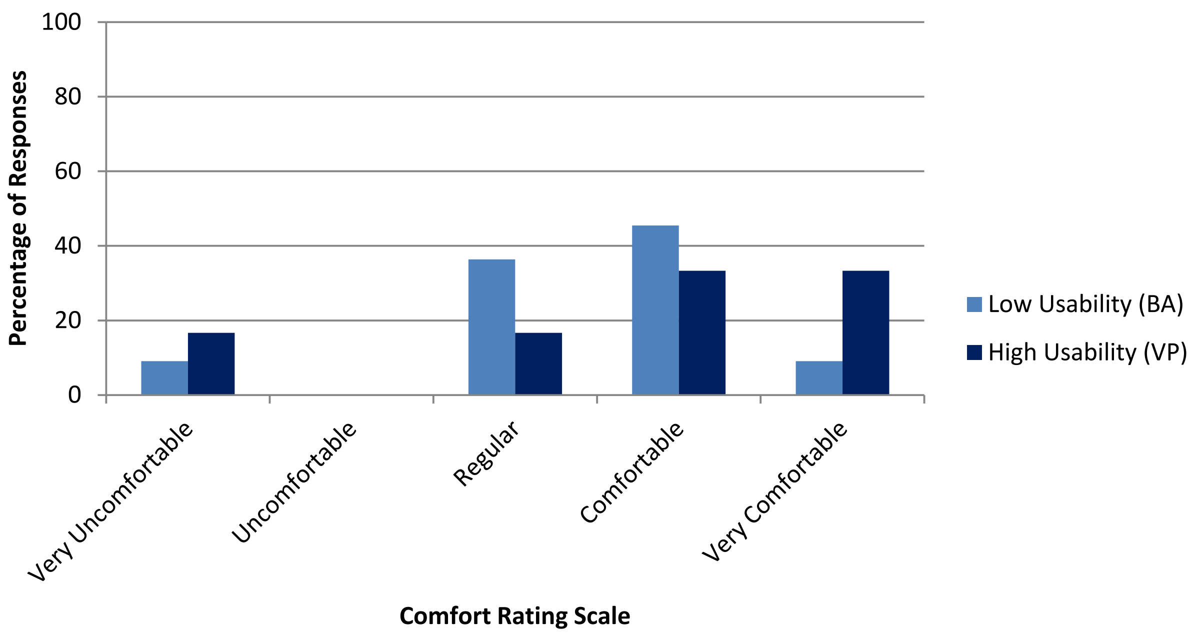

Figure 29. Self-reported comfort levels with high and low usability thermostats in the evening

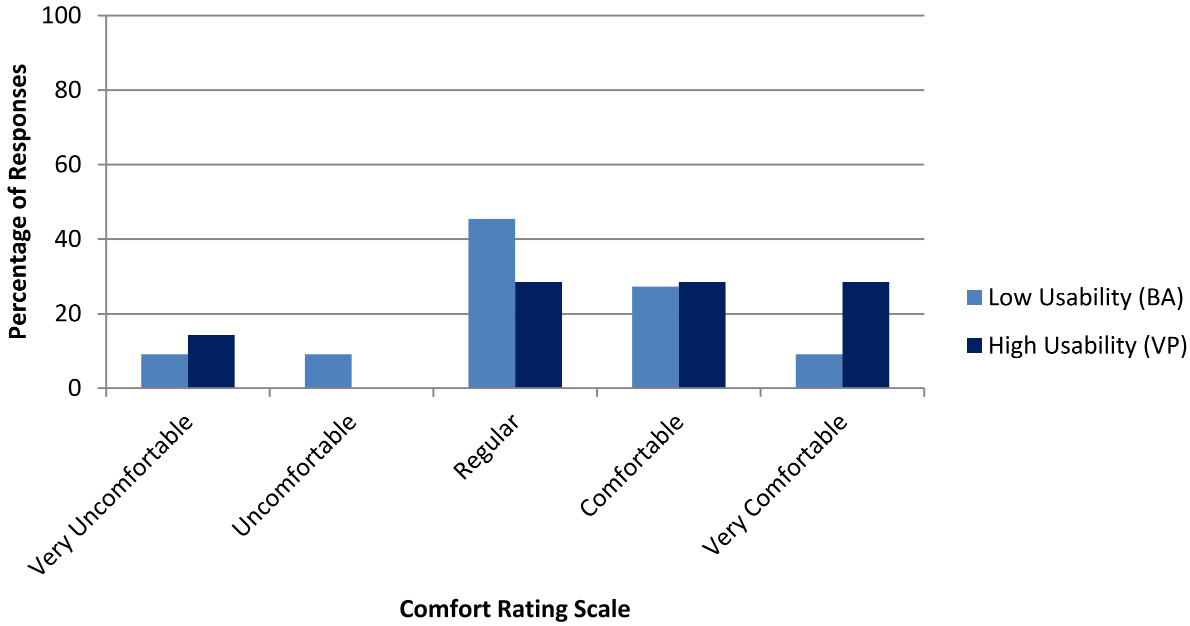

Figure 30. Self-reported comfort levels with high and low usability thermostats at night

These results should be used with caution, considering the small sample size and self-report biases that tend to skew results to be more positive and socially acceptable.

3.7 Gas Consumption

Throughout the study period we conducted weekly gas meter readings for all participating apartments to see if gas consumption differed depending on the usability of thermostats. This apartment building uses gas for space and water heating.

Gas consumption is metered for every apartment individually and all apartments have the same heating system. We found that apartments with a high usability thermostat consumed the same amount of gas as apartments with a low usability thermostat ($p = 0.73$; see Figure 31 for the weekly gas consumption plot).

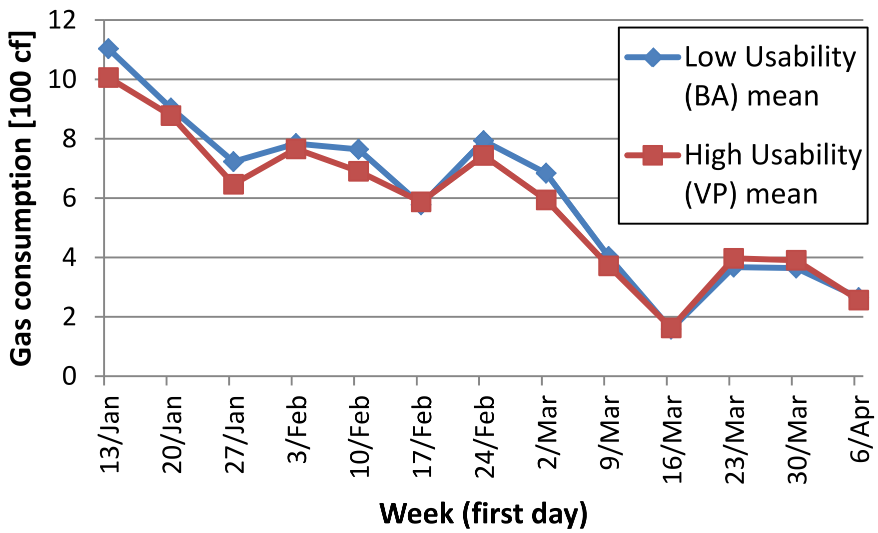

Figure 31. Weekly gas consumption in high usability (VP) and low usability (BA) apartments

3.8 Data Validity Checks

Gas consumption data can also be used to check if our sensor data are valid. For that purpose, we compared apartment gas consumption and furnace "on" time for a given period (January 12–March 13, 2012). Apart from differences in hot water consumption, furnace activity should be linearly correlated with gas consumption over a given period. As Figure 32 shows, there is a very good correlation between gas usage and the time that the furnace was on.

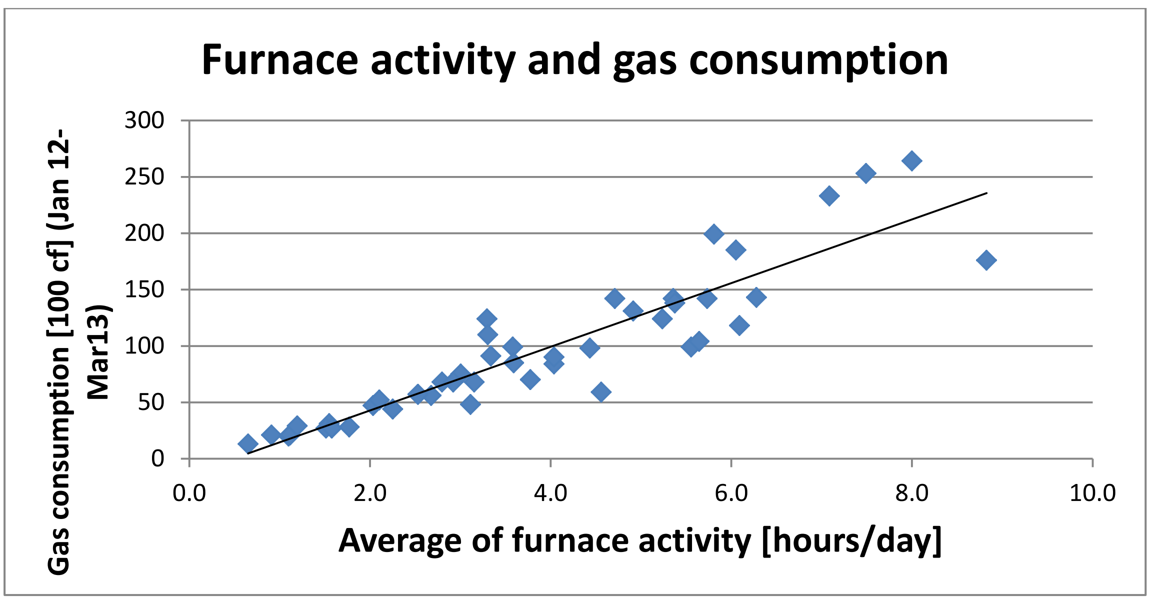

Figure 32. Correlation of furnace activity and gas consumption

In several apartments, we noticed that the indoor air temperature did not fall below the lower set point temperature every night. This could occur because of mild weather, high performance building envelope construction, and/or occupant behavior. To find out what causes are most likely, we collected information about the outdoor air temperature and building envelope and used the data to perform thermal simulations using the EnergyPlus whole-building energy simulation program. We used these simulations to predict expected temperature variation of indoor air temperature and exterior wall surface temperature. Our analysis shows that the building construction and mild winter were not primarily responsible for units whose air temperature does not decay below the set point temperature. Instead, it appears that manual thermostat overrides are the most likely explanation for why some apartments' temperatures rarely fell below the default set point temperatures (see Appendix D for details).

4 Conclusions

4.1 Results and Discussion

The main objective of this project was to evaluate the impact of thermostat usability on facilitating energy saving behaviors of thermostat users. Specifically, are home occupants with a high usability thermostats more likely to use them to save energy than people with a basic thermostat? To answer this question, we collected field data from 63 apartments in an affordable housing complex and used an analytical approach to infer occupant interaction with thermostats from nonintrusive temparature and furnace on–off state sensor data. Our analysis focused on four types of occupant interaction with thermostats that can lead to energy savings: nighttime setbacks, daytime setbacks, vacation holds, and reprogramming. Table 10 summarizes the project's main findings related to these types of occupant interaction with their thermostats.

Table 10. Summary of Main Results

	Low Usability (BA)	High Usability (VP)
Number of Apartments per Group With Valid Datasets	31	32
NIGHTTIME SETBACKS		
Minimum Nighttime Temperature (2:00 a.m. to 4:00 a.m.)	69.4	69.5
Mean Nighttime Temperature (2:00 a.m. to 4:00 a.m.)	71.6	71.2
Nighttime Setback (% of Apartments), T≤62°F	3.2%	3.1%
DAYTIME SETBACKS		
Minimum Daytime Temperature (10:00 a.m. to 4:00 p.m.)	70.1	69.7
Mean Daytime Temperature (10:00 a.m. to 4:00 p.m.)	71.8	71.6
Daytime Setback (% of Apartments), T≤62°F	3.2%	0%
PERMANENT HOLD ANALYSIS		
% of Apartments With Hold Events	49%	25%
Temperature of Hold Events	75.3	74.4
Average Duration per Hold Event	1.8 days	1.9 days
REPROGRAMMING ANALYSIS		
# of Apartments With Reprogrammed Schedule	4 (13%)	0 (0%)
Group Average of Rescheduled Temperature (Average Weighted by Hours per Day)	73.8°F	NA

We found that usability did not influence energy saving behaviors of study participants. We found no significant difference in temperature maintained in apartments that had either high or low usability thermostats. The minimum and mean nighttime and daytime setback temperature was 70°F–71°F in both conditions—considerably higher than the energy saving default of 62°F.

Perhaps the reason why usability had no impact on the use of energy saving settings was the low proportion of households that ended up using thermostat-enabled energy saving settings. Only 3% of households used default nighttime setbacks, regardless of the thermostat usability. No household in the high usability condition used daytime setbacks and only 3% used them in the low usability condition. Although many households used the permanent hold feature, it was used to maintain a high temperature and not to keep it at a constant low level for the time when the apartment was unoccupied. More households in the low usability condition used the hold function than in the high usability condition, possibly because the button was more salient than a touch screen tab. Correspondingly, the few cases of reprogramming that we found in the low usability condition seem rather incidental and do not involve any meaningful lowering of the temperature.

These results could be explained by one of the following theories. First, our results could mean that the high usability thermostat was not sufficiently easy to use. A better thermostat could make programming or maintaining an energy saving schedule easier and therefore would have been more likely to be used by home occupants.

Second, study participants did not understand that there is a relationship between thermostat setting and their heating bill. An educational intervention that made such a relationship clearer, as well as an explanation of the advantages of using a setback schedule, might have produced very different results.

A third theory is that study participants were able to use energy saving settings on their thermostats but chose not to do so. This interpretation of results is realistic considering how much and how often study participants adjusted their thermostats to override the default schedule. Regardless of the thermostat model, they managed to keep the temperature at the level that ensured their comfort and negated any energy saving features. Why this happened is the question that warrants careful consideration and future research. If we consider that the three main factors that are essential for any behavior to take place are motivation, ability, and trigger (Fogg 2009), increasing the usability of programmable thermostats is driving only one component of the behavior change triad—ability. It does little, however, to increase *motivation* or set up situational *triggers* that make behavior happen.

Further development of climate control technology is likely to improve usability and make it easier for anybody to use thermostats. This means that motivation is a key variable that is missing from any attempts to make energy saving via thermostats more predictable and reliable. As part of our survey, we asked study participants if they used setbacks to save money or energy. The majority of respondents chose and agreed with both motivations. If we look at the actual behavior of study participants, though, it is driven by one dominating factor—thermal comfort. To achieve comfortable temperature study participants made regular adjustments to their thermostat settings and overrode any program that would enable saving energy and money.

If we take it as a given that thermal comfort has a much higher priority in individual decision making than saving energy and money, energy saving features enabled by thermostats must preserve individual comfort levels. Analysis of temperature data from our sample is unambiguous in terms of what temperature study participants prefer in their homes even when they sleep—it is well above currently used default settings (62°F) and even above the 70°F used in nonsetback periods.

A further insight gained from our study is a poor relationship between self-reported survey data and observed measurable behavior. Participants have drastically overestimated their use of energy saving features such as daytime and nighttime setbacks and vacation holds. The only measure where there was consensus between self-reported and observable data was apartment temperature that was comfortable for study participants. Both temperature sensors and survey respondents have agreed on 72°F.

4.2 Limitations

One limitation of this study stems from the fact that it was carried out in an affordable housing building where residents differ from average U.S. demographics. Our survey data indicate that most participants in the study had a low education level and few if any children or elderly family members. Most units in the building are reserved for low-income tenants. Thus, our results cannot necessarily be directly generalized to an average U.S. family. Our findings are, however, valuable for the affordable housing market, in which reducing utility costs is one of its top priorities. Moreover, our study is a strong test of the hypothesis that people are only interested in saving energy to save money. If people who have a restricted income are not interested in saving energy to save money, it is unlikely that people with an average or above average income will be compelled by financial incentives to change their heating behavior.

Another limitation of the study results from the specific thermostat models we used. Our study was carried out with only two types of thermostats. One had a high usability score and the other one was sold as a more basic model. Although thermostat usability was evaluated using the same usability metrics, we cannot guarantee that our results were not affected by the specifics of these two models and to what extent they can be generalized to other models available on the market.

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Appendix A: Central Department of Energy Institutional Review Board Letter

PROTECTING HUMAN SUBJECTS

Central Department of Energy Institutional Review Board (CDOEIRB)
FWA00015568
Phone: (865) 576-1725

DATE:	August 24, 2011
TO:	Olga Sachs, Ph.D.
FROM:	Central DOE IRB
STUDY TITLE:	[255215-2] Field Evaluation of Programmable Thermostats: Usability, Comfort and Energy Savings
IRB REFERENCE #:	11-124
SUBMISSION TYPE:	Response/Follow-Up
ACTION:	APPROVED
APPROVAL DATE:	August 24, 2011
EXPIRATION DATE:	August 25, 2012
REVIEW TYPE:	Expedited Review
REVIEW CATEGORY:	Expedited review category 10 CFR 745.110(b)(1)

Thank you for your submission of Response/Follow-Up materials for this research study. The Central DOE IRB has APPROVED this protocol. This approval is based on an appropriate risk/benefit ratio and a study design wherein the risks have been minimized. All research must be conducted in accordance with this approved submission.

This project has received Expedited Review based on the applicable federal regulation as noted above.

Please remember that informed consent is a process beginning with a description of the study and insurance of participant understanding followed by a signed consent form. Informed consent must continue throughout the study via a dialogue between the researcher and research participant. Federal regulations require each participant receive a copy of the signed consent document.

Please note that any revision to previously approved materials must be approved by this office prior to initiation. Please use the appropriate revision forms for this procedure.

All UNANTICIPATED PROBLEMS and SERIOUS and UNEXPECTED adverse events must be reported to this office. Please use the appropriate adverse event forms for this procedure. All FDA and sponsor reporting requirements should also be followed.

Please report all NON-COMPLIANCE issues or COMPLAINTS regarding this study to this office.

Please note that all research records must be retained for a minimum of three years.

- 1 - Generated on IRBNet

Based on the risks, this project requires Continuing Review by this office on an annual basis. Please use the appropriate renewal forms for this procedure.

If you have any questions, please contact Becky Hawkins at 865-576-1725 or Becky.Hawkins@orise.orau.gov. Please include your study title and reference number in all correspondence with this office.

Appendix B: Participant Survey 1

Dear Broadway Tower resident,
Thank you very much for taking your time to answer our questions. Your time and your opinion are highly valuable to us. On the next two pages you will find a few questions concerning your household and your old thermostat. This applies to the thermostat you had installed previous to the new one. Please answer all questions as they apply to your previous thermostat.
Your data will be treated completely confidential and anonymously.
It should take around 10 minutes to answer all questions. After you finish answering the questions, drop the survey off at the ***office on the first floor*** at your earliest convenience (last drop-off date: Friday, December 16).

RAFFLE

Remember: **By taking part in this survey you are eligible for our raffle worth of 500 dollars in Target gift cards! You will get your ticket from the office on the first floor when you drop off this survey.**

---

1. Are you: ☐ male ☐ female 2. Please indicate your year of birth: ☐

3. How many members are in your household? ☐

4. How many children under age 12 live with you? ☐

5. How many people over age 60 live in your apartment? ☐

6. How long have you lived in this apartment? ☐ ears Mont ☐

7. How long do you think you will stay in this apartment? Another ☐

8. Please indicate your highest level of education/schooling:

☐ Some school ☐ High school diploma ☐ some college ☐ Associate's degree
☐ Bachelor's degree ☐ Professional certification ☐ Master's degree ☐ Doctorate

Below are some questions about your comfort with the indoor temperature at home.

The temperature in my home is…	**Very uncomfort able**	**A little uncomfort able**	**Regular**	**Comfort able**	**Very comfortable**	Not applic able
...on weekdays in the morning.	☐	☐	☐	☐	☐	☐
...on weekdays in the afternoon (leave blank if working)	☐	☐	☐	☐	☐	☐
...on weekdays in the evening.	☐	☐	☐	☐	☐	☐
...on weekdays during the night.	☐	☐	☐	☐	☐	☐
...on weekends when I am home.	☐	☐	☐	☐	☐	☐
...on weekends when I come back from	☐	☐	☐	☐	☐	☐

having been away for more than two hours.						
...on weekends during the night.	❑	❑	❑	❑	❑	❑
...when I come back from a vacation.	❑	❑	❑	❑	❑	❑
At which temperature to do you feel the most comfortable at home?	Winter: Between ____ °F and ____ °F Summer: Between ____ °F and ____ °F					

Below are a few questions around your use of the thermostat.

	never	seldom	occasionally	often	very often	n.a
I regulate the temperature according to how comfortable I (my family) feel.	❑	❑	❑	❑	❑	❑
I regulate the temperature so I don't have to wear a sweater.	❑	❑	❑	❑	❑	❑
I turn down the thermostat when I leave the house.	❑	❑	❑	❑	❑	❑
I turn down the thermostat when I go to bed.	❑	❑	❑	❑	❑	❑
I lower the temperature when I go on vacation.	❑	❑	❑	❑	❑	❑
I lower the temperature of the thermostat to save money.	❑	❑	❑	❑	❑	❑
I lower the temperature of the thermostat to save energy.	❑	❑	❑	❑	❑	❑
I adjust the thermostat:	Please circle: Daily Weekly Monthly Never					

That is all!
Thank you very much for helping us with our project, your time and effort are very valuable to us.
Please drop this survey off at the *office on the first floor* at your earliest convenience (last drop-off day: Friday, December 16).

You will get your *RAFFLE* ticket from the office on the first floor. Bring this survey with you, and let them know your apartment number. For us to match the raffle tickets, please indicate your apartment number below:
I live in apartment number: __________

Appendix C: Participant Survey 2

Dear Broadway Tower resident,
Below you find a few questions about your household regarding energy use and the new thermostat.

As a Thank-You for taking this survey, you will enter a raffle for 10 gift cards for each worth $50!! Get your raffle ticket from the office on the first floor by filling out and handing in your survey. The raffle will be held on Friday, April 20th, so make sure you collect your ticket before that day!
Your answers will be treated completely confidential, they are solely for research purposes, and the building management does not see your answers.

Thank you very much for your help!!!

How many people live with you? ____________
How many people are working **day shifts**?_________ Normal work hours:________________________
How many people are working **night shifts**? _______ Normal work hours:________________________
What time does the **first person** get up?___________ What time does the **last person** get up?_________
What time does the **last person** go to bed? _________
How many people are usually home during the day on weekdays?______________________________________

Some questions about the new thermostat in your apartment:
Did anyone in your household read the manual for the new thermostat? ❑ **Yes** ❑ **No**
Who adjusts the thermostat in your household? (check all that apply)

❑you ❑your husband/wife/partner (please circle) ❑your son/daughter (please circle) ❑your mother ❑ your father ❑other (please specify) ____________

How many times per day does anyone in your household adjust the thermostat?
____

Do you agree?	**Yes**	**No**	**Don't Care**	Comments
It's easy to use the thermostat.	❑	❑	❑	
I like how the thermostat looks.	❑	❑	❑	
I like using the thermostat.	❑	❑	❑	
I would recommend this thermostat to others.	❑	❑	❑	
This thermostat helps me save money.	❑	❑	❑	

Do you…..	**Never**	**Seldom**	**Occasionally**	**Often**	**Very Often**
…lower the temperature when you leave the house?	❑	❑	❑	❑	❑
…lower the temperature when you go to bed?	❑	❑	❑	❑	❑
…lower the temperature when you go on vacation? (if applicable)	❑	❑	❑	❑	❑
…lower the temperature to save money?	❑	❑	❑	❑	❑
…lower the temperature to save energy?	❑	❑	❑	❑	❑

What have you and others in your household usually worn in the past 3 months at home? (check all that apply)

❑ Sweater ❑ Long-sleeves ❑ T-Shirt ❑ Shorts ❑ Pants ❑ Hat

Other:____

Heating in your apartment

Did you use electric space heaters during the winter? Yes ❑ No ❑

If yes, for which rooms did you use it/them?____

Did you have problems with the furnace during the winter? Yes ❑ No❑

Do you remember when and for how long? (if not, approximate)____

If you used another method, other than the thermostat/furnace or electric space heaters to heat your home, please specify here what you used:

Other comments:

Please tell us how comfortable you are in your apartment:

The temperature in my home is…	**Very uncomfortable**	**A little uncomfortable**	**Regular**	**Comfortable**	**Very comfortable**	Not applicable
...on **weekdays** in the morning.	❑	❑	❑	❑	❑	❑
...on **weekdays** in the afternoon (leave blank if working)	❑	❑	❑	❑	❑	❑
...on **weekdays** in the evening.	❑	❑	❑	❑	❑	❑
...on **weekdays** during the night.	❑	❑	❑	❑	❑	❑
...on *weekends* when I am home.	❑	❑	❑	❑	❑	❑
...on *weekends* when I come back from having been away for more than two hours.	❑	❑	❑	❑	❑	❑
...on *weekends* during the night.	❑	❑	❑	❑	❑	❑

...when I come back from a vacation. (if applicable)	❑	❑	❑	❑	❑	❑
At what air temperature to do you feel the most comfortable at home?	Winter: Between ____ °F and ____ °F Summer: Between ____ °F and ____ °F					

Are you ❑male ❑ female

What year were you born?_________________________

How many children under age 12 live in this apartment? ____________

How many people over 60 live in this apartment? _________________

Optional: What is the highest education received by anyone in your household?

____

Are you or anyone in your household in school right now? ❑Yes ❑No

Your apartment number:_____________

Remember: Get your raffle ticket from the office on the first floor by April 20th!!!

Thank you so much for helping us with our project, your time and effort are very valuable to us.

Fraunhofer Center for Sustainable Energy Systems CSE
25 First Street
Cambridge, MA 02141
Call us: 617-575-5720
Write to us: hfresearch@fraunhofer.org

Appendix D: Thermal Simulation Results

During the analysis period from January 12 through March 6, actual winter air temperatures were mild in comparison to typical Boston weather, as shown in Figure 33 (Weather Underground 2012). The average outdoor air temperature was 35.8°F, or 5.5°F warmer than the typical Boston average of 30.2°F. These warmer outdoor air temperatures could have reduced the number of nights when indoor air temperature remained higher than thermostat set point temperatures.

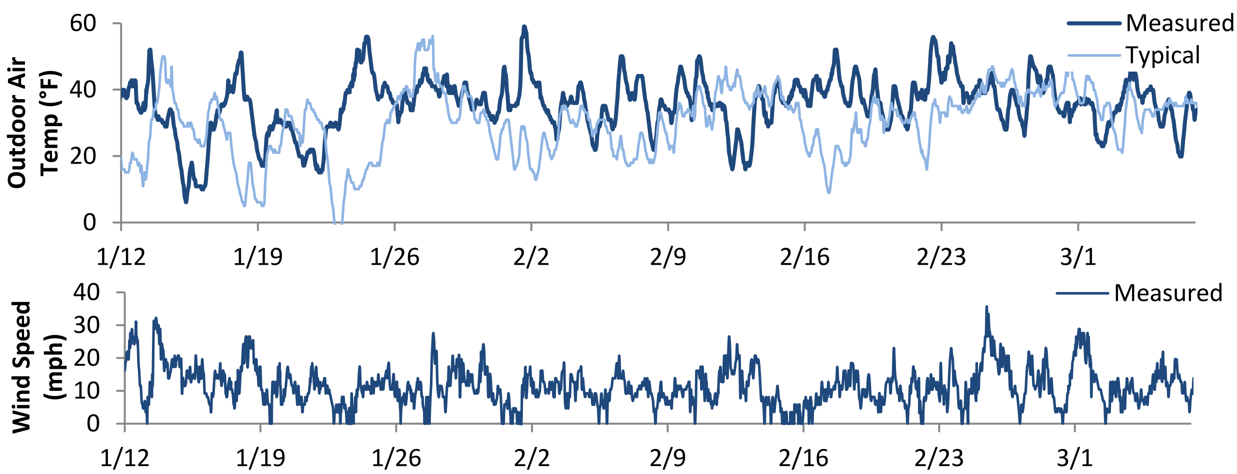

Figure 33. Measured outdoor air temperature from Boston Logan Airport

We estimate that the test building envelope could be slightly more insulating (about 6% or R-1 higher) than typical brick construction. According to the building project coordinator, the building envelope is brick with metal studs and R-13 fiberglass insulation. Many units have large glass sliding doors leading to balconies. Metal stud construction might slightly improve the overall opaque wall because of a reduced effective framing factor.[1] The glazing fraction of the test building was 23.3%, slightly higher than the 15% assumed in the Building America benchmark. The roof was about 35% more insulating than typical construction; however, this would likely only affect thermal transfer on upper floors.

We used the Building Energy Optimization tool to create an EnergyPlus model of a typical apartment unit as built, and for comparison, the same apartment unit with standard construction. Table 11 shows the key inputs. We modified the typical Boston weather data file by overlaying actual outdoor air temperature and wind speed data. With these models, we calculated the expected indoor air and indoor wall surface temperature histories over the study period to see how the two buildings compared. In both cases, we assumed that the thermostats were set to their default settings.

[1] Although metal studs have a much higher thermal conductivity than wood studs that increases thermal bridging, they also enable a reduced framing factor (8% for metal studs versus about 25% for wood framing) and therefore a slightly higher opaque wall R-value.

Table 11. Summary of Key Modeling Parameters

	Actual Building	Benchmark-1	Benchmark-2
Orientation	Northeast and Southwest	Northeast and Southwest	Northeast and Southwest
Window Percentage	23.3%	23.30%	15.0%
Wall Construction	Brick Air gap ½-in. Plywood 2 × 4 **metal studs**, 8% framing R-13 fiberglass insulation Gypsum wall board	Brick Air gap ½-in. Plywood 2 × 4 **wood studs**, 25% framing R-13 fiberglass insulation Gypsum wall board	Exterior Finish ½-in. Plywood 2 × 4 **wood studs**, 25% framing R-13 fiberglass insulation Gypsum wall board
Opaque Wall R-Value	12.6	11.8	10.5
Window R-Value	0.5	0.5	0.5
Overall Wall R-Value	9.8	9.1	9.0
Roof Construction	Asphalt ¾-in. Plywood 4-in. Rigid Insulation ¾-in. Plywood 3⅝-in. Insulation Gypsum wall board	Asphalt ¾-in. Plywood 4-in. Rigid Insulation ¾-in. Plywood 3⅝-in. Insulation Gypsum wall board	Roof membrane ¾-in. Plywood R-16 Insulation Gypsum wall board
Roof R-Value	29.4	29.4	18.6
Air Change Rate	10.3	10.3	10.3
All other inputs	BEopt Defaults	BEopt Defaults	BEopt Defaults

Figure 34 shows the simulated interior surface temperatures of the exterior wall of southwest-facing apartments. Northeast surface modeling results were similar, but had faster decay caused by reduced solar gain throughout the day. All cases showed that temperature decayed below the night setback temperature on most days. As expected, the brick cases take longer to decay than the nonbrick case.

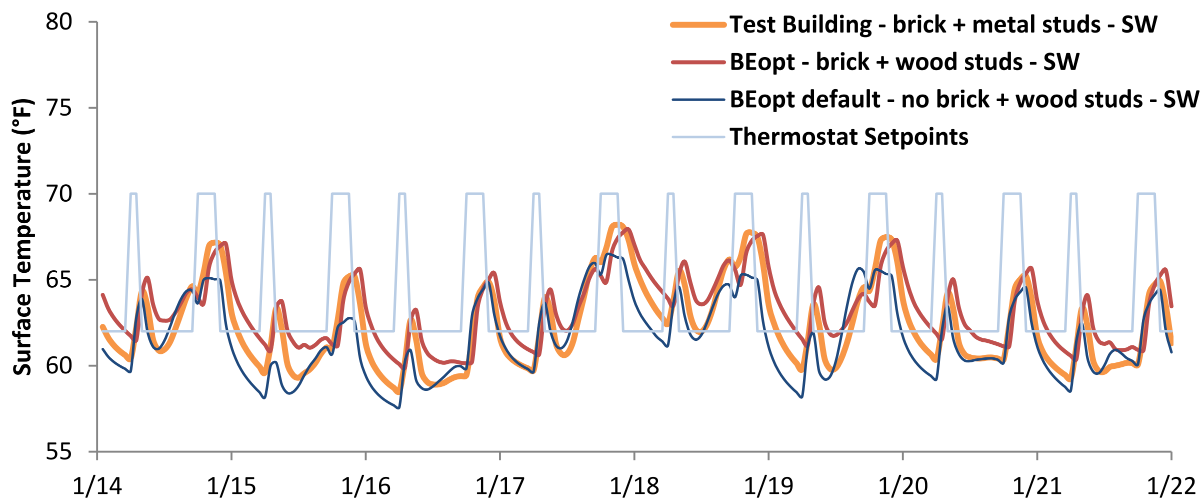

Figure 34. Simulated interior surface temperatures of exterior southwest wall

Measured air temperatures from two apartments were plotted with the simulation results in Figure 35. Both apartments showed a significant variance and rarely dropped below the set point temperatures. As with surface temperature, we find that for the cases modeled, temperature behavior does not vary significantly.

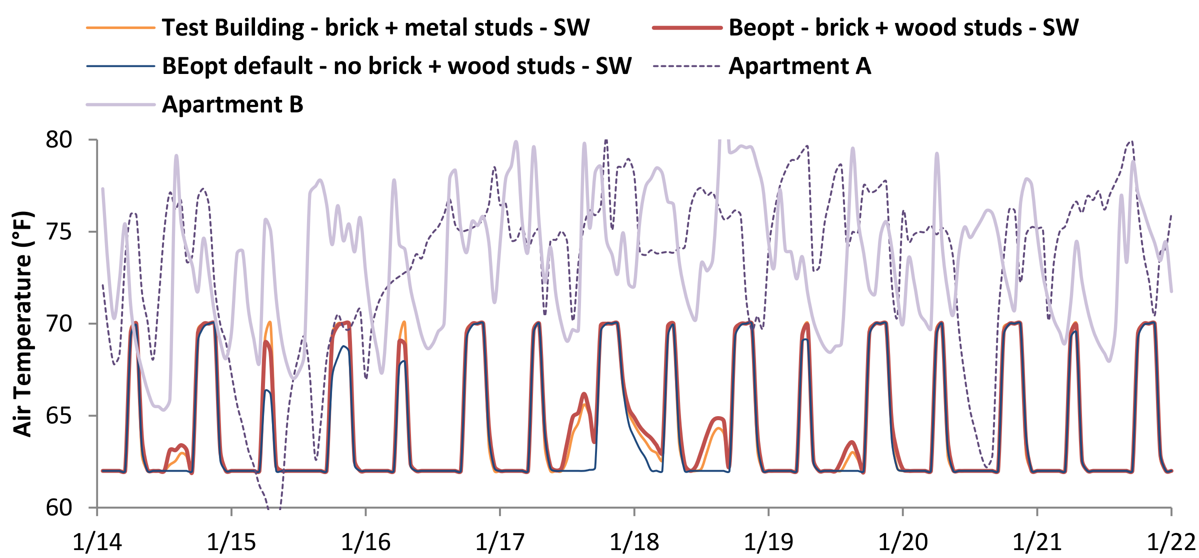

Figure 35. Simulated air temperatures in the conditioned zone and measured air temperatures in two apartments in the experimental building

Based on this analysis, it appears that the building construction and mild winter are not primarily responsible for units in which air temperature does not decay below the set point temperature. Instead, it appears that manual thermostat overrides are the most likely explanation for why some apartments' temperatures rarely fell below the default set point temperatures.

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DOE/GO-102012-3804 ▪ December 2012

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