ENERGY RESEARCH AND DEVELOPMENT DIVISION

Appendix A: Basic Components of a Thermostat

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APPENDIX A:
Basic Components of a Thermostat

APPENDIX A defines and describes basic components of a thermostat in greater detail and presents other preliminary control design decisions.

Basic Components of a Thermostat

A smart thermostat contains seven main components:

- **Sensors:** Basic thermostat functions require, at minimum, a single room temperature sensor. Additional sensors could monitor humidity, outside temperature, and other inside temperature points. Occupancy could be determined through infrared sensors. It could also be determined when a thermostat is connected to another system that monitors occupancy such as security systems.
- **Actuators:** Thermostats use a mechanical or electronic switch or relay to turn on or off the target space conditioning equipment.
- **Control logic:** A simple thermostat's control logic is a feedback loop that compares the target temperature with the current measured temperature. This determines when to turn on or off space conditioning equipment. Mechanical thermostats handled this, plus anticipation (to prevent overshooting the target) and hysteresis,[1] while modern programmable thermostats provide anticipation, hysteresis, and other features through electronics. Programmable thermostats use different temperature setpoints and modes depending on programs entered by the users. In certain thermostats, data are read from the settings, UI, and sensors. Such data are then used to create a set of algorithms that determines when the system switches on and off. New smart thermostats offer additional control functionalities, including remote control, event-driven control (for example, changing the setpoint when the house is unoccupied), and learning (for example, learning occupant preferences, occupancy patterns, and system lag).
- **User interface:** UI provides a means for input for thermostat control and an information display. UIs allow users to change target temperature settings, and on programmable thermostats, input a schedule of changing temperature settings while displaying information such as current and target temperatures. Remote interfaces include web portals on computers, mobile (smartphone) applications, TV interfaces, intelligent personal assistant such as Apple Siri (Apple, n.d.) or Amazon Alexa (Amazon, n.d.), and remote controls.
- **Communication interface:** A thermostat should communicate with a space conditioning system, generally through wired connections (at a minimum). Additional capabilities require communication such as: 1) arranging home area network

[1] Hysteresis prevents frequent switching of HVAC equipment to prevent mechanical failure via a deadband temperature (typically 1ºF [–17°C]).

connection, 2) receiving price or reliability signals from an energy provider, 3) streaming local weather forecasts, and 4) receiving control signals through some form of optimization service. This requires communication through various protocols.

- **Memory:** Programmable thermostats usually require data storage; memory can be permanent or volatile (i.e., disappears when power is disconnected). Data, such as time of the day and target temperature for each program, are needed for the thermostat control logic.
- **Power supply:** Modern thermostats require some form of power supply for operation. Batteries or low-voltage alternating current (AC) power from the space conditioning equipment typically provide this power. Thermostats often employ both systems, using the batteries to preserve settings in the event of power outages or other failures.

Thermostat Architecture and Control Logic Design

The following section of this appendix details the thermostat architecture and control logic design.

Connectivity

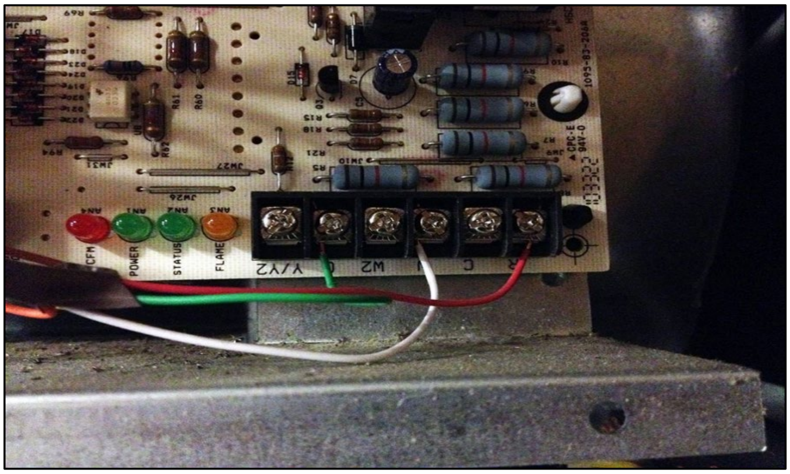
In its base model, the physical thermostat interface at the wall communicates to a smartphone or tablet via BLE. The thermostat has access to the internet through this smartphone or tablet, uploading and downloading data periodically (for example, intended to be at least one time per month). SW updates are also downloaded through this mechanism. When the thermostat is not connected, the data are stored in memory local to the device. The intent is to store approximately one month's worth of operational data. This approach overcomes the problem of low penetration of broadband in LIHs while still providing some degree of device connectivity.

One extended module — direct Wi-Fi — is an addition to the base thermostat model, since more than 50% of the target market does have broadband. When a home Wi-Fi connection is available, the thermostat can be extended through an onboard Wi-Fi chip to connect to the internet directly through the wireless access point and modem. While the second option is technically preferable, the base model may be the only viable option in certain households.

Power

In addition, the base model is battery powered: developers did not assume that HVAC equipment would "power" the thermostat. Developers do not know how many HVAC systems currently do not support electrical power; the assumption is that all air conditioners have some electrical component for control (for example, a C-wire or some capability of work around), but some heating systems do not have any electrical components. The research team anticipated that due to the mild California climates discussed in Chapter 1 and an older building stock, many LIHs are in older dwellings with simpler and older HVAC equipment. It could be assumed that a C-wire is not necessarily available to power the thermostat (see Figure A-1). Thus, the base model of the reference design will rely solely on battery power, such as two to three AA batteries for a targeted period of six months.

Figure A-1: Missing C-Wire on the Thermostat



Although the thermostat can run on battery power for six months, the thermostat is also intended to be compatible and capable of connecting to a C-wire if the HVAC system has one.

Interface

One project goal was to aim for a low-priced thermostat, at $60 (originally) and $75 (eventually). Since one of the most expensive parts of a thermostat is the UI, the research team decided to use a smartphone or tablet for the sophisticated input (for example, programming) and remote control of the thermostat, while maintaining a simple UI on the wall wired to the equipment. This was an important difference in thermostat design compared to other thermostats currently on the market.

Sensors

Temperature and humidity sensors were included in the base version of the thermostat. Occupancy sensors could be included in expansion modules. Preliminary specifications for sensors are shown in Figure A-2.

Figure A-2: Target Specification for Temperature and Relative Humidity Sensors

Specifications

Temperature ranges

Heat:	45 to 79 °F (7 to 26 °C)
Cool:	45 to 92 °F (14 to 33 °C)
Display:	40 to 100 °F (5 to 37 °C)
Sensitivity:	+/- 1 °F (0.5 °C)
Operating:	32 to 130 °F (0 to 55 °C)

Humidity Range

Display:	20 to 90% R.H.
Sensitivity:	+/- 5% R.H.
Operating:	5 to 95% R.H (non-condensing)

Source: EPA

Controls and Control Design

The design intent of the overall architecture of the thermostat was driven primarily by decreasing costs, reducing energy consumption,[2] and maintaining usability. The thermostat is designed to control the heating and/or cooling systems in the living space(s) to provide thermal comfort to residents over the changing days and seasons while reducing energy consumption.

The control functionality available include ON/OFF, a timer (15-minute increments), and default schedule (updated with a mobile interface), with less learning available due to limited memory and computation given battery power and no internet. Data collection and DR signals would occur through the mobile device. The overarching control paradigm (UI and internal algorithms) needs to balance energy with thermal comfort.

Thermal comfort is defined by ASHRAE Standard 55 as the "condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation" (ASHRAE, 2004). This project assumes a more simplistic approach that residential thermal comfort will be highly variable depending on the health, age, gender, activity, clothing, and other factors of the residents as well as the outdoor temperature, thermal characteristics (for example, insulation, mass) of the house, and HVAC equipment (size, age, efficiency).

HVAC systems have very slow dynamics — it takes time to heat up or cool down the house. Thus, the control systems need to consider this lag. The energy consequences of an action (for example, heating) are not instantaneous. To evaluate savings, one must consider a larger period since the system stores energy in different components (for example, thermal mass within the house, refrigerant in HVAC equipment).

The main strategy to save energy in residential HVAC systems is to reduce the runtime of the heating and cooling systems. The thermostat can enable this strategy in many ways:

- Reduce the difference in temperature between indoor and outdoor temperatures. (The main driver of energy use is heat transfer through the building envelope.)
  - When the house is NOT occupied, reduce/increase setpoints to let the indoor temperature drift towards the outdoor temperature.
    - Estimate occupancy (for example, schedules involve easy to deploy one-touch away functions for short absences or vacations).
    - Avoid discomfort when the occupant(s) return home (for example, maximum drift to recover to target indoor temperature, occupancy prediction).
  - When the house is occupied, adapt indoor temperature to outdoor conditions, season, activity level (for example, asleep) or use dynamic effects (for example, blast of air upon occupant arrival home during hot weather, then slowly increase the setpoint).

[2] Reducing energy consumption was historically directly correlated with bill savings. With TOU rates, it is important to differentiate bill savings with energy savings moving forward.

- Avoid conditioned temperature setpoint overshooting.
- Improve EE (for example, run fan after switching AC off, do not use resistance heat in the HP).
- Provide advice or tips to the occupant to use low-no energy alternatives: open windows in evening, reduce solar gains.

Another conflicting goal is to reduce wear and tear on the HVAC equipment. This is frequently obtained by reducing short cycling (that can have a negative impact on comfort). Basic functionality of the UI is outlined in Table A-1.

Table A-1: Control Functionality in the Wall and Phone Interface

Priority	Function	Wall Interface	Mobile Platform Interface
1	OFF (Heat ON or Cool ON)	Push button	Virtual push button or equivalent
2	Change the desired temperature (to be warmer or cooler)	Up/Down arrow buttons	Up/Down arrow buttons or equivalent functionality such as the use of sliders
3	Basic system feedback	LED lights or similar designs	Lighted interface and colors (could add sound)
4	Machine learning and optimization	Limited with base module in reference design stage, with examination of methods to improve optimization in pilot stages.	Can turn off – includes fault detection and diagnosis and model-predicted control, uses occupancy (if sensors are available) to modify target temperatures, implements adaptive comfort model
5	Display current temperature	Analog – LEDs in a semi-circle with printed text or similar functionality	Analog or digital – LEDs in a semicircle, or linear with printed temperature text, with background color indicating expected comfort
6	Timer	Push button to advance number of intervals (1-4)	Button to advance intervals, add number of intervals, and end with clock time
7	Away, Holiday, or Vacation modes	Not implemented	Potentially a single push button(s) that puts the thermostat into an energy saving mode for a period of time
8	Display target temperatures	Analog – LEDs in a semicircle with printed text	Analog or digital – LEDs in a semicircle, or linear with printed temperature text
9	Establish schedule	Not implemented; default schedule in place	Allows setting of a schedule with at least four time periods and four user-customizable periods

Priority	Function	Wall Interface	Mobile Platform Interface
10	Provide feedback on monthly budget	Not implemented	Allows user to set a monthly budget and see an updated rough estimate of running HVAC energy costs

Beyond the simple controls outlined in Table A-1, the researchers developed a framework of control logic in several layers. The base layer, 0, focuses on basic safety, layer 1 consists of direct control algorithms, layer 2 involves manual and static algorithms, layer 3 involves user input, and layer 4 includes supervisory control and intelligent algorithms. The layers imply priority, especially in the lower layers, such that safety issues (for example, minimum runtime and off time of the compressor) take precedence over the timer, which takes precedence over the hysteresis, which takes precedence over schedule. The following table outlines the overall control logic layers. The lower levels are embedded in the wall modules, while higher levels depend on memory constraints and persistence of internet connection — for example, assume once per year, once per month, or hourly (see Table A-2).

Table A-2: Control Logic Layers

Layer	Description	Variable Impacted	Example
Layer 0 – Safety and Consistency Rules	Safety limits to variables and operations	Setpoints or Heat/Cool calls	Minimum-maximum setpoint bounds, minimum runtime and minimum off for compressor
Layer 1 – Direct Control Algorithms	Traditional features found in thermostats	Heat/Cool calls	Smart recovery, hysteresis
Layer 2 – User Interaction	User inputs that override setpoints and intelligence	Setpoints	Hold or Timer, schedule
Layer 3 – Supervisory Control	Intelligent algorithms	Setpoints	Model predictive control (MPC)

Layer 0

Table A-3 outlines Layer 0: basic safety and consistency rules. Regarding HW, there are three relays to control: the heater (W), cooling — compressor (Y), and fan (G). In addition, there are four buttons: ON/OFF, TIMER, UP, and DOWN.

- ON/OFF button
  - OFF – just current temperature displayed
  - ON – current temperature and both heating and cooling setpoints displayed)
  - Under consideration: RESET – hold button for five seconds

- TIMER button
    - One push — first quarter (upper right) segment LED lit
    - Second push — first and second quarter (lower right) segment LED lit
    - Third push — first, second, and third quarter (lower left) segment LED lit
    - Fourth push — all quarter segment LEDs lit
    - Fifth push — resets to zero — nothing lit
    - Default is 15-min intervals, configurable by mobile app
    - LEDs turn off sequentially as the timer counts down
- UP/DOWN buttons
    - UP (button on right): one push advances both heating and cooling setpoints 2°F
    - DOWN (button on left): one push: reduces both heating and cooling setpoints down 2°F (–17°C)

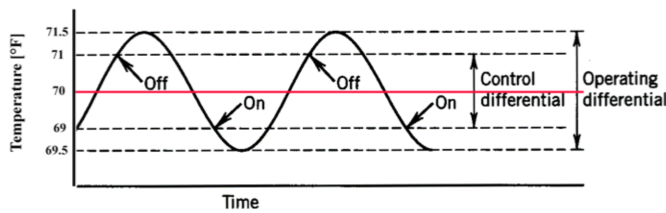
Table A-3: Layer 0 — Basic Safety and Consistency Rules

Rule	Description	Notes
Compressor minimum time ON	Safety feature to avoid short cycling for A/C	Just a timer (5 min)
Compressor minimum time OFF	Safety feature to avoid short cycling for A/C	Just a timer (5 min)
Furnace minimum time ON	Safety feature to avoid short cycling for heating	Just a timer (5 min)
Furnace minimum time OFF	Safety feature to avoid short cycling for heating	Just a timer (5 min)
When cooling ON, turn on fan as well	Control both the compressor and blower fan relay	Both relays ON
Check fan is working if the compressor is ON (relay stuck, or fan broken)	If the compressor is ON, but temperature is not decreasing, check that fan is working	Feedback from inside temperature
Boundaries to maximum–minimum temp setpoints		Minimum-maximum heat is 35-75°F (2°-24°C); minimum-maximum cool is 75-95°F (24°-35°C)
Either heat or cool relay are ON at the same time — never both		
Heat setpoint must be below cool setpoint		Minimum deadband is 6°F (–14°C) (default is 8°F [–13°C])
System match		
Different strategy for gas/electric heating		

Layer 1: Direct Control Algorithms

The layer 1 strategies include algorithms that directly impact equipment relays (the setpoints remain unchanged) (Table A-4).

Table A-4: Layer 1 — Direct Control Algorithms

Strategy	Description	Notes
Hysteresis on setpoints	Cool or heat beyond the setpoint (this reduces short cycling equipment). For example, if the heating setpoint is 70°F (21°C) (red line below), the heating relay would turn on at 69°F (21°C) and turn off at 71°F (22°C), using a ±1°F (0.6°C). symmetric hysteresis. For cooling, the relay would turn on at setpoint +1°F (–17°C) and off at setpoint –1°F (–18°C) 	The hysteresis needs to be adjustable. Default is to set +1°F (–17°C) around setpoint, symmetric for now (maximum hysteresis is 2°F [–17°C]).
Timer	The thermostat remains on for the length of time set by the timer then turns off. The user can change the setpoint then activate the timer, or activate the timer then change the setpoint. The timer does not trigger HVAC equipment.	Interval is configura-ble; default is 15 minutes (maximum is 1 hour).
Fan blowing after AC turned off (also for heating)	When the cooling coil is switched off, keep running the FAN for a few minutes to get “free” cooling.	This is slated to be an option with adjustable time.
Pre-comfort recovery	The system calculates the time derivative of temperature (how much time it takes to reduce or increase 1°F [0.6°C] given the house and equipment) and starts X min earlier to reach setpoint (target temperature) exactly at the scheduled time.	Since this strategy can waste energy and complicates higher-level control strategies, it will only be activated as necessary.
Advanced smart recovery	Advanced version of pre-comfort recovery uses weather data and a simplified model of the house to optimize start and stop times.	This can be considered a supervisory control strategy if it changes setpoints.
Optimal HP management	Variation of advanced smart recovery to avoid using the second stage (HP electric resis-tance), which is much more expensive.	Detection of HPs is necessary if HPs are included.

Strategy	Description	Notes
Optimal humidity control)	Not included for this module.	Add to next steps.

Layer 2: Manual and Static Automatic Algorithms

This layer describes algorithms that impact setpoints, such as a regular schedule or occupant overrides (Table A-5).

Table A-5: Layer 2 — Static Automatic Algorithms and Overrides

Strategy	Description	Notes
Schedule	Time events that relate to occupancy schedule and sleep – (for example, 6 AM: Home-Morning, 9 AM: Away; 6 PM Home-Evening, 10 PM: Sleep). Default modalities are Home-Morning, Away, Home-Evening, and Sleep; extra modalities can be created.	Each time modality has a user-adjustable heating and cooling setpoint temperature. A wizard on the mobile app can help users choose a typical mostly-home-all-day or mostly-away-weekdays, or a variable schedule.
Override	If the user changes the temperature set-points, this setting temporarily overrides the scheduled setpoints until the next scheduled epoch begins.	
Occupancy sensor override	If occupancy or no occupancy is detected, this overrides setpoints if occupied during scheduled unoccupied hours (for example, Away) or unoccupied during scheduled occupied hours (Home-Morning or Home-Evening).	The default time will need to be determined if no occupancy is detected during an occupied epoch.
Hold	The mobile phone app permits a type of definite (not indefinite) Hold function (maintain a setpoint for a duration of time).	

Layer 3: User Interaction

The user has the choice to engage regularly with the thermostat (fully manual mode) to "set it and forget it." The user can employ the simple wall module to turn on and off the thermostat, change the setpoints, and set a timer to turn on the heat or cooling for a given amount of time. The user can employ the more sophisticated mobile interface on a smartphone or tablet to perform the same operations as on the wall module and can also set a schedule, turn off intelligence, set a monthly budget and see how the running total compares to this budget, and view alerts such as maintenance needs or DR events among other tips.

Layer 4: Supervisory Control Algorithms

Supervisory control algorithms require additional power draw and are therefore considered based on C-wire availability or other methods to power the thermostat (thus increasing cost) (Table A-6).

Table A-6: Layer 4 — Supervisory Control Algorithms

Model	Smart Control Strategy	User Input
	Learning a schedule (similarity-based auto-population of the programmable schedule)	User can activate or switch off intelligence.
	Adaptive MPC-based HVAC cost optimization respecting the above (learned or programmed) schedule and the associated discomfort constraints	User can activate or switch off intelligence and choose whether to use the (similarity-based) learned schedule or the original user-defined schedule.
Expansion +	Adaptive MPC-based HVAC cost optimization respecting the private information retrieval (PIR)-supported similarity-based learned schedule and the associated constraints	User can activate or switch off intelligence and choose whether to use the (PIR-supported similarity-based) learned schedule or the original schedule.

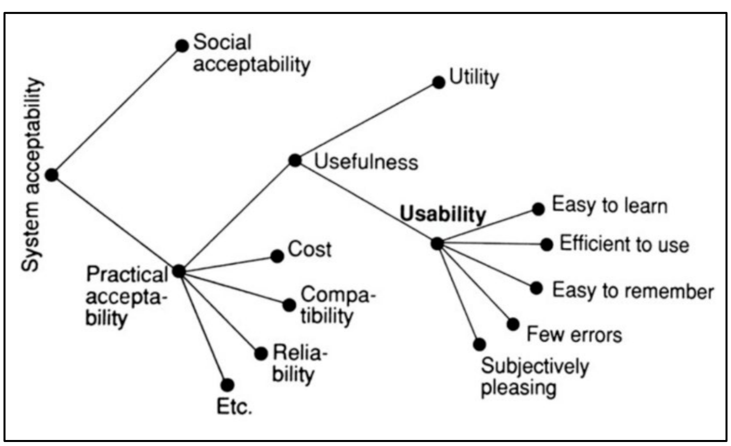
User Interface Design

The following section provides additional information on background materials and research efforts to develop the thermostat's UI.

Developing Metrics for Thermostat Usability

This report considers a "good" thermostat design as one that is not only easy to use but also provides needed user functions cost effectively and, in a manner, compatible with existing equipment. Nielsen (Figure A-3 (Nielsen, 1993)) provides a diagram that the team uses to explain the various factors involved in system acceptance and adoption of new technology, including the role of usability.

Figure A-3: Nielsen Factors of System Usability



Source: Jakob Nielsen, *Usability Engineering*

As previously discussed, the EPA review and other studies indicate that people find programmable thermostats difficult to understand, which then causes a lack of confidence and motivation to overcome difficulties in programming. User complaints collected from secondary research include energy use misconceptions, lengthy operating manuals, and social and practical barriers to using thermostats. User misconceptions are important as they may potentially encourage incorrect use that cannot be easily overcome by better interfaces. When users complained about the thermostats, they noted their complexity, small size of text and buttons, confusing symbols and terms, and the number of steps needed to complete basic device programming. Several studies indicated disparate attitudes towards thermostats where some users preferred never to adjust their thermostats, while other users were afraid of touching them. Note that these groups will have different priorities for top-level features.

The team developed six tasks for each user to complete important functionalities of programmable thermostats. These tasks were also chosen in consideration of their effect on residential energy conservation.

- **Task 1 – Set Heat:** Users were asked how they would like to set their thermostat to HEAT mode if it were wintertime. The HEAT-OFF switch is a common control found in typical thermostats. The setting was OFF at the start.
- **Task 2 – Time & Day:** Users were asked to set the date and time of the thermostat.
- **Task 3 – Current Settings:** Users were asked to identify and read current settings such as the thermostat temperature.
- **Task 4 – Future Settings:** Users were asked to identify the future temperature setting. Users were told that they only needed to identify the temperature already programmed and did not need to change any of the temperature program settings.
- **Task 5 – Vacation/Hold:** Users were asked to imagine they were going on vacation and needed to set their thermostat to maintain the same temperature during the time they were away.
- **Task 6 – Future Scheduling:** Users were asked to program an entire week of set-points. Note that none of the subjects were able to complete the task.

Many of the thermostat interfaces were both difficult and complicated for the user, which led to frustration and major barriers to task completion. Usability tests were determined by successful completion, time to completion, and ending time for incomplete tests. This provided a means to evaluate the device as well as attribute problems. The goal was to identify keys to success to sustained and persistent thermostat usability. The team assumed that successful task completion meant the subject found the interface usable from a point of view that was strictly functional. Ease of learning was the key attribute of this usability lab test.

The team developed, computed, and tested four novel metrics appropriate to thermostats and similar devices:

- **Time and success:** Whether the task was successfully completed and the time it took to complete the task.

- **Path length:** A series of button presses it took to get to a certain desired task. Path length was determined by the thermostat user's manual. Number of functions used was determined and calculated by the number of functions a user attempted to complete a task —- both successful and unsuccessful actions. For example, when a user attempted to press an area of a device that was not touch sensitive, this was also considered a function as part of the path length.
- **Button mash:** Button mash can be defined as the number of times a user tried to interact with the interface without changing any programming and/or state of the thermostat. These can also be defined as actions that had no effect on the state of the thermostat.
- **Confusion:** Confusion can be defined as a summary of all the hesitations[3] that users experienced trying to complete a task.

The metrics provided an identical ranking of the thermostats. In later work with the EPA, the team determined that the Time and Success metric could be used solely as an indicator of usability (and was the easiest to implement).

User Interface Design Guidelines

Users had higher success rates with thermostat displays with positive examples of guidelines such as clear feedback mechanisms, possible visible actions, and consistency and standardization of information. Other guidelines identified by the team that seemed to be missing are detailed in Table A-7 alongside secondary research sources that support these suggestions.

Table A-7: Guideline for Successful Thermostat Displays

Guideline Name	Reference	Good Example	Poor Example
Available option visibility	Polson and Lewis 1990; Norman 2002	Large screen, multiple windows, menu	Cover hides buttons and features
Occasional use considerations	Polson and Lewis 1990, Nielsen 1993, Norman 2002, Bordass et al. 2007, Shneiderman et al. 2009	Features available upon first glance	Cover hides buttons and features
Controls feedback	Karjalainen 2009, Bordass et al. 2007, Shneiderman et al. 2009	Buttons provide an audible beep when touched	Touchscreen not always responsive
System and real-world matching	Nielsen 1993	Drag pointer to change setpoint on analog scale	Up/down arrow buttons only on selected screens

[3] In this setting, a hesitation is defined as a stop or pause in interacting with the thermostat that lasted for more than three seconds — an indicator that the user was unsure of what needed to be done to complete a task.

Guideline Name	Reference	Good Example	Poor Example
Natural mapping usage	Norman 2002	2-D, tabular format for visualizing day/time/temp setpoint	Menu labels not descriptive; non-standard abbreviations
Standards and consistency	Nielsen 1993, Norman 2002, Shneiderman et al. 2009	2-D, tabular format for visualizing day/time/temp setpoint	Not clear what constitutes a button on the touchscreen and what is text
User control and freedom	Nielsen 1993, Karjalainen 2009	"OK" button	Hold/return button allows user to exit and go to next, no way to cancel vacation setting
Recovery, recognition, and error prevention	Polson and Lewis 1990, Nielsen 1993, Norman 2002, Shneiderman et al. 2009		No confirmation
Usage efficiency and flexibility	Norman 2002	Pop-up balloons to see temperature	
Work effectively	Bordass et al. 2007	One touch buttons for energy use/comfort mode during day	
Designs that are both aesthetic and minimalistic	Polson and Lewis 1990, Nielsen 1993, Norman 2002, Bordass et al. 2007, Karjalainen 2009, Shneiderman et al. 2009	Color, graphics	Switches, a button, and touch screen; three font types (segmented, dot matrix, stroke)
Readily available help and documentation	Nielsen 1993, Karjalainen 2009	Wizard	Cryptic instructions on inside of cover

Thermostat displays with positive examples of the guidelines summarized in Table A-7 performed better. However, this varied by task. For example, subjects using the web display in general performed well as this provided more capabilities such as larger screen and more user familiarity with web-based displays. The work also noted that that some sectors of the population (for example, LI seniors) may still require a stand-alone and simple device —-differing from the results detailed in Table A-7. For this project, the expectation was that the wall display would be simple from usability, power conversion, and cost perspectives. Additional functionality through a smartphone display would have been preferred.

The guidelines in Table A-7 are useful in determining thermostat task completion. Results of this effort also show visibility of available options associated with walk-up-and-use feature (e.g., availability of information on main screens) as one of the more important features in ease of use. For example, covers that hid buttons on certain thermostats, most likely for simplified appearance and aesthetics, seemed to reduce thermostat usability as it pertained to completing tasks that required the use of these buttons. Users appeared confused when information was not available on the home screen. Unclear terminology (for example, setting the time on the smart thermostat) also caused confusion.

Standards and consistency were also pertinent in enabling better thermostat usability. For example, hybrid thermostats — with buttons on the HW as well as touchscreens — caused user confusion as it was unclear what was a button that could be pressed and what could not. A limited number of users in usability testing could set the day and time and enable hold functions using the hybrid thermostat interfaces. A combination of non-standardized instructions and lack of user familiarity with terms such as Settings or Setpoint, Current, and Hold seemed to create confusion. Hybrid thermostat interfaces also caused operational inconsistencies. It was unclear which words on the touchscreen were touch sensitive (a button) versus which words on the touchscreen were used for informational purposes.

Previous usability studies have shown feedback on user behavior may be critical to thermostat usability and associated user satisfaction (Sonderegger & Sauer, 2009). Previous usability tests show that lack of user feedback prompts may have been an issue in thermostat usability. These tests showed that users made errors when they failed to save changes as there was no confirmation prompt like computer interfaces provide (e.g., "Do you want to save changes?").

Work identified additional best practices that were not covered in Table A-7. For example, availability of many critical options at first glance with few choice layers[4] was more important than the total number of actions required to achieve a task (i.e., path length) (Shneiderman, 1988). In another example, many web designers state that it takes longer to decide when presented with the option in a large set of options versus a smaller set (Seow, 2005), (Mavrogianni et al., 2013). This is most likely because each decision point represents a chance to get lost with the number of choices exacerbating confusion. A third example is the importance of a user knowing where one is in the process. A user could become confused as to whether they were able to edit and make changes in the thermostat settings or were just in a "read only" mode. With respect to reducing cognitive load and improving visual aesthetics, another issue involves development of a clear hierarchy so that the most frequently used functions are displayed prominently (e.g., such as the most important options being in the largest font). These attributes would help prevent the user from getting lost and would thus help the user develop more confidence in terms of the interface.

Persona Development

Persona creation can include personal biases and might not represent the target population. Hence, some amount of user research is required to supplement persona creation. To narrow

[4] Choice layers can be summarized as the number of choices within a given screen. For example, a menu (Level 1) with x choices, each of which (Level 2) has y choices, each of which (Level 3) has z choices and so on.

down to a real user of the low-cost thermostat, the project team thought of the categories of people who would be using it. Thermostat users can be divided into three broad categories: 1) people who do not have any idea about energy saving and do not care about it; 2) people who know about energy saving and need motivation to act to save energy; and 3), people who actively engage in energy saving activities and are concerned about energy utilization in general. Included in these three LIH categories are early technology adopters and slow adopters. Among these categories, there is further subdivision into categories of age groups, which relate to various levels of responsibilities and thereby translate to various behavioral patterns. The researchers decided on the categories of students, working adults, and senior citizens.

Hardware Reference Design Details

The HW reference design thermostat, as shown in Figure A-4, can control a standard single-stage heating and/or cooling system with a circular fan. The design features a temperature sensor, humidity sensor, PIR sensor, real-time clock, and 1-Mbit electrically erasable programmable read-only memory (EEPROM). Wireless communication is achieved via the 802.15.4 radio or the BLE radio. The thermostat can be powered by 3 AA batteries or by 24 VAC power. The design also includes a simple UI with four buttons and LED-based temperature and setting indications. The UI can easily be replaced with a custom board by connecting to the main thermostat board via pinouts for the I2C bus, a power supply, two analog pins, and four digital pins.

The following list details the bill of materials (BOM) for the reference design.

- AT30TS74 – temperature sensor
  - The AT30TS74 temperature sensor has a configurable resolution of 9–12 bits and a typical accuracy of ±1.8°F (1°C).
- HDC1080 – humidity and temperature sensor
  - The HDC1080 humidity and temperature sensor has a configurable resolution of 8, 11, or 14 bits for humidity and 11 or 14 bits for temperature. The typical accuracy for humidity and temperature is ±2% and ±0.4°F (0.2°C), respectively.
- MCP7940N – real-time clock
  - The MCP7940N is a real-time clock/calendar with static random access memory.
- AT24CM02 – device storage/memory
  - The AT24CM02 provides 2 Mbits (256 Kbytes) of serial EEPROM. (Note: The original version of the Hamilton thermostat included AT24CM01 chips.)
- PCA9557 – input/output ports
  - The PCA9557 is an 8-channel I/O parallel port expander. The expander is used to control the three latching relays (EE2-3TNUH-L) that actuate the heating system, cooling system, and circular fan.

- TLC59116 – LED drivers
  - The TLC59116 is a 16-channel constant-current LED sink driver with 256-step (8-bit) linear programmable brightness. The Hamilton thermostat interface board includes three TLC59116 chips.
- EKMB1101111 – motion sensor
  - The EKMB1101111 is a fully integrated PIR motion sensor with 1 µA low current consumption. The output of the PIR sensor is connected to pin PA06 of the SAMR21 chip and P05/AIN6 of the NRF51822 chip.

Communication

Communication between the SAMR21 chip or the NRF51822 chip and the other components of the HW reference design is primarily achieved via the shared I2C bus. Communication between the SAMR21 chip and the NRF51822 chip is achieved over an SPI link. The HW reference design is capable of wireless communication via the 802.15.4 radio (built into the SAMR21 chip) and the BLE radio (built into the NRF51822 chip).

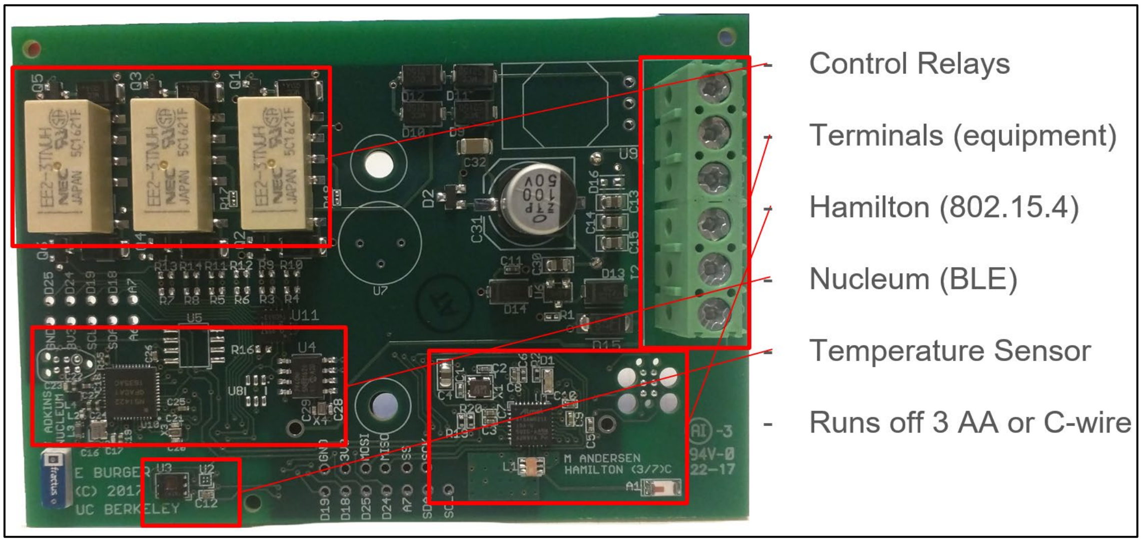
Relays

The main board of the HW reference design includes three EE2-3TNUH-L dual-coil latching signal relays for actuating a heating system (W wire), cooling system (Y wire), and circular fan (G wire). Each relay is rated for a coil voltage of 3 V direct current (DC), a contact current of 2 amps (A), and a switching voltage of up to 250 VAC. Because the EE2-3TNUH-L is a latching relay, it maintains the contact position indefinitely without requiring current to be applied. Thus, each relay contains two coils (one for setting and one for releasing), and a current pulse is applied to either coil to change the contact position. Note that applying a current to one of the coils over a long period of time will damage the relay.

Each relay is connected to either the W wire (heat), Y wire (cooling), or G wire (fan). Setting a relay will connect the respective wire to the R/Rh/Rc wire, and releasing the relay will sever the connection. The relays are controlled via the PCA9557 8-channel input/output (I/O) expander. The W relay is connected to I/O0 for setting and I/O1 for releasing, the Y relay to I/O2 for setting and I/O3 for releasing, and the G relay to I/O4 for setting and I/O5 for releasing.

Lastly, the HW reference design is capable of simultaneously connecting the G wire when the W relay or Y relay is set. Adding the R18 jumper will cause the W relay to connect both the W and G wires to the R wire when the relay is set. Adding the R17 jumper will cause the Y relay to connect the Y and G relays to R.

Figure A-4: Soldered Hardware Reference Design Printed Circuit Board with Thermostat Components



Power

The HW reference design is battery powered. The Hamilton thermostat main board includes a 3 AA battery holder and an AP2210 3.3 VDC 300 mA low-dropout (LDO) regulator. If necessary, the regulator can be bypassed by adding the R1 jumper.

If a C-wire is available, the thermostat can also operate on 24 VAC power. For AC/DC conversion, the main board includes a full wave bridge rectifier and an OKI-78SR 36 VDC to 3.3 VDC 1.5 A buck (step-down) converter. The thermostat is designed to allow for operation on 24 VAC power with battery backup.

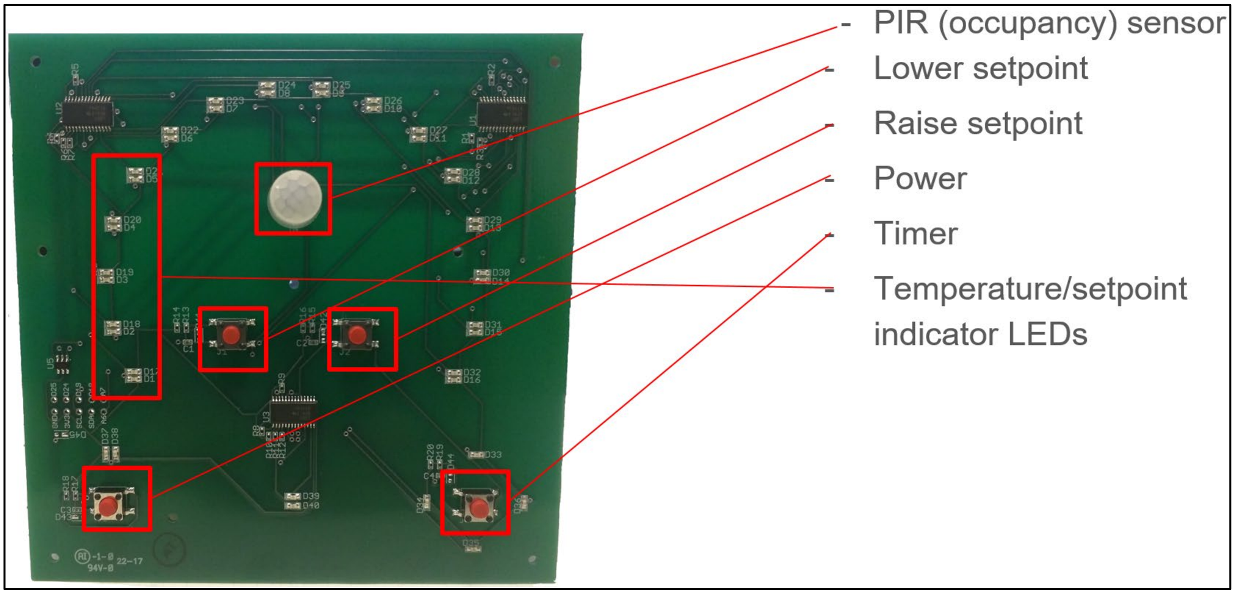
User Interface

The HW reference design has a simple and intuitive UI for communicating the current temperature measurement and setpoint and for enabling a user to perform basic operations such as setting the mode (heating, cooling, off) and adjusting the setpoint. The interface board includes four buttons: one for setting the mode, two for adjusting the temperature setpoint, and one for setting a temporary temperature hold.

The board also includes 40 LEDs for denoting the thermostat settings. To communicate the current temperature measurement and setpoint, 32 of the LEDs are arranged in an arc around the center of the board (16 for the measurement and 16 for the setpoint). The LEDs are controlled via three TLC59116 16-channel LED sink drivers.

The interface board is connected to the main thermostat board via pinouts for the I2C bus (serial data [SDA] and serial clock [SCL]), power (+3.3 VDC and ground [GND]), analog pins A6 and A7, and digital pins D18, D19, D24, and D25 (see Figure A-5).

Figure A-5: Human Interface Board with 40 Green and Red Light Emitting Diodes



Bill of Materials and Estimated Costs

Table A-8 provides estimated costs associated with the reference HW design. Note that these are all off-the shelf products not intended for product manufacturing. It is assumed that many of these costs would decrease.

Table A-8: Hardware Bill of Materials for Reference Prototype

Device	Cost (when buying 1000 units	Number of Components Needed	Total Cost (Components)
NRF51822	$1.918	1	$1.92
Latching Relay	$1.691	5	$8.46
Balun	$0.41	1	$0.41
Antenna	$0.25	1	$0.25
Crystal	$0.577	1	$0.58
LED	$0.568	1	$0.57
Push Button	$0.8	3	$2.40
Temperature Sensor	$0.624	1	$0.62
Flash Memory	$0,5	1	$0.50
Humidity Sensor	$1.546	1	$1.55
USB Chip	$2.65	1	$2.65
USB Connector	$0.26	1	$0.26
Headers	$0.03	10	$0.30
LDO	$0.36	1	$0.36

Device	Cost (when buying 1000 units	Number of Components Needed	Total Cost (Components)
UVLO	$0.41	1	$0.41
Battery Contact	$0.50	6	$3.00

Bluetooth Interface Design

The following section details specifics on designing the Bluetooth interface required for thermostat communication and data transfer.

Requirements for Data Exchange

The mobile app connects to the thermostat HW using a BLE protocol to perform tasks such as pairing, changing thermostat configuration, receiving operating data, and synchronizing schedules. Additionally, the onboard clock on the HW unit is synchronized through the app.

Data flows

The app needs to provide the following:

- Synchronized time based on current time. This must be done when the Lydia app connects to the Lydia HW for the first time and need not be done on every connection.
- User's manual setpoints
- User preference mode (Heat+Cool, Heat Only, Cool Only)
- Schedules, including DR events
- Timer action event (number of minutes): The user can set timer on app, and the timer must be executed when connected.

The HW unit needs to provide the following:

- Current temperature
- Current state: heating/cooling/none
- Temperature buffer data with acknowledgement
- Runtime buffer data with acknowledgement
- Setpoint buffer data with acknowledgement

Table A-9, Table A-10, Table A-11, and Table A-12 provide the temperature stored data transfer format in the temperature HW unit.

Table A-9: Format of Data Transfer for Temperatures Stored in Temperature Buffer in Thermostat Hardware (1 of 4)

0	1	2	3	4	5	6	7	8	9	10	11
Year	Month	Day	Hour	Min	Num elements (N)	[0] Diff time LSB	[0] Diff time MSB	[0] Current temp	[0] Relative humidity	[1] Diff time LSB	[1] Diff time MSB

Table A-10: Format of Data Transfer for Temperatures Stored in Temperature Buffer in Thermostat Hardware (2 of 4)

12	13	14	15	16	17	18	19	20	21	22	23
[1] Current temp	[1] Relative humidity	[2] Diff time LSB	[2] Diff time MSB	[2] Current temp	[2] Relative humidity	[3] Diff time LSB	[3] Diff time MSB	[3] Current temp	[3] Relative humidity	[4] Diff time LSB	[4] Diff time MSB

Table A-11: Format of Data Transfer for Temperatures Stored in Temperature Buffer in Thermostat Hardware (3 of 4)

12	13	14	15	16	17	18	19	20	21	22	23
[4] Current temp	[4] Relative humidity	[5] Diff time LSB	[5] Diff time MSB	[5] Current temp	[5] Relative humidity	[6] Diff time LSB	[6] Diff time MSB	[6] Current temp	[6] Relative humidity	[7] Diff time LSB	[7] Diff time MSB

Table A-12: Format of Data Transfer for Temperatures Stored in Temperature Buffer in Thermostat Hardware (4 of 4)

24	25	…	…	…	..	…	..	6+ 4* (N-1)	6+ 4* (N-1)+1	6+ 4* (N-1) +2	6+ 4* (N-1)+3
[7] Current temp	[7] Relative humidity	…	….	…	….	….	….	[N-1] Diff time LSB	[N-1] Diff time MSB	[N-1] Current temp	[N-1] Relative humidity

Table A-13, Table A-14, Table A-15, and Table A-16 provide the format of data transfer protocols for runtimes. Note: Data transfer protocol is like the previous case, except the data belongs to the runtime data category.

Table A-13: Format of Data Transfer for Runtimes Stored in Runtime Buffer in Thermostat Hardware (1 of 4)

0	1	2	3	4	5	6	7	8	9	10	11
Year	Month	Day	Hour	Min	Num elements (N)	[0] Diff time LSB	[0] Diff time MSB	[0] Cool inf	[0] Heat info	[1] Diff time LSB	[1] Diff time MSB

Table A-14: Format of Data Transfer for Runtimes Stored in Runtime Buffer in Thermostat Hardware (2 of 4)

12	13	14	15	16	17	18	19	20	21	22	23
[1] Cool inf	[1] Heat inf	[2] Diff time LSB	[2] Diff time MSB	[2] Cool inf	[2] Heat inf	[3] Diff time LSB	[3] Diff time MSB	[3] Cool inf	[3] Heat inf	[4] Diff time LSB	[4] Diff time MSB

Table A-15: Format of Data Transfer for Runtimes Stored in Runtime Buffer in Thermostat Hardware (3 of 4)

12	13	14	15	16	17	18	19	20	21	22	23
[4] Cool inf	[4] Heat inf	[5] Diff time LSB	[5] Diff time MSB	[5] Cool inf	[5] Heat Inf	[6] Diff time LSB	[6] Diff time MSB	[6] Cool inf	[6] Heat inf	[7] Diff time LSB	[7] Diff time MSB

Table A-16: Format of Data Transfer for Runtimes Stored in Runtime Buffer in Thermostat Hardware (4 of 4)

24	25	…	…	…	..	…	..	6+ 4* (N-1)	6+ 4* (N-1) +1	6+ 4* (N-1) +2	6+ 4* (N-1) +3
[7] Cool inf	[7] Heat inf	…	….	…	….	….	….	[N-1] Diff time LSB	[N-1] Diff time MSB	[N-1] Cool inf	[N-1] Heat info

Table A-17, Table A-18, Table A-19, and Table A-20 provide the format of data transfer for setpoints stored in setpoint buffer in thermostat HW.

Table A-17: Format of Data Transfer for Setpoints Stored in Setpoint Buffer in Thermostat Hardware (1 of 4)

0	1	2	3	4	5	6	7	8	9	10	11
Year	Month	Day	Hour	Min	Num elements (N)	[0] Diff time LSB	[0] Diff time MSB	[0] Cool setpoi nt	[0] Heat set-point	[1] Diff time LSB	[1] Diff time MSB

Table A-18: Format of Data Transfer for Setpoints Stored in Setpoint Buffer in Thermostat Hardware (2 of 4)

12	13	14	15	16	17	18	19	20	21	22	23
[1] Cool set-point	[1] Heat set-point	[2] Diff time LSB	[2] Diff time MSB	[2] Cool set-point	[2] Heat setpoint	[3] Diff time LSB	[3] Diff time MSB	[3] Cool set-point	[3] Heat set-point	[4] Diff time LSB	[4] Diff time MSB

Table A-19: Format of Data Transfer for Setpoints Stored in Setpoint Buffer in Thermostat Hardware (3 of 4)

12	13	14	15	16	17	18	19	20	21	22	23
[4] Cool set-point	[4] Heat set-point	[5] Diff time LSB	[5] Diff time MSB	[5] Cool set-point	[5] Heat setpoint	[6] Diff time LSB	[6] Diff time MSB	[6] Cool set-point	[6] Heat set-point	[7] Diff time LSB	[7] Diff time MSB

Table A-20: Format of Data Transfer for Setpoints Stored in Setpoint Buffer in Thermostat Hardware (4 of 4)

24	25	…	…	…	..	…	..	6+ 4* (N-1)	6+ 4* (N-1)+1	6+ 4* (N-1) +2	6+ 4* (N-1)+3
[7] Cool set-point	[7] Heat set-point	…	….	…	….	….	….	[N-1] Diff time LSB	[N-1] Diff time MSB	[N-1] Cool setpoint	[N-1] Heat setpoint

The most significant bit of the cool and heat setpoint signifies the following:

- IF bit 7 of cool/heat setpoint is 1, it has been set via the app.
- IF bit 7 of cool/heat setpoint is 0, it has been set via the HW interface.

Table A-21 and Table A-22 provide the format of data transfer for schedules from app to thermostat HW.

Table A-21: Format of Data Transfer for Schedules from App to Thermostat Hardware (1 of 2)

0	1	2	3	4	5	6	7	8	9
< schedule >						< schedule >			

Table A-22: Format of Data Transfer for Schedules from App to Thermostat Hardware (2 of 2)

10	11	12	13	14	15	16	17	18	19
< schedule >						< schedule >			

- REGULAR VALUES of Byte 0
  - Bits 0-3 => represent the schedule number for the day beginning from 0-4 (maximum of five schedules)
  - Bits 4-7 => day of the week that belongs to the schedule (0-6 represent Sunday through Saturday)

- SPECIAL VALUES of Byte 0
    - 0x0F => The four bytes in the schedule correspond to the following: <month (0-12)><day (0-31)> <hour (0-24)> <minute (0-60)>
    - 0xF0 => The four bytes in the schedule correspond to the following: <duration hours><duration minutes><heat setpoint> <cool setpoint>
    - 0xFF => End of Schedules. The four bytes in the schedule are ignored.
- Byte 1 – Byte 4: Values of these bytes for the regular values of Byte 0
    - Byte 1: Value of hour in 24-hour format (0-24)
    - Byte 2: Value of minute (0-60)
    - Byte 3: Cool setpoint
    - Byte 4: Heat setpoint

Table A-23 provides an example of sending all schedules, including DR events.

Table A-23: Thermostat Sending All Schedules Including Demand Response Events

Byte 0 of Schedule (Binary format)	Byte 1 – Byte 4 of Schedule
0000 0000	First schedule for Sunday
0000 0001	Second schedule for Sunday
0000 0010	Third schedule for Sunday
0000 0011	Fourth schedule for Sunday
0000 0100	Fifth schedule for Sunday
0001 0000	First schedule for Monday
0001 0001	Second schedule for Monday
0001 0010	Third schedule for Monday
0001 0011	Fourth schedule for Monday
0001 0100	Fifth schedule for Monday
0010 0000	First schedule for Tuesday
…	…
0010 0100	Fifth schedule for Tuesday
0011 0000	First schedule for Wednesday
…	…
0011 0100	Fifth schedule for Wednesday
0100 0000	First schedule for Thursday
…	…
0100 0100	Fifth schedule for Thursday

Byte 0 of Schedule (Binary format)	Byte 1 – Byte 4 of Schedule
0101 0000	First schedule for Friday
…	…
0101 0100	Fifth schedule for Friday
0110 0000	First schedule for Saturday
…	…
0110 0100	Fifth schedule for Saturday
0000 1111	DR event: <month (0-12)><day (0-31)> <hour (0-24)> <minute (0-60)>
1111 0000	DR event: <duration hours><duration minutes><heat setpoint> <cool setpoint>
1111 1111	End of schedules (4 bytes in this segment are ignored)

Figure A-6 and Figure A-7 provide the order of read/write BLE characteristics.

Figure A-6: (1 of 2) Read-Write Characteristics Between Mobile Applications (Labeled as Android App) and Thermostat Hardware (Labeled as LITA HW)

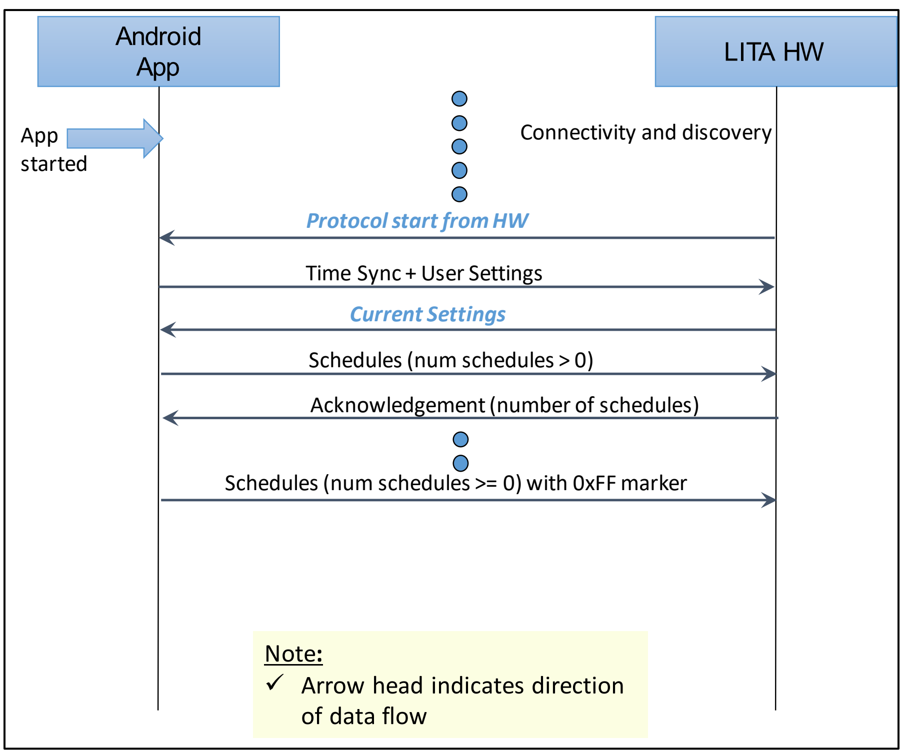
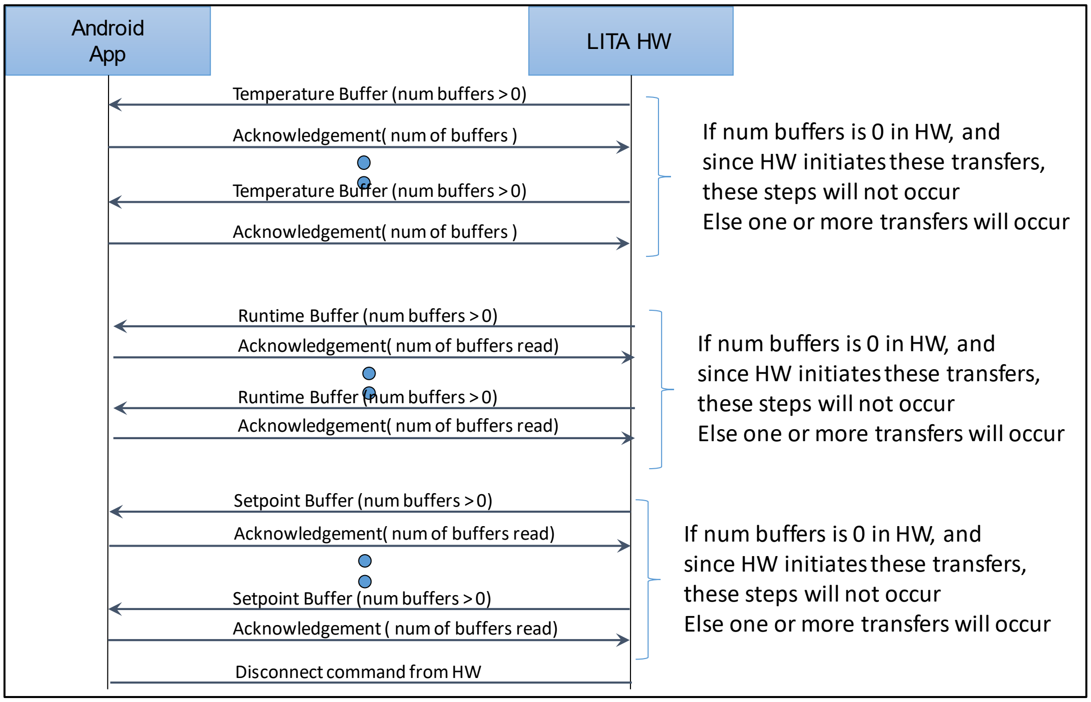


Figure A-7: (2 of 2) Read-Write Characteristics Between Mobile Applications (Labeled as Android App) and Thermostat Hardware (Labeled as LITA HW)



Combining Multiple Characteristic Data Bytes in a Single Transmission

The HW module does take more time when working with different characteristics; hence, it was decided to use just one characteristic for read and write. To be able to conserve battery power on the HW, it was decided to check out the maximum capacity of the transmission buffer, which was 128 bytes for the RN-4871 module on Lydia. The ability to use multiple characteristic data bytes in a single transmission is beneficial.

The protocol, therefore, remains the same, but whenever possible, developers combined multiple data bytes into a single read/write unit on a single characteristic. Towards this goal, developers have added a two-byte wrapper at the beginning of the data for each transmission and will allow the format to support combining of multiple data types (see Table A-24).

Table A-24: Method for Combining Multiple Characteristic Data Bytes in a Single Transmission

Byte 0	Byte 1	Byte 2	Byte 3	....	....	....	Byte	....	Byte (N-1)
(N) Length of data in this package including this byte	Number of characteristics formats com-bined in this message; if only one type of data, this will be set to 1	<ID for characteristic data>	<Data bytes for the characteristic>				<ID for next characteristic data>	<Data bytes for the characteristic>	

Byte Number	Byte Content Description
Byte 0	(N) Length of data in this packet including this byte
Byte 1	Number of characteristic formats combined in this message; if only one type of data, this will be set to 1
Byte 2	<ID for the characteristic data>
Byte 3 thru Byte (N-2)	<Data bytes for the characteristic>
Byte (N-1)	<Data bytes for the characteristic>
Byte	<ID for next characteristic>

Table A-25 provides identifiers for a defined list of thermostat characteristics.

Table A-25: Identifiers for Defined List of Characteristics

Service Name	Identifier (one byte)
Current Settings	0x01
Status from HW	0x03
Temperature Buffer	0x05
Runtime Buffer	0x07
Setpoint Buffer	0x09
Time Synchronization	0x02
User Parameters	0x04
Schedules	0x06
Status from App	0x08

Demand Response Capabilities

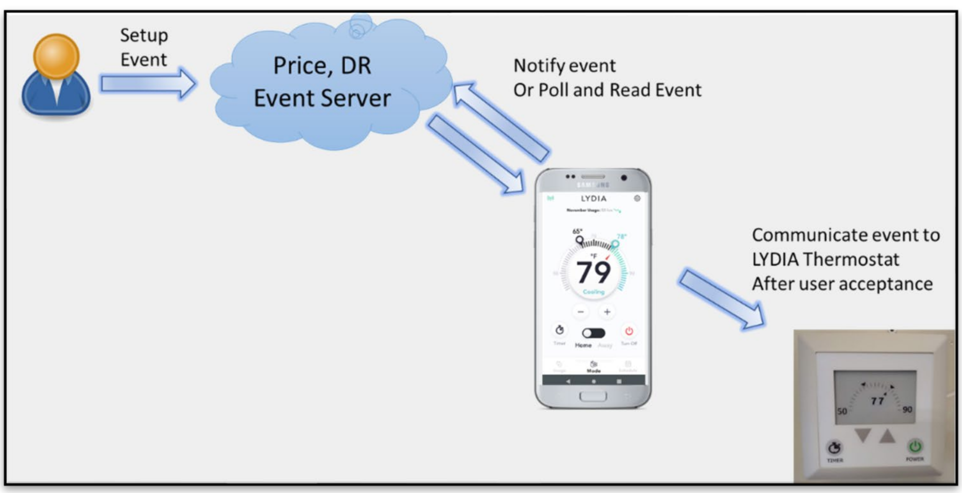
The project's HW does not have direct broadband access, which is the method employed in most research and production systems. However, the coverage in LI communities for broadband is low. As per system design, sending DR signals to these HW units through the Bluetooth and smartphone connection has been considered. The reason this system works is that smartphone penetration is high in LI communities because of several government programs and because of the lower cost availability for some consumers. The system has abstracted away a strong UI from the Lydia HW unit and now centers on the smartphone app. The smartphone app has become the gateway between the end user thermostat HW and the cloud for DR events, data analytics, pricing signals, and a host of other features found in modern smart thermostats. However, basic functionality is still maintained in the HW, where the user could change the comfort band, trigger a timer function, or turn off the thermostat HW for savings.

End-to-End Demand Response

DR events are set up in the cloud. Because the smartphone app is the gateway to thermostat HW, it becomes a necessary first step to propagate the signal to the smartphone app. This could happen in two ways: 1) The smartphone app could receive notifications after registration and authentication, with the cloud instance containing the DR events, or 2) when the user launches the smartphone app, the app will check the cloud instances for the existence of DR events.

This mechanism transmits the event to the app. The next step in the process is to inform the user and get their opt-in/opt-out for participation in the event. This is an essential step which would now take place in the smartphone app. If DR events have been received by either of the two methods indicated above, the app will then display the events to the user with UI elements to indicate acceptance/no acceptance of the event. If the event is accepted, the event details are communicated to the thermostat HW over Bluetooth. Once the thermostat HW receives the DR event, it stores the event in permanent storage known as ferroelectric random-access memory (FRAM). This is necessary since the base design to conserve battery power turns off the submodules in the HW. Hence, writing the DR event to FRAM will allow the event to be triggered when the time is right. Since the Lydia HW has a real-time clock, it will execute the DR event as per the event timing and details. This three-tier architecture will allow DR events in multiple formats and sources to be handled with ease, again providing a nice long-term vision and strategy for the HW to support DR events without modifications of the thermostat embedded firmware. If, by contrast, the user does not accept the event, the event is not communicated to the HW. In either case, the smartphone app keeps track of the event in its local database and will not show it to the user again in successive launches of the application. After the event is completed, the setpoints are reverted to the original values, and the event in FRAM is cleared (see Figure A-8).

Figure A-8: End-to-End Demand Response Schematic



Learning Algorithms for Determining Occupant Comfort Band

Traditional assumptions around thermal comfort have been rigid and broadly generalized in building standards such as ASHRAE 55 based on statistical averages of tested populations. These assumptions are applied to energy models that shape industry understanding and design of energy efficient buildings. Devices such as smart thermostats provide increased environmental information and control with respect to specific buildings and occupants. As a result, the potential for more adaptive rather than rigid models of comfort — which are inherently subjective and unrigid — can provide opportunities for energy savings and even increased occupant satisfaction.

Methodology

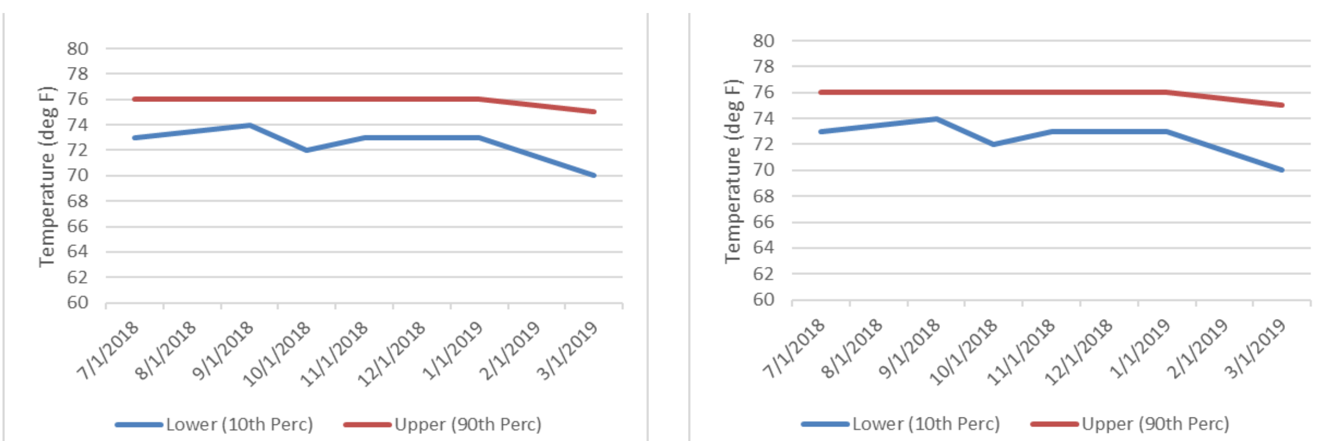
The methodology for understanding thermal comfort is based on analysis of operational thermostat data from residential homes. Thermal comfort bands were assessed for five different homes and at different times of year including winter, summer, and shoulder season to account for the variability of comfort across homes and seasons.

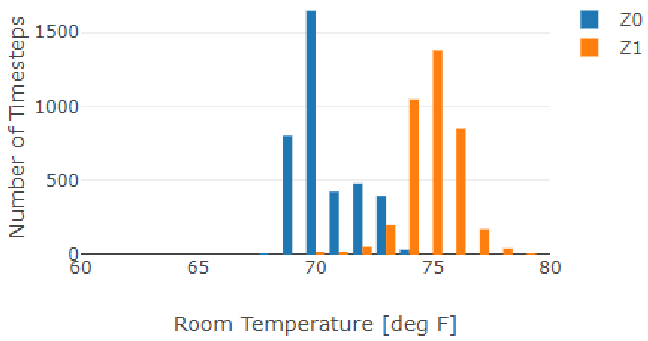
Since "comfort" is a subjective measure that cannot be directly observed in the absence of direct surveys, this analysis uses the operating state of the heating/cooling system as a proxy for comfort. This analysis assumes occupants are comfortable at a given room temperature reading from the smart thermostat if the HVAC system is not running. This assumption is based on the thermal comfort threshold at which an occupant's discomfort motivates them to turn on heating or cooling. These measurements are directly observable with widely available smart thermostat technology.

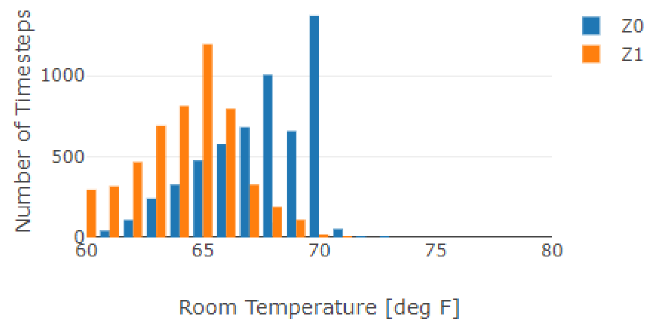
When generating an adaptive model based on operational data, one consideration is how long data should be considered relevant. Models that more heavily weight recent observations will be more responsive to movements in the trend. Models that consider a larger period of observations will make the model less susceptible to noise and outliers. The length of this window should depend on the timespans over which system dynamics occur. For this analysis, data collected over a month were selected to provide a sufficient distribution and averaging of temperature observations while adequately separating the environmental conditions corresponding to the changing seasons, as shown in Figure A-9.

The algorithm developed uses a residential multi-zone HVAC system and models each zone's comfort band separately based on two parameters, namely, room temperature and HVAC runtimes.

Figure A-9: Average Monthly Comfort Bands for Two Different Homes for Algorithm Development







The algorithm can be stated as follows:

- Step 0: Set up thermostat to provide room temperature and HVAC run status.
- Step 1: Collect zone-level data for one month.
- Step 2: Determine per-zone per hour range of indoor temperatures when the HVAC status is off.
- Step 3: Determine the 10th and 90th percentile of the temperature range.
- Step 4: Determine customer's thermal comfort band: {T10 to T90}.

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Appendix B: Field Test Plan

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APPENDIX B:
Field Test Plan

APPENDIX B details additional information on all aspects of a field test plan — usability testing as well as HW and mobile application demonstration testing.

Script Used for Thermostat Usability Testing

The following information contains the script used by the project team to conduct usability testing.

Initial Directions

This is a newly designed thermostat we are testing and that may be installed in apartments like yours sometime in the future. We are interested in finding out how residents would use these thermostats, whether they are easy or difficult to use, and what residents may like or dislike about them.

While you're here, I'm going to ask you to pretend that this is your thermostat and we are in your home. It is controlling the temperature, air conditioning, and heating in your home. I will ask you to imagine familiar scenarios where you might typically use your home thermostat.

When I give you a scenario, I would like you to pretend you are actually using the thermostat in your home. The display of the thermostat is working, but it is not currently controlling the heating and cooling systems. When you answer my questions and use the thermostat, I want you to speak your thoughts out loud [if more than one person: to each other and/or me]. I won't answer questions because I want to see how you try to figure it out. It may be uncomfortable to talk out loud but do your best. I will remind you to keep talking. Don't worry if you don't know what to do — just tell me what about the thermostat is confusing. That information is very important to us. Your telling me when you aren't sure how to do something will help us give the developer feedback to make this thermostat better and easier to use.

OK, first scenario…

The next section will detail the various usability tests given to participants. The section will be in script format.

Task 1: Read Current Temperature

This task is intended to see if the user can read the current temperature using the thermostat itself, the mobile app, and/or a combination of both.

- BASELINE STATE: OFF
    - INITIAL PROMPT: *You want to know what the temperature is in your house. Can you tell me what the temperature is by looking at the thermostat?*
        - RESPONSE: Accurate
            - *OK. How did you figure that out?*

- RESPONSE: Inaccurate
  - *OK. How did you figure that out?*
  - *The green light is showing the temperature to be X.*

Task 2: Turn On Thermostat

This task is intended to see if the user can turn on the thermostat from an OFF state.

- BASELINE STATE: OFF
  - INITIAL PROMPT: *Can you tell me whether the thermostat is On or Off? (If they hesitate, remind them to feel free to push buttons.)*
    - ANY RESPONSE
      - *OK. How did you figure that out?*
      - *[If Off] Please turn it On.*
      - *What do you think it means when the thermostat is On?*
      - *What is the current temperature?*

Task 3: Change Temperature

This task is intended to test the usability of the various options in which the user can change the temperature of the thermostat.

- BASELINE STATE: ON
  - INITIAL PROMPT: *Pretend it is too hot in your home and you want to cool it down. How would you do this?*
    - ACCURATE RESPONSE (pressed down arrow three times)
      - *OK. Do you think the air conditioner would be on now?*
      - *Why do you think that?*
      - *What temperature do you think the air conditioner will cool the house to?*
    - INACCURATE RESPONSE
      - *OK. Do you think the air conditioner would be cooling your home now?*
        - [If yes] *How can you tell?*
        - [if still inaccurate] *Once the settings are lower than the current temperature, the air conditioner will start cooling.*
        - [If not sure] *OK, talk to me about what you are seeing on the thermostat that you are not sure about.*
        - [Encourage to keep trying; if still not sure, point to setpoints and down arrow] *Once the settings are lower than the current temperature, the air conditioner will start cooling.*
        - [Once "cooling"] *What temperature do you think the air conditioner will cool the house to?*

Task 4 Set Timer

One of the unique functions that is different from this thermostat to others is the timer function. This test will evaluate usability/intuitiveness of the timer button.

- BASELINE STATE: Cooling ON
  - INITIAL PROMPT: *Now pretend you're going to be leaving your home. You want your thermostat to keep cooling until you leave in about 30/10 minutes, but then shut off. What could you do to your thermostat to make it do that?*
    - ACCURATE RESPONSE (Press timer button twice)
      - — *OK. Explain to me what you think you just did*.
    - INACCURATE RESPONSE
      - — *OK. Explain to me what you think you just did*.
      - — [If still inaccurate] *This is actually a timer button. How might you use it?*
      - — [If still inaccurate] *If you press it once, it sets a timer for 15 minutes. Press again and it sets the time for 30 minutes. Does that make sense to you or not?*
    - FINAL PROMPT: *What do you think happens after the timer runs out in 30/15 minutes?*

Task 5: Turn Off

The final test is to evaluate the intuitiveness of the ON/OFF button by testing to see if the user can turn the thermostat OFF.

- BASELINE STATE: Cooling and Timer ON
  - INITIAL PROMPT: *Actually, you've just got a call and you need to leave now — not in 30 minutes. You want to turn your air conditioner off. What's the easiest way to do this?*
    - ACCURATE RESPONSE (Press Off button)
      - — *OK. Explain to me what you think you just did.*
      - — *What do you think it means when the thermostat is Off?*
    - INACCURATE RESPONSE
      - — *OK. Explain to me what you think you just did*.
      - — [If still inaccurate] *It's not actually Off yet. Do you want to try something different?*
      - — [If still inaccurate] *This is the Off button*.
      - — [After they turn it Off] *What do you think it means when the thermostat is Off?*

Finally, there will be some optional questions that, depending on structured usability test, the tester may ask the participant. Note that these are semi-structured questions and are not a compulsory part of the evaluation.

1. Overall, how useful do you think this thermostat would be for your home?
2. Follow-ups: How do you think you would use it? Would you use the ON/OFF feature? When/How? The timer feature? When/How?
3. What do you think the two red lights mean?
4. How does this thermostat compare to your current thermostat? Follow-ups: What is your thermostat like? How do you typically use it?
5. Do you pay close attention to your household energy bills?
6. Do you do things around the house to conserve energy?
7. Do you have a smartphone?
8. Do you have internet service for your home?

Project Participation Consent Agreement

Participation consent was a critical consideration for the project team during this project. As a result, it was important to develop a Project Participation and Consent Agreement that would be used as a way of recruiting project participants and ensuring that they have consented to data sharing and overall project participation (see Figure B-1).

Figure B-1: Project Participation Agreement

ELECTRIC POWER RESEARCH INSTITUTE (EPRI)

CALIFORNIA CUSTOMER-CENTRIC DEMAND MANAGEMENT DEMONSTRATION

Program Participation Enrollment Agreement

Name: ______ **Phone Number:** ______

Email: ______

Street Address: ______ **Apt.** ______ **City:** ______ **State:** ______ **Zip:** ______

System Installed: ______

1. I am voluntarily enrolling in the California Customer-Centric Demand Management using Load Aggregation and Data Analytics Demonstration (Study) to be administered by the Electric Power Research Institute, Inc. (EPRI) and its technology provider, Intech Corporation and Chai Energy. (The Partners) as is described more fully below. In exchange for my participation in the Study, an energy management system (EMS) has been installed and will be maintained for the above party at the referenced location. The EMS , as well as the installation thereof, will be at no charge to the undersigned. The term of participation begins January 1, 2018 and ends December 31, 2020, with the test period for the Study scheduled to begin on commencement of participation and end on or before December 31, 2020. In consideration for the EMS being provided at no charge to the undersigned, I hereby consent, until December 31, 2020, for The Partners to install and service and for EPRI extract data from the EMS at no charge to any of them until the undersigned unenrolls from the Study or December 31, 2020, whichever comes first. No warranties are provided by with respect to the Study or the EMS. The electrical cost of service for operation of the EMS, and any removal after December 31, 2020, will be at your expense.
2. During the undersigned's participation in this Study, the undersigned will agree to setup and maintain a local Wi-Fi network at its expense to either allow the EMS to be connected to the Internet through my Wi-Fi network or to wirelessly transmit information over other wireless networks as may be selected by EPRI or The Partners. The undersigned agrees to allow Study-related data to be transmitted over these wireless networks during my participation in the Study. I will call EPRI's Program Manager, Ben Clarin, 650-855-2317, if I am aware that the EMS is not working or is disconnected if our Wi-Fi network is non-operational, or if help is needed to reconnect the EMS, or if electric service is out. In all instances, the undersigned agrees to exercise the same reasonable care over the EMS that is exercise over equipment owned by the undersigned, and the undersigned will not intentionally damage or alter the EMS during the Study.
3. The undersigned understands that one purpose of this Study is to generate data to help EPRI and EMS understand how anticipating customers manage their electricity use pursuant to cooperative research award granted to EPRI by the California Energy Commission (CEC). The undersigned agrees that it will not be entitled to any financial consideration for participation in the Study, but that the data collected is important to the Study.
4. The undersigned agrees, as part of voluntarily participating and for the consideration received under this Study, to answer all questions and surveys that EPRI and The Partners present to me, in good faith and to the best of our ability during participation in the Study. I understand and agree that certain personally identifiable information (PII) including my name, home address, apartment number, and utility customer account number may be collected. I hereby do grant EPRI, and The Partners the right to use and share this PII with each other for any method or purpose, but it is NOT intended to be made public. The undersigned understands that administrative, technical and physical safeguards may be used to protect the undersigned's information, including industry standard methods to protect that information. However, the undersigned recognizes that no system is completely secure or "hacker proof." The undersigned also understands that it is also responsible for taking reasonable steps to protect its personal information against unauthorized disclosure or misuse. The undersigned understands that EPRI or The Partners may be required or compelled by law to release the information extracted from the EMS which may include, but is not limited to, the undersigned's gas or electric equipment operation, temperature set points, overall energy usage and my customer attributes and behavior. I understand and agree that this information may be analyzed and derived to create results that may be reported separately or in the aggregate from other Study participants, and these results will be made public. I understand and agree that EPRI, CEC and The Partners and their agents are beneficiaries of this Agreement; with the right to use, publish, publicize and make multiple derivations from the undersigned's information.
5. If the installed Wi-Fi components of the EMS cease working or the undersigned wishes to no longer participate in the Study, I will call the Program Manager referenced above. In response, we may be contacted by EPRI or The Partners (by phone, email, or other means) to have our equipment reconnected, repaired, replaced or removed. The undersigned will provide the subcontractor or technician with reasonable access to the above referenced location for the free service of the device, thru December 31, 2020.
6. If during the Study the undersigned relocates from the above premises, or these premises are leased to another entity or person, then the undersigned agrees to call the Program Manager prior to our move-out to provide notice about the move. The undersigned also agrees that if another entity or person takes possession of the premises during the Study, then they will be informed of the Study and that their occupancy is subject to this agreement by providing them with a copy of this document prior to their move-in.
7. The undersigned acknowledges that the responsibility and liability is limited to EPRI and The Partners and their agents for the installation of the EMS and Wi-Fi, and it is further acknowledged that this specifically excludes losses of all types including but not limited to personal injury, property damage, bodily harm, death, third party liability or any other claim, cost or expense directly arising out of the operation of gas and electric appliances and other equipment situated at the above location. Further, the undersigned understands and agrees that to make a successful claim for losses due to the installed EMS, that the undersigned must first contact The Partners, or the EMS component part manufacturer's warranty department for resolution and if not, this will void the undersigned's right to claim to losses. The undersigned understands that it has the responsibility to manage and pay for the energy consumption of gas and electric appliances and equipment and all other energy-using items at the above referenced location.

By signing below, **the undersigned** ***does certifies that it is the occupant or authorized representative of the above listed entity at the referenced address, who has read these terms and conditions in this Agreement, and understands them, and agrees to be bound by them. (If any questions, please call the EPRI Program Manager at 650-855-2317)***

Site Host's Authorized Signature: ______ *Date:* ______

Project Participation Introductory Recruitment Document and Survey

As discussed in Chapter 2, the project team created an introductory recruitment flyer. The flyer also included a survey to provide general information on the recruited project participants. Figure B-2 shows the introductory recruitment document, and Figure B-3 provides the survey questions used.

Figure B-2: Project Introductory and Recruitment Document

Smart Thermostat Update at City Gardens

In our commitment to sustainability and providing our tenants affordable and healthy communities, LINC Housing, alongside the Electric Power Research Institute has secured a California Energy Commission Grant to demonstrate how smart technologies can better help budget their energy costs. Over the next few months starting in May, a member of the LINC Housing City Gardens staff will be installing LYDIA, a smart thermostat that can be connected with select mobile phones. A few frequently asked questions (FAQs) are answered below:

Frequently Asked Questions

Will I have to pay for the thermostat, the app or any part of the project?
The tenant will not be responsible for any costs for the project. The thermostat is free of charge to the tenants. All installations and removal will be covered by the project.

Does the thermostat need Internet/Wi-Fi?
No – the thermostat can be controlled from your phone in the unit without the Internet/Wi-Fi as long as you have a mobile phone.

How do I control the thermostat?
With each installation, a member of the City Gardens staff will provide you with a Quick Start Manual. For those with mobile devices, the thermostat app will provide tutorial to help customers better understand how to control his /her thermostat.

Will other people be controlling my thermostat?
No. No one without your permission can control your thermostat.

Can I program a schedule into my thermostat?
If you have a smart phone, yes. If you do not have internet, the thermostat will work like a normal thermostat.

Will my thermostat change temperature automatically?
Possibly. The thermostat, with your permission, may create a schedule by learning when you increase and decrease the temperature. The thermostat will then take into account how hot or cold you like your apartment and manage comfort while helping try to decrease your energy bill. You can always stop and change this by adjusting

Does the thermostat app work in other languages?
Yes, the text on the screen can be in different languages including Spanish.

How should I use my thermostat?
Go ahead and use your thermostat as you would normally.

What would be expected of me?
To be eligible to participate, a LINC City Gardens staff member will provide you with a quick 3 question survey and two (2) customer agreements for you to sign. In the event that you have a medical condition or any other reason to not participate, please let us know.

Anything else expected?
Members of the LINC Housing City Gardens Staff and the project team may contact you during the project to take a quick survey on your satisfaction and usability of the thermostat.

Why are we doing this?
In its efforts to provide healthy and affordable communities, LINC housing believes that the new thermostats will it easier to control air conditioning and heating.

Figure B-3: Survey Questions Used

Survey Questions

In preparation of the project, we would appreciate if you would answer the following questions.

1. (a) Does someone who lives in your home own a smart phone (circle one)? Yes or No
   (b) If yes to above, what type of phone you have?
   ___ iPhone
   ___Samsung
   ___Android
   ___ Other Please Specify ________________________
2. (a) Do you own a tablet such as an iPad (circle one)? Yes or No
   (b) What type of tablet is it?
   ___ iPad
   ____Amazon Fire
   ____ Google Nexus
   ____ Samsung
   ____ Other Please Specify ______________________
3. Does your home have internet connection?
4. What is your building/unit number?

Approach to Project Impact Evaluation

As discussed in Chapter 2, this project takes a five-pronged approach to assessing the extensibility of the thermostat developed with this project: 1) collect data at three levels, 2) understand system usability, 3) leverage existing/parallel initiatives, 4) understand implementation issues, and 5) revisit project drivers.

Data Collection at Three Levels

The project approached this effort with an understanding of how data can be valuable at the aggregate. Conventional utility initiatives rely on qualitative results via survey data and quantitative results obtained through advanced metering infrastructure (AMI) or other utility-specific billing data.

The project team will look at leveraging the "thermostat as a sensor." This entails understanding that preference, performance, and environmental information can potentially be gleaned from these data sources to better attribute energy impacting behaviors or HVAC optimization strategies from the thermostat.

Table B-1 details the parameters collected by the thermostat HW.

Table B-1: Data Parameters Collected from the Thermostat

Data Parameter	Summary
Timestamp	Time in which an event occurs. To save memory and battery life, data will be saved by state changed vs. polled.
Thermostat setpoint	Heating and cooling setpoints of the thermostat.

Data Parameter	Summary
Indoor temperature	Current indoor room temperature in which the thermostat is installed.
Indoor relative humidity[5]	Current indoor relative humidity.

The overarching approach is to shift the bulk of the data acquisition to the app and reduce the amount of data acquisition and storage needed on the HW. It is also essential to conserve battery life in terms of the HW. This approach necessitates event-driven data acquisition seen in the industry today.[6] The triggering event for data collection on the HW side is setpoint changes, whether driven manually or via the mobile application. The HW will have to store only data that are different from current sample, i.e., a threshold-based event-driven model. BLE restricts the amount of data that can be transferred to a few bytes per transfer.

As the main point of connectivity in this project involves alternatives to Wi-Fi, data will be transferred through Bluetooth, leveraging a customer's phone as a "data mule." When the app is synchronized with the HW, the HW sends all data in its cache to a central server after an extended period of absence. The thermostat was designed to hold approximately one month of data before erasing cached data. Such data are then used to enable learning algorithms to improve building energy performance while understanding customer preference information collected from this data.

In addition to the data parameters collected by the thermostat, external parameters such as outdoor temperature and outdoor humidity will be collected. At first, external parameters will be collected by a server backend from external weather data sources. A more sustainable model will be developed to collect external data parameters. This collection will be completed via publicly available weather data application programming interfaces (APIs).

Customer smart meter data will be collected from all members or pilot participants. In addition, periodic surveys will be conducted of project participants.

In summary, the project team will take a holistic approach to data collection, understanding that attribution, calculation, and persistence have been challenging in utilities providing programs to connected devices that: 1) are subjected to rapid technology change, and 2) are a combination of behavioral intervention and system optimization. As a result, the project team will examine both the smart thermostat as well as survey and utility data to better understand and address the three main components by:

- **Calculation:** Quantification and verification of energy-related impacts will be completed using smart meter data.
- **Attribution:** Understanding of what features are driving energy impacts will be gained through a combination of qualitative survey results and quantitative data from the thermostats themselves.

[5] This data parameter may only be available in pilot stages. Developers are evaluating the necessity for these types of data for production level development.

[6] The primary reason for event-driven data acquisition for smart thermostat manufacturers and service providers is to minimize operational costs associated with data acquisition and storage.

- **Persistence:** Persistence of energy impacts will be evaluated using both smart meter data (for energy-related calculations) and thermostat-level data (for attribution indicators).

Understanding System Usability

To complement data collection, the project team will understand usability by conducting and evaluating how customers are using their thermostats during the entire PoP of the project. These tests are intended to better understand how users evaluate certain critical functions of the thermostat and will influence design decisions on the final thermostat specification.

Identification of Complementary Demonstration and/or Pilot Activities

The project team understands the limitations of the project's sample size and understands that there are currently other parallel initiatives ongoing in DACs, affordable housing, and LI spaces. As a result, it will be important to be cognizant of lessons learned in these parallel research activities to better understand how they can be leveraged alongside this research effort. Additional information on future activities was discussed in Chapter 4, Technology/Knowledge/Market Transfer. It is important to note the differences in how and why the thermostat is deployed as part of these efforts. A summary of differentiating deployment factors follows:

- **Use case for deployment:** What specific customer and utility use cases are the smart devices or DAC solutions being leveraged for? Are the use cases focused on EE, DR, or rate management? Or are they part of a solution of technologies aimed at addressing a building code driver such as zero net energy (short term) or decarbonization (long term)?
- **Building stock:** Will the focus be on single-family or multifamily homes? Will the buildings be owned or rented? This will be important as this will address how/if pilots can be leveraged for both impact evaluation comparison and aspects such as lessons learned from implementation challenges. Building vintage will also play a role as age of building will have an effect, as will whether any type of deep energy upgrades were completed.
- **Programmatic qualifiers or method of delivery:** Some utility programs will have programmatic qualifiers or methods of delivery that could potentially complement how programmatic qualifiers or bundling (as opposed to technical solutions) can address some of the project research questions. For example, one of the main research questions is to address the digital divide by proposing a technical solution that is not reliant on consumer Wi-Fi as its main form of connectivity. Two potential programmatic solutions are: 1) select only customers that have proven to have Wi-Fi connectivity or 2) leverage communities where community Wi-Fi or broadband is deployed or there are plans in place to deploy it. It is important to understand that programmatic qualifiers do mean limitations in achievable program potential.
- **Climate zones:** It is important to understand the various climate zones and utility service territories under which these programs are deployed. This factor will also impact HVAC stock and familiarity by trade allies.

The project team leveraged the following initiatives as they are currently working in parallel with this research effort (see Table B-2).

Table B-2: Some Projects Tracked During This Project's Period of Performance

Pilot/Demon-stration Site	Project Summary	In Relation to the Project
Ontario, CA	Deep retrofits (including smart thermostats) in affordable housing	A similar project team approach has been taken where thermostat implementation challenges can be understood.
Fresno, CA	Deep retrofits (including intelligent HVAC controls) in affordable housing	Implementation and HVAC compatibility challenges can be examined, and potential data can be collected (thermostat TBD).
Pomona, CA	High performance community with circuit-level metering to better understand HVAC consumption	Implementation and HVAC compatibility challenges and data collected from the Pelican Wireless thermostat can be evaluated.
PG&E	Deployment of smart thermo-stats to help affordable housing customers manage TOU rates	Current discussions focus on what can be shared during the project's PoP.
SCE	Deployment of smart thermo-stats to help affordable housing customers manage TOU rates	Current discussions focus on what can be shared during the project's PoP.
SDG&E	Deployment of smart thermo-stats to help affordable housing customers manage TOU rates	Current discussions focus on what can be shared during the project's PoP.
SDG&E	Deployment of voice assistants to help affordable housing customers manage TOU rates	This project is developing voice actions to help customers manage TOU rates.
Fresno Housing Authority	Deployment of smart thermostats for ENERGY STAR® portfolio	Large deployment of smart thermostats. Fresno Housing Authority has agreed to share building data and possibly sub-metered data to better understand energy impacts. Technical challenges will be gleaned via interviews with property managers and maintenance staff.
Austin Energy	Deployment of smart thermostats for EE and DR	Member of the TAC — willing to share implementation challenges.

Pilot/Demonstration Site	Project Summary	In Relation to the Project
NYSERDA/National Grid	Deployment of smart thermostats for EE (NYSERDA) and DR	Member of the TAC — currently in discussion of what could be shared as part of this project.

Understand Implementation Challenges

As previously discussed, it is not only important to understand, quantify, and verify energy impacts but also to examine any challenges that may arise during programmatic implementation, commissioning, and operation. For example, many of the technical turndowns from previous smart thermostat pilot projects in affordable housing spaces occur in concert with HVAC compatibility challenges (CEC, 2016). Other challenging areas have involved customer perception, drivers to program scalability such as the leverage of trusted property managers and CBOs, and recruitment of program participants. Chapter 3, Project Results, details several key lessons learned from this project.

Revisiting and Linking Research Objectives to Field Test Plan

Finally, the final goal is to understand that technology is moving quite rapidly, and parallel work can be leveraged. However, it is also important to understand and revisit many of the research questions associated with this project. The project team plans to review the overall field test plan objectives and research points of departure to 1) evaluate if the research question is still viable, and 2) develop a general approach to addressing research questions.

The project team is investigating numerous research questions in a space of rapid technology change while attempting to develop a product. It is thus important to consider all aspects and be nimble with a field test plan to gain what is necessary and valuable in the space. The goal will be to 1) complete a pilot design not only to quantify and verify impacts but also understand customer satisfaction concerns and potential issues, 2) demonstrate and collect operational data in order to answer specific research questions, and 3) glean results via a pilot design as well as partnering with other similar initiatives to understand potential implementation issues.

The next section will discuss in depth pilot design to quantify and verify impacts.

Pilot Design to Quantify and Verify Impacts

Over the last decade, the energy industry has increasingly emphasized the use of more rigorous experimental methods to evaluate program impacts. This new emphasis may in part be due to a reinvigorated interest in utility programs featuring behavioral interventions — those where energy and demand savings rely in some part on customers to change their behavior. The impacts of these interventions can be more complicated to measure than traditional technology-based programs, and they invite greater skepticism regarding how extensible the results from pilot studies are to a greater population. These issues have no doubt led to an increased scrutiny of utility pilot design and evaluation practices.

One outcome has been the development of several useful documents to inform the designs of pilot programs tailored for the utility industry (CEC, 2016; Todd et al., 2012; EPRI, 2013a; EPRI, 2013b; Stewart, & Todd, 2015; EPRI, 2010; Wayland, 2015; Morris & Smith, 2015).

Given that there already exists such a trove of pilot design guidelines and approaches, this section will not delve deeply into the details of various design approaches. Rather, its purpose is to provide a summary of experimental pilot design approaches, with a specific focus on opt-in device-based pilots (such as smart thermostat pilots).

There are two broad categories of pilot design approaches:

- **Experimental Designs:** This is a type of pilot design where the allocation of customers to treatment and control groups is determined randomly. Treatment groups generally receive what is to be tested (such as a thermostat or an offer of a thermostat), while the control group does not.
- **Quasi-Experimental Designs:** This refers to all other types of pilot designs where randomization is not used (or it was intended to be used, but it could not be properly implemented).

Within these categories, a project team faces an array of choices when designing and implementing pilots involving connected devices, and these choices have consequences and associated costs and benefits. Balancing scientific rigor with the on-the-ground reality is ultimately a business decision that should be considered carefully. Following are some of the main considerations:

- From a scientific rigor perspective, there is no alternative to a properly executed experimental design. Such pilots deliver the most reliable results, but in the practical world, many other considerations come into play. Randomizations are often difficult to implement from an operational or regulatory perspective.
- If experimental designs are not possible, quasi-experimental approaches are available, and some may be more suitable than others in any given situation. Quasi-experimental designs are generally easier to implement, but from a statistical point of view, they are more difficult to analyze because they are subject to additional conditions that must be satisfied in the data. As a result, quasi-experimental designs may not always work as anticipated.
- The expected response to the intervention is an important factor in deciding which approach to use. In quasi-experimental settings, a larger number of confounding factors remain unaccounted for, and they may overwhelm the ability to detect the true response if it is expected to be relatively small. Therefore, in evaluations where larger responses are expected (such as for many event-based DR pilots), quasi-experimental methods are more likely to succeed than in cases where the intervention is expected to have a weak response.
- Another factor to consider is the extent to which the outcome may be driven by unobserved factors outside of the control of the proposed intervention. When there is a limited number of ways in which the intervention may be influenced by confounding

factors, the quasi-experimental setting is more likely to succeed. For example, interventions that link outcomes directly to the underlying technology are easier to quantify in quasi-experimental settings, such as automatically controlling customers' HVAC systems via thermostats during discrete and relatively short DR event periods. This can be compared to outcomes that are more likely to be affected by human behavior in all its complexity, such as understanding the overall energy savings impacts of a smart thermostat over one or more seasons.

The project team encouraged the use of experimental approaches in this project, as they specifically targeted EE (that is, the impacts of the thermostats on overall energy use) for two reasons:

- This is a research project, so the use of the most rigorous methods is appropriate.
- There are intriguing claims regarding the EE potential of smart thermostats.

In the end, however, project developers realized some experimental designs would not be possible as the project would be performed at the preference/discretion of the site provider, its property managers and residential service coordinator(s), and the population recruited for participation. The project team has conducted several smart thermostat pilots and has used a combination of experimental and data-driven approaches (Robinson et al., 2016).

The project team has revisited the targeted research questions and proposed a preliminary analysis plan to quantify impacts of the smart thermostat or technical features of the smart thermostat (see Table B-3).

Table B-3: Revisit of Overall Project Research Question and Approach to Quantification of Impacts

Research Question	Approach to Quantify Impacts
Efficiency impacts associated with the smart thermostat	The preference was to have experimental (recruit and deny/delay) approaches to recruitment, which would be subject to recruitment numbers and customer satisfaction considerations.
Demand response	Events were planned to be randomized where certain participants received the thermostat while others did not. Evaluations could be completed where a baseline of similar weather normalized days could be used.
Bill impacts associated with the smart thermostat	The preference was to have experimental (recruit and deny/delay) approaches to recruitment, which would be subject to recruitment numbers and customer satisfaction considerations.
Effectiveness of BLE as an alternative to customer Wi-Fi	As this is a technology demonstration, deployment would be the main part of an assessment, completed with parallel smart thermostat initiatives.

Research Question	Approach to Quantify Impacts
Usability of an intelligent thermostat	This approach would involve a combination of a usability study and qualitative survey results during the project PoP and collection of data from the thermostat.
Evaluation of thermostat battery life	This approach involved a combination of a laboratory evaluation and field testing of battery life.[7]

[7] It is important to note that the prototype version will use 2 AA batteries, while the production version plans to use 9V batteries due to the need to provide off-the-shelf electrical enclosures.

CALIFORNIA ENERGY COMMISSION

CALIFORNIA NATURAL RESOURCES AGENCY

ENERGY RESEARCH AND DEVELOPMENT DIVISION

Appendix C: Additional Information: Recruitment, Installation, and Testing Results

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APPENDIX C:
Additional Information: Recruitment, Installation, and Testing Results

Table C-1 summarizes the usability issues observed in each task. Counts of respondents and the UI elements involved in the issues were also provided for each issue.

Table C-1: Usability Testing Results Grouped by Testing Tasks

Task	Issue Observed	Number of Participants Who Encountered Issue (Total 16)	Design Elements Involved
1.Read current temperature when thermostat OFF	None — task was easy to understand, and no issues were observed except for language barriers in two users.	N/A	
2.Turn ON	Four users, especially older ones, had trouble recognizing the buttons.	4	Low contrast on the buttons.
			Distraction of white sensor in center.
3 (a) Read current temperature when ON	One user was not sure of the current temperature due to extra lights.	1	Two red lights and a green light are on at the same time.
3 (b) Change temperature	Unable to complete the task unassisted.	9	Two red lights indicate upper and lower bounds of a "comfort band"; only when the green light indicated the current temperature was out of bounds would it start cooling/heating.
	Had some level of confusion about two red lights.	13	
	Thought green light was temperature setting.	2	
	Not sure what temperature the house would cool to.	8	
	Pushed timer button.	1	Low contrast on the buttons.
4.Set time	Unable to complete the task unassisted.	8	
	Unable to recognize timer.	4	Low contrast on the buttons. Timer button is not something users first looked for (e.g., auto setting).

Task	Issue Observed	Number of Participants Who Encountered Issue (Total 16)	Design Elements Involved
	Thought AC would turn on in the set amount of time, not turn off.	1	
	Pushed too many times.	1	
	User attempted to twist the timer button rather than push it.	N/A	The shape and pattern of the button may communicate "twist" not "push."
5.Turn OFF	Not able to complete the task unassisted.	4	
	Pushed timer button until all timer lights turn off.	3	Lights that turn from ON to OFF may carry different and too many meanings in this design.
	Thought green light meant on.	1	When OFF, the green light is on to indicate current temperature.

Detailed Survey Responses

Figure C-1, Figure C-2, Figure C-3, and Figure C-4 provide a graphic portrayal of survey responses of the recruited pilot participants as part of the two project sites; this information is summarized in Chapter 3.

Figure C-1: Smartphone Ownership in Santa Ana Community

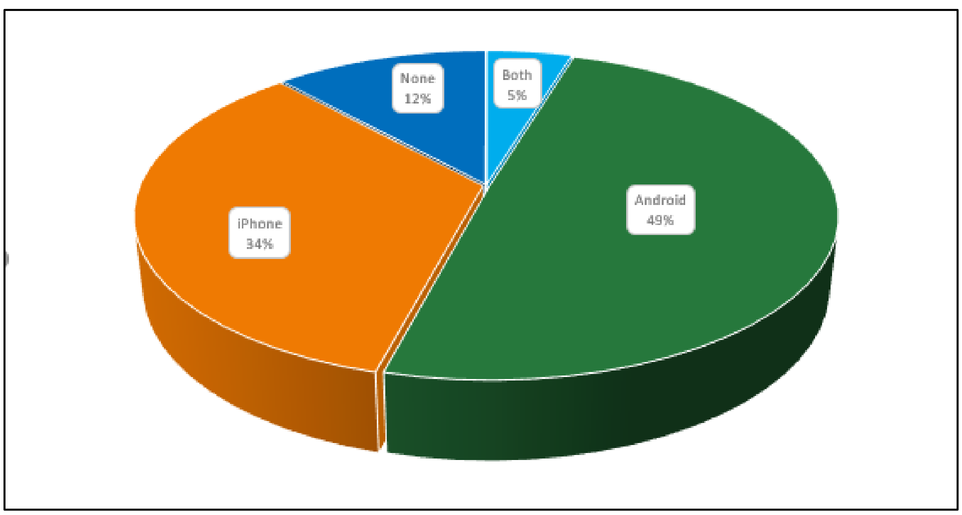


Figure C-2: Personal Internet in Santa Ana Community

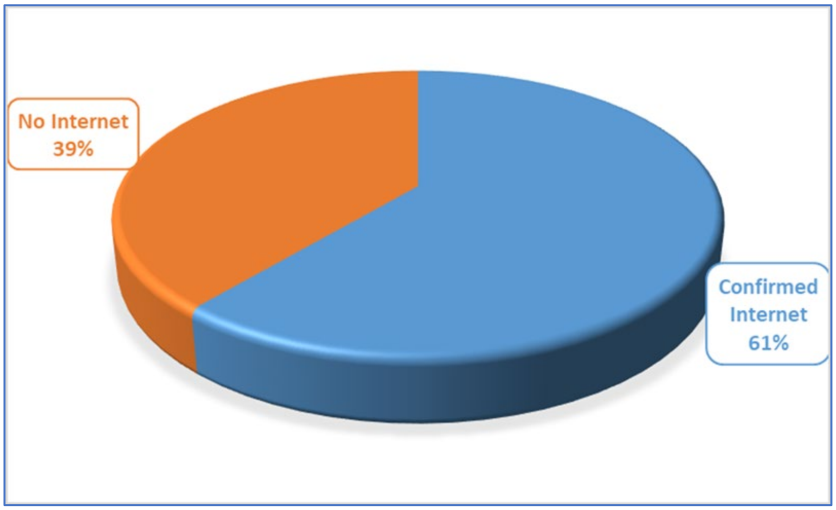


Figure C-3: Preferred Language in Santa Ana Community

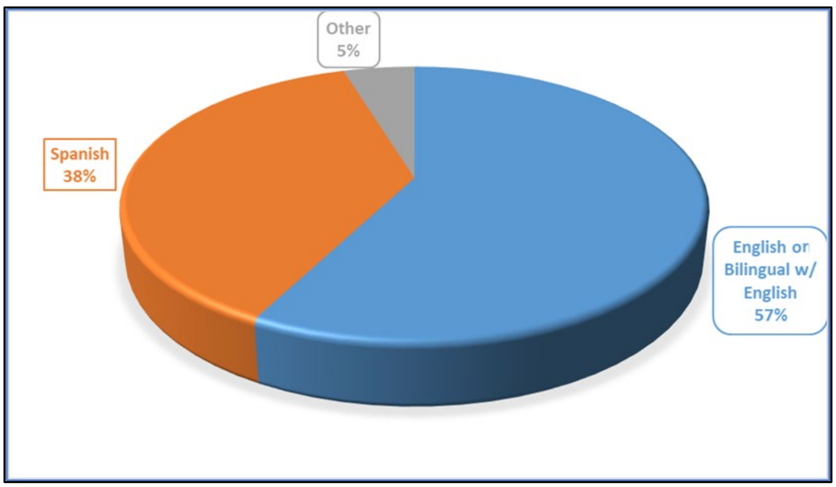
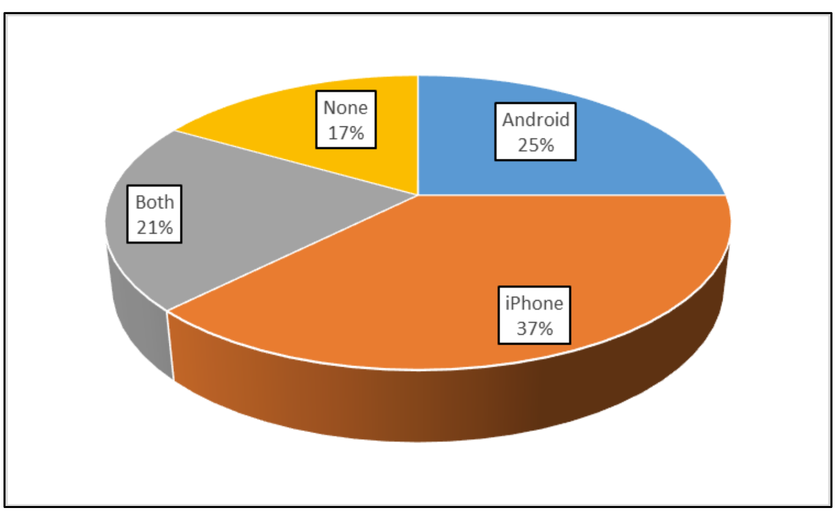


Figure C-4: Smartphone Ownership in Sacramento Community



Thermostat Installation and Commissioning Plans

Figure C-5 shows material provided to maintenance staff to install and commission the Lydia thermostat along with a field deployment strategy that minimizes overall project risk associated with emerging technology projects.

Figure C-5: Thermostat Installation and Commissioning Guide – One-Page Document Given to Maintenance Staff Members to Commission and Install Lydia

1. Power off the furnace and air conditioning systems connected to the original thermostat.
    a. This can be done by flipping the breaker at the electrical panel or pulling the disconnect to the systems.
2. Carefully remove the original thermostat unit from the wall.
    a. Most can be simply pulled off from off the wall.
3. Check the voltage on the wires to be sure the systems are turned off.
4. Remove the original thermostat backplate housing from the wall.
5. Wrap the exposed leads of the thermostat wire with electrical tape.
6. Mount the Lydia back plate onto the wall.
7. With one person holding the main portion of the Lydia thermostat, carefully attach the thermostat wires from the wall to their appropriate terminals on the thermostat unit one at a time.
    a. The backside of the board is covered to prevent shortening the board.
8. When all the wires are installed, protective covering can be removed from the back of the thermostat.
9. Re-energize the HVAC system and begin basic test functions.
10. Power on the thermostat and open app on the phone. Then, while following Bluetooth pairing protocol:
    a. Click the gear icon in the app and select to pair to new device section.
    b. Enter the serial number of the thermostat unit to begin pairing.
    c. Pair process will end when current temperature reading on app matches temperature reading on unit.

1. Power off the furnace and air conditioning systems connected to the original thermostat.
    a. This can be done by flipping the breaker at the electrical panel or pulling the disconnect to the systems.
2. Carefully remove the original thermostat unit from the wall.
    a. Most can simply be pulled off the wall.
3. Check the voltage on the wires to be sure the systems are turned off.
4. Remove the original thermostat backplate housing from the wall.
5. Wrap the exposed leads of the thermostat wire with electrical tape.
6. Mount the Lydia backplate onto the wall.

7. With one person holding the main portion of the Lydia thermostat, carefully attach the thermostat wires from the wall to their appropriate terminals on the thermostat unit one at a time.
    a. The backside of the board is covered to prevent shorting the board.
8. When all the wires are installed, the protective covering can be removed from the back of the thermostat.
9. Re-energize the HVAC system and begin basic test functions.
10. Power on the thermostat and open the app on the phone. Then, while following Bluetooth pairing protocol:
    a. Click the gear icon in the app and select pair to new device section.
    b. Enter the serial number of the thermostat unit to begin pairing.
    c. Pairing process will end when current temperature reading on the app matches temperature reading on the unit.

A more detailed presentation was given to the maintenance staff members at the beginning of the project.

Staggering Field Deployment

Staggering field deployment was a strategy used to minimize risk associated with an emerging technology project. See below for the six-stage plan on field deployment.

- Stage 1 — Friendly Deployments: (n=7). Participants constitute the on-site management and maintenance staff. This stage would provide the lowest risk and greatest opportunity to elicit feedback.
- Stage 2 — Android owners that primarily spoke English: (n=25). Original mobile application was built on the Android platform. iPhone compatibility was to be completed in a second version.
- Stage 3 — Primarily English speakers and no iPhone: (n=19).
- Stage 4 — Primarily English speakers with no smartphone (n=4).
- Stage 5 — Smartphone owners and not primarily English speakers: (n=31).
- Stage 6 — No smartphone and not primarily English speakers: (n=5).

Note that number of installs (n=91) is less than the number recruited (n=100). Nine potential project participants were disqualified due to technology turndowns and other criteria determined by the project team.

Prototype Hardware/Firmware Changes

After the first prototype deployment, the project team maintained logs of version updates made both to the thermostat firmware and the thermostat app. The following tables

(Table C-2, Table C-3, Table C-4, Table C-5, and Table C-6) show updates to the thermostat's firmware completed during the project's PoP. Note that firmware changes completed were tracked after first prototype launch.

Table C-2: Prototype Hardware/Firmware Changes — ON/OFF Functions

Status and/or Triggers	Screen Responses	Notes (Usability Observations, Design Rationale, Trade-offs)
1.1 Status: power OFF	Empty screen, if no action on the unit, stay empty.	In the previous version, a power icon was shown on the upper right corner of the screen to indicate ON/OFF status, which was unclear whether it meant ON or OFF. An empty screen is more intuitive to indicate OFF.
1.2 Status: power OFF, Action: press POWER button	Screen flashes to update elements in order — temperature scale, two setpoints together, current temperature number, current temperature tick mark.	
1.3 Status: power ON, Action: press POWER button	The whole screen flashes to turn empty.	

Table C-3: Prototype Hardware/Firmware Changes — Current Temperature

Status and/or Triggers	Screen Responses	Notes (Usability Observations, Design Rationale, Trade-offs)
2.1 Status: power ON No user action, no sensor update	Screen displays temperature number in the center of screen and tick mark pointing to the corresponding position in the inner side of scale "arc."	
2.2 Status: power ON Trigger: Sensor automatically updates a new temperature	Tick mark flashes to disappear. Then temperature number in the screen center flashes to update. The tick mark flashes to reappear pointing to the new scale position.	

Table C-4: Prototype Hardware/Firmware Changes — Setpoints

Status and/or Triggers	Screen Responses	Notes (Usability Observations Design Rationale, Trade-offs)
3.1 Status: power ON No user action	Screen displays both heating and cooling setpoints in pair — heating setpoint as the tick mark on the left cooling setpoint on the right, both on the outer side of the scale arc —	

Status and/or Triggers	Screen Responses	Notes (Usability Observations Design Rationale, Trade-offs)
	pointing to the corresponding positions.	
3.2 Status: power ON Action: press UP button once	Both setpoints flash to disappear then reappear pointing to next 1 degree (half of scale interval) to the right. It takes about 25 seconds to complete the update (from pressing the button to the completed screen update).	In the previous version a "+" or "-" icon would flash on the top of the screen to indicate the unit is processing the action trigger, then the setpoints started to move when the next internal cycle arrived (which was set to check the update with a minute interval). Setpoints are then updated separately one by one. The previous version caused too long of a wait to see setpoint movement after pressing the button. In addition, the setpoints moved separately, and users could not know if the UP/DOWN button controlled only one side of the setpoint or both. The new version improves the response time to have immediate screen response to user action. The trade-off of this change is higher power consumption (because the internal cycle update now runs at a higher frequency), making the new version unit rely on the C-wire to secure the power resource, otherwise the battery life will be significantly reduced over the previous version. The setpoints also move together in the new version, so that users will see the UP/DOWN correspond to moving the “band” together.
3.3 Status: power ON Action: press UP button N times successively	If N≤5, then both setpoints flash to move N*(½) scale intervals to the right. If N>5, then both setpoints flash to move 2½ scale intervals to the right.	Because each screen update takes 25 seconds the unit calculates the accumulated effect of the actions then updates the screen all at once to avoid sequential long waits for updates triggered by each press.

Status and/or Triggers	Screen Responses	Notes (Usability Observations Design Rationale, Trade-offs)
3.4 Status: power ON Action: press DOWN button once	Both setpoints flash to disappear, then reappear pointing to the next 1 degree (half scale interval) to the left.	
3.5 Status: power ON Action: press DOWN button multiple times successively	If N≤5, then both setpoints flash to move N*(½) scale intervals to the left. If N>5, then both setpoints flash to move 2½ scale intervals to the left.	
3.6 Status: power ON Action: press UP button M times and DOWN button N times successively	Both setpoints flash to move (M-N)*(½) scale intervals to the right (if M>N) or left (if M<N). If M=N, both setpoints flash but stay in the current position. If M>5 (or N>5), then M=5 (or N=5).	
3.7 Status: power ON Action: press UP or DOWN button as in 3.2–3.6 but with right setpoint hitting the right temperature scale boundary or the left setpoint hitting the left temperature boundary	The right setpoint stays at the right boundary (90°), or the left setpoint stays at the left boundary (50°), with the relative distance between the two setpoints remaining the same.	

Table C-5: Prototype Hardware/Firmware Changes — Heating/Cooling

Status and/or Triggers	Screen Responses	Notes (Usability Observations, Design Rationale, Trade-offs)
4.1 Status: power ON, current temperature tick mark is between two setpoints	No text of "Cool" or "Heat" is shown.	4.1 Status: power ON, current temperature tick mark is between two setpoints.
4.2 Status: power ON, current temperature tick mark is between two setpoints Trigger: current temperature tick mark ends up on the right of the right setpoint (cooling setpoint), either due to temperature update or setpoints update	A "clicking" sound can be heard, and the bottom part of the screen flashes to show the text "Cool".	4.2 Status: power ON, current temperature tick mark is between two setpoints. Trigger: current temperature tick mark ends up on the right of the right setpoint (cooling setpoint), either due to temperature update or setpoints update.

Status and/or Triggers	Screen Responses	Notes (Usability Observations, Design Rationale, Trade-offs)
4.3 Status: power ON, current is "Cool" Trigger: current temperature tick mark ends up in between two setpoints, either due to temperature update or setpoints update	A "clicking" sound can be heard, and the "Cool" at the bottom part of the screen flashes to disappear.	4.3 Status: power ON, current is "Cool" Trigger: current temperature tick mark ends up in between two setpoints, either due to temperature update or setpoints update.
4.4 Status: power ON, current temperature tick mark is between two setpoints Trigger: current temperature tick mark ends up on the left of the left setpoint (heating setpoint), either due to temperature update or setpoints update	A "clicking" sound can be heard, and the bottom part of the screen flashes to show the text "Heat".	4.4 Status: power ON, current temperature tick mark is between two setpoints Trigger: current temperature tick mark ends up on the left of the left setpoint (heating setpoint), either due to temperature update or setpoints update.
4.5 Status: power ON, current is "Heat" Trigger: current temperature tick mark ends up in between two setpoints, either due to temperature update or setpoints update	A "clicking" sound can be heard, and the "Heat" at the bottom part of the screen flashes to disappear.	4.5 Status: power ON, current is "Heat" Trigger: current temperature tick mark ends up in between two setpoints, either due to temperature update or setpoints update.

Table C-6: Prototype Hardware/Firmware Changes — Timer

Status and/or Triggers	Screen Responses	Notes (Usability Observations, Design Rationale, Trade-offs)
5.1 Status: power ON Timer OFF No user action	Same as power ON status #3.1.	
5.2 Status: power ON, Timer OFF Action: press TIMER button once	Upper left corner of screen flashes then shows clock icon.	In the previous version, there were settings of "15 min", "30 min", "45 min", "60 min" corresponding to "press once", "press twice", "press three times", "press

Status and/or Triggers	Screen Responses	Notes (Usability Observations, Design Rationale, Trade-offs)
		four times". Pressing more than four times will reset to Timer OFF. The issue with the previous version is that the same timer icon has no distinction between different time length settings, and users may lose track of how many times they press and not be able to figure out the setting outcome from the screen feedback. In the new version, the timer is simplified to have only one setting when it is on, only set at 15 min. If users want to set other time length levels, they can set it from the app.
5.3 Status: power ON, Timer OFF Action: press TIMER button multiple times successively	Same as #5.2.	In the new version, screen update only takes action on the first press, so that even if users continue pressing the button, they will only set the timer once.
5.4 Status: power ON, Timer ON Action: press TIMER button once	The clock icon at the upper left corner flashes and disappears (i.e., back to #5.1).	
5.5 Status: power ON, Timer ON Action: press TIMER button multiple times successively	Same as #5.4.	
5.6 Status: power ON, Timer ON Trigger: 15 min time has elapsed	The screen flashes to turn empty (as in #1.1 status power OFF).	

Second Round of Usability Testing

A second round of field-testing results were completed in a different LI community using a similar approach, as detailed in APPENDIX B. Results of that test are discussed below. Note that these results include lessons and results of the HW reference design. Results are organized by task usability. This is then followed by further results obtained from posttest interview questions, and the System Usability Scale (SUS) score and comparison. Both rounds of usability testing results are summarized. Recommendations for future development of this product or other smart thermostats are also provided below.

Turning the Thermostat ON

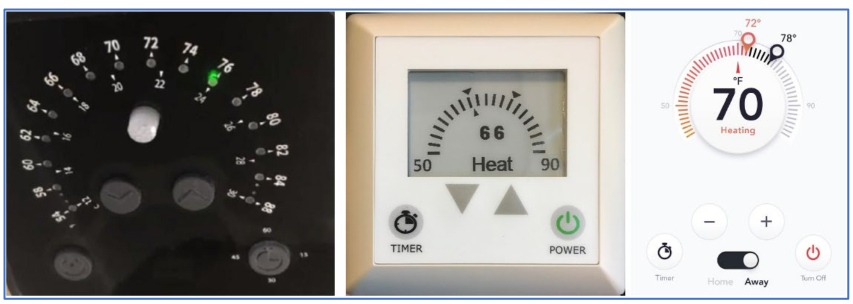
Most participants could recognize the power button when asked to turn on the thermostat. However, a few participants had trouble seeing the power button clearly in the reference design. As a result, a recommendation from the first round of usability testing on the reference design was to increase the color contrast of the power symbol compared to the button itself. When the prototype thermostat addressed that concern, no such issues were identified during the second round of usability testing.

Another issue with the reference design was that users could not tell the difference between OFF and ON states. This was potentially due to the illuminated green LED that indicated the current temperature. The prototype addressed this as no information is displayed on the screen when the thermostat is turned OFF. However, usability tests indicate that there may have been negative implications for user experience. If the device takes a while to arrive at an accurate temperature reading after being turned on, that hinders the user from easily getting current temperature readings.

Reading the Current Indoor Temperature

Figure C-6 provides current indoor temperature readings for the three user interfaces that were part of this project. Users easily identified the current temperature across the mobile application, the reference design, and the prototype. The reference design's green LED light that was visible in both ON and OFF states made the current temperature clearly identifiable to users.

Figure C-6: Current Temperature Reading from All Three Platforms



Pictured Left to Right: HW reference design, HW prototype, mobile application

Although most users could correctly identify the current indoor temperature on the HW prototype and accompanying app, a couple of participants did confuse one of the thermostat setpoints with the current indoor temperature. These users thought the large number in the center was a setpoint versus the actual indoor temperature.

Making Temperature Changes

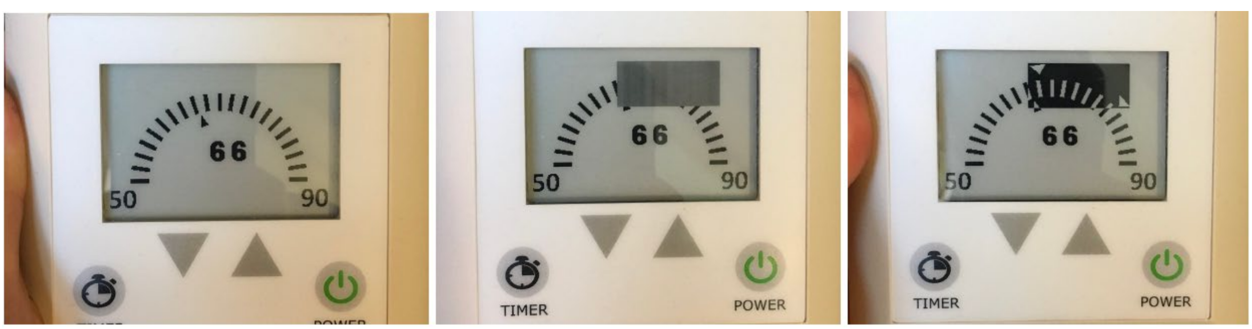
Users understood how to increase or decrease temperature on the reference HW design, the prototype HW design, and the mobile application. In addition, they appreciated user interfaces that provided immediate feedback to confirm that a temperature change was acted upon. This was available on both the HW reference design and the mobile app, as shown in Figure C-7.

There was a lag time between pressing an arrow and seeing a change in temperature on the HW prototype. This created significant user confusion and resulted in users pressing the arrows (“button mashing”) when they did not see an immediate response from the user interface.

Figure C-7: Labeled Setpoints That Change Immediately upon User Action on Hardware Reference Design

The result was higher or lower thermostat setpoints than desired by the user as users could not figure out how many times to press the button to get to a desired setpoint without any form of immediate feedback by the user interface. One participant commented, “It needs to show you the temperature moving as you click buttons.” The project team tried to address this challenge without compromising other requirements of this project such as thermostat cost and power capabilities (see Figure C-8).

Figure C-8: Setpoint Change Process on Second Hardware Iteration



Setpoints disappear, then blinking box around new setpoint location, then reappearance of setpoints

Setting Timer

The first HW iteration and the app allow setting a timer for 15, 30, 45, or 60 minutes, whereas the second HW iteration only enables a 15-minute timer. Half of the HW reference design participants were able to complete the task involving the timer without any assistance. Some users had trouble seeing the button clearly, and a few tried to turn the timer button rather than push it. It took a little experimentation and/or guidance to realize the button could be pressed multiple times to increase the timer duration (indicated by the LED orb around the button lighting up in quarterly increments with each press and turning off with the fifth press).

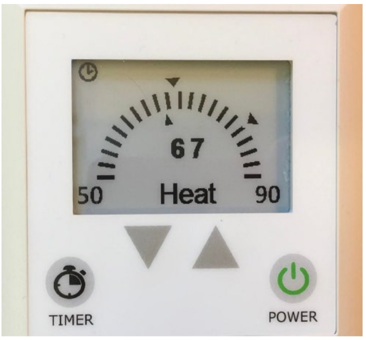
Some users misunderstood the timer function to be scheduling it to turn on rather than off in 15, 30, 45, or 60 minutes.

The timer button design was more straightforward in the second HW iteration and app design labeled TIMER (Figure C-9). Again, the lag in the second HW presentation confused users because they expected an immediate response. Only one participant accurately determined that the timer on the second iteration was for 15 minutes. Other guesses included 10 minutes (the icon on the digital display resembles a clock in the two-o-clock position).

On the app, like the first HW reference design, participants did not quickly realize they could set the timer for different intervals, and they did not always notice the banner that appeared at the top of the app counting down the time. Some participants tried to increase the timer duration by pressing the + button or going into settings (the settings icon is near the timer banner). Like the first round of usability participants, a few second-round participants misunderstood the function to be scheduling it to turn on rather than off.

Regarding the utility of the timer, about one-quarter of first-round participants said they would use it at night. Only one second-round participant cited the nighttime use case (perhaps this was due to the seasons or first iteration testing round in summer and second iteration in winter, if running the A/C at bedtime is more common than running the heater). Another use case offered was to turn heat on while bathing children so the house would be warm when they got out of the bathtub. To better promote understanding and use of the timer function, it should be named something more suggestive of the potential use cases (for example, Heat/Cool Boost, Quick Cool/Heat, Cool/Heat Blast).

Figure C-9: Time Icon Displayed When 15-Minute Timer is Set on Second Hardware Iteration



Turning Thermostat OFF

Most participants in both testing rounds were easily able to turn the thermostat off when prompted to turn off heating or cooling. Most liked this feature and thought they would use it. Several participants noted the utility of this feature for enabling children and elderly family members to complete the task of turning OFF heating or cooling.

Away Setting (App Only)

The Away setting was not intuitive to users because the setpoints did not change in a meaningful way when they first switched to Away, and there were no prompts to change the setpoints or indications of the purpose of the feature (Figure C-10). In addition, the Away setting always defaulted to Heat+Cool mode even if the mode set for Home was Heat or Cool only. Switching to Away should automatically create a default setback for the user and a tutorial wizard should explain this feature when the user first explores it. It should also default to the same mode as Home settings.

Several users accidentally increased or decreased their setpoints in the Away setting, thinking they were adjusting them in Home. Like OFF mode, having a cue across all screens to indicate that the Away setting is active would be helpful. Furthermore, when moving on to the Scheduler task, participants did not make the connection that they could not turn on the Schedule without switching back to Home mode. A prompt in the Scheduler to change to Home to initiate scheduling would address this issue. Some participants said they would use the Away feature, but many did not find it relevant. Most participants expressed that they or other household members are always home, which makes the Away feature less useful. Of those who considered changing settings when leaving, most preferred to just turn the thermostat off. One participant noted that it would be more useful in the summer. These findings validate the decision to not include the Away feature on the HW and only provide it on the app. Further usability testing after the improvements to the Away setting would help determine if this is a useful feature to retain in the app.

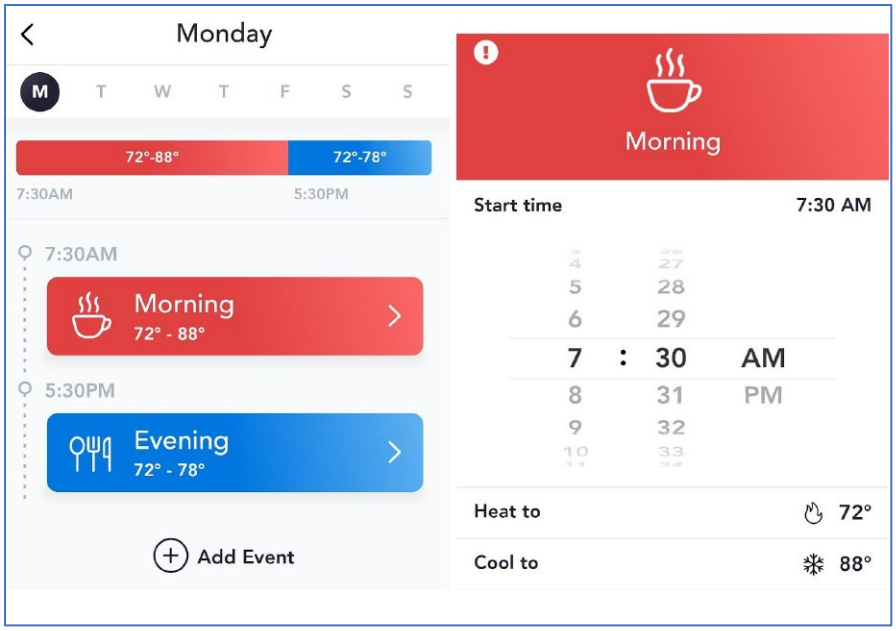
Figure C-10: Home and Away Mode in the App

Scheduler (App Only)

All participants were able to locate the scheduler. Most were able to program the schedule, with two points of confusion: dual setpoints and absence of end times for events. The confusion around the dual setpoints described with the changing temperature task was compounded in the scheduler. Even participants who eventually grasped the meaning of the two setpoints on the temperature gauge in the main screen were again perplexed about it, perhaps because it is shown in different formats compared to the gauge (Figure C-11). The "Heat to" and "Cool to" language in the editing events screen confused people; as one participant noted, "It's winter, so why would we be cooling?" Looking at event temperature ranges in the daily schedule (for example, 72–82°F [22-28°C]), participants often confused the cooling and heating setpoints or again misunderstood the setpoints to be a range within which the temperature would vary. A single setpoint would dramatically improve the scheduler usability.

The second issue, no end times for events, caused confusion because participants typically did not care to schedule an entire day, but instead had preferences for specific time periods. For example, several participants wanted to schedule the heater to come on in the morning and to a lesser extent in the evening but were less concerned with a concrete midday schedule. Once they input start times for morning and evening events and deleted daytime and nighttime events, they did not realize that the whole day up to the evening event would be encompassed in the morning event, and the whole night in the evening event. To fit user preferences and enable energy savings, the scheduler should allow gaps between events during which the thermostat would default to OFF rather than forcing setpoints for all times.

Figure C-11: Reviewing and Editing Events on the Scheduler



Usage Screen (App Only)

Most participants generally appreciated the usage screen (Figure C-12 and Figure C-13), but many found it to be too much information and could not imagine specific uses for it. It reminded some of features on their energy bills. Percent difference compared to previous day, neighbors, or goal did not seem significantly or differentially motivating. Some expressed preference for comparing the current month to the same month last year. Most users said they would not be interested in seeing their usage compared with similar households or setting usage goals (Figure C-12). A few participants expressed that their energy costs are so low that this information is not motivating.

Providing strategically timed notifications during peak hours or perhaps just when users interact with the thermostat during peak hours or when they are using the scheduler would likely be more effective than a retrospective usage screen. Maintaining the usage screen seems worthwhile, but the information should be simplified, for example, to note heating and cooling usage separately in the statistics at the top of the screen and exclude the Set to Away and Turned off settings data from the bar chart shown in Figure C-13. The monthly comparison view was not tested, but it might be more meaningful than daily comparisons since it could be used to gauge the potential cost of the bill compared to the previous month. Comparing to the same month of the prior year at the end of each month, as is common practice in energy feedback programs, could also be effective. A notification at the end of each month via the app to encourage users to check the usage screen could increase engagement. Providing an element of intermittent rather than continuous feedback is another strategy to increase engagement.

Figure C-12: Usage Screen Statistics (Top of Usage Screen)

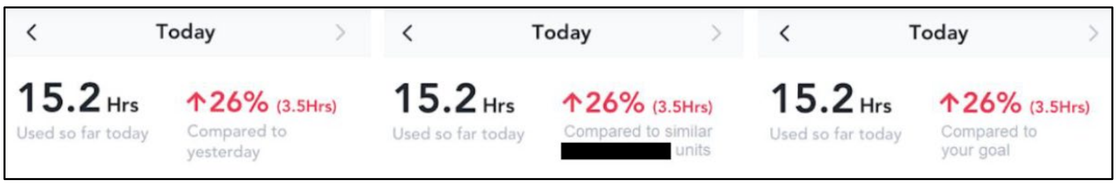
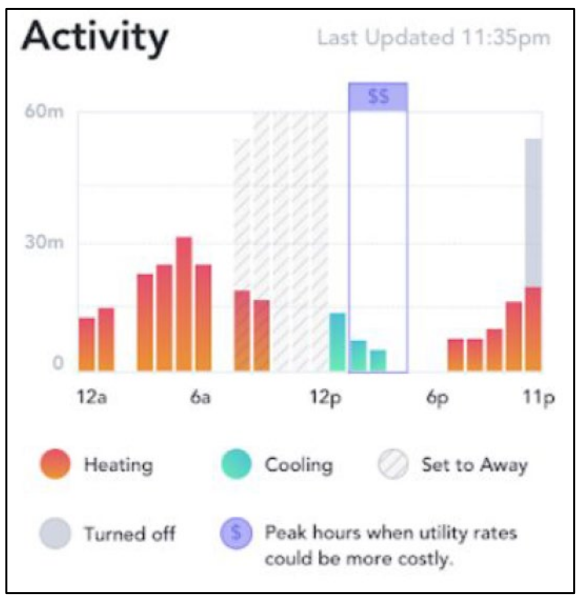


Figure C-13: Usage Screen Statistics (Bottom of Usage Screen)



Posttest Interview Questions

Most participants had a smartphone and liked the idea of having an app to control their thermostat. Only a few participants said they would likely not use the app. Some were disappointed that the app would not work outside the home, but most still appreciated it, particularly those with mobility impairments and elderly participants. Except for the second HW iteration, most participants preferred the Lydia system to their current thermostat. Several participants noted that they would want or need training with the system before using it. These usability testing results can inform training materials.

System Usability Scale (SUS)

The average SUS score for Lydia among second-round usability testing participants was 69. A SUS score of 68 is considered average. It is worth noting that most participants had trouble with the language in the SUS, either because English was not their first language, and/or the terminology was unfamiliar. Furthermore, some participants expressed that their current thermostat was quite unsatisfactory and thus may have been judging the Lydia against a relatively low standard. These observations suggest caution when interpreting results and special consideration when using the SUS in future studies with populations in LI housing or other DACs.

CALIFORNIA ENERGY COMMISSION

CALIFORNIA NATURAL RESOURCES AGENCY

ENERGY RESEARCH AND DEVELOPMENT DIVISION

Appendix D: Additional Information: Technology and Knowledge Transfer Activities

April 2024 | CEC-500-2024-032-AP

APPENDIX D: Additional Information: Technology and Knowledge Transfer Activities

APPENDIX D details additional technology and knowledge transfer activities that can be used to supplement the information provided in Chapter 4.

Technical Advisory Committee

The project team assembled a TAC encompassing various stakeholder groups to elicit feed-back on elements of the project during its PoP. TAC members also helped contextualize results and provide additional secondary research and feedback on the results and lessons learned from designing, demonstrating, and deploying Lydia as part of this project. TAC member roles were accurate as of the time in which they contributed to the TAC (Table D-1).

Table D-1: Technical Advisory Committee Members

TAC Member Name	Organization	Role
Omar Siddiqui	EPRI	Project Manager
Ram Narayanamurthy	EPRI	Principal Investigator
Ben Clarin	EPRI	Technical Contributor – Connected Devices
Minhua Long	EPRI	Technical Contributor – Behavioral Research
Therese Peffer	UC Berkeley	Smart Thermostat Subject Matter Expert
Marco Pritoni	UC Berkeley	Smart Thermostat Subject Matter Expert
Sarah Outcault	UC Davis	Behavioral Expert
Angela Sanguinetti	UC Davis	Customer Behavioral Expert
Matt Smith	San Diego Gas & Electric (SDG&E)	SDG&E EE Program Manager
Tarun Kapoor	Pacific Gas and Electric (PG&E)	EE Program Manager
Paola Benassi	PG&E	PG&E Energy Saving Assistance (ESA) Program Manager
Kate Zeng	SDG&E	SDG&E EE/DR and Zero Net Energy (ZNE) Program Manager/Codes and Standards

TAC Member Name	Organization	Role
Jerine Ahmed	Southern California Edison	SCE Emerging Technologies Lead
Brad Williams	California Energy Commission	Commission Agreement Manager
Abigail Daken	US EPA	Project Manager of Connected Thermostat Program
Bill Mann	Duke Energy (Ohio)	Smart Thermostat Program Manager
Carol Burwick	Duke Energy (Ohio)	Smart Thermostat Program Manager
Robert Weber	Bonneville Power Administration	Residential EE Technical Lead
Kari Binley	ecobee, Inc.	Business Development – West Coast
Dave Brenner	Fresno Housing Authority	Site Provider Low Income Multifamily Energy Retrofit Program (LIMF)
Joe Shiau	Southern California Gas Company (SoCalGas)	EE Project Manager
Michelle Cook	SoCalGas	SoCalGas AB 793 Lead
Justin Hill	Southern Company	Research Engineer – Connected Devices
Nick Lange	Vermont Energy Investment Cooperative	Smart Thermostat Project Manager
Rian Troth	California Public Utilities Commission (CPUC)	ESA Program Analyst
Owen Howlett	Sacramento Municipal Utility District	Customer Program Manager
Zachary Sussman	Consolidated Edison (NY)	Smart Thermostat Project Manager
Mark Martinez	Southern California Edison	Demand Response Lead at SCE
Dave Holland	Honeywell Inc.	Connected Home Lead
John ScicchitanNYSERDA	Smart Thermostat LI Project Manager	
Tony Albers	Venstar	Smart Thermostat Manufacturer
Alan Meier	UC Davis	Smart Thermostat Expert
Peter Klint	Eversource (MA)	EE Program Manager

TAC Member Name	Organization	Role
Dave Martin	Intwine Connect	CEO – IoT Manufacturer
Joey Schmitt	Action Research	Project Manager of NYSERDA Low-Income Thermostat Program
Poornima Eber	National Grid	National Grid Thermostat Project Manager
Jean Lamming	CPUC	
	Regulatory Analysis CPUC LI DR	
Suzanne Frew	Snohomish PUD	
	DSM Program Manager	
Michelle TirtLinc Housing Corporation	LIMF Developer	
Rebecca Schaaf	Stewards of Affordable Housing for the Future	LIMF Group
Shanon Lampkins	Bridge Housing	LIMF Developer
Phil Markham	Southern Company	DSM Program Supervisor
Jason Dudley	Salt River Project	EE/DR Project Specialist
Denise Kuehn	Austin Energy	Director of Customer Programs
Mark Cosby	Evergy (formerly Westar)	Customer Program Specialist
Joanna Perez-Green	CPUC	Regulatory Analyst – AB 793
Sarah Lerhaupt (Appleman)	CPUC	Regulatory Analyst – EE Programs in Multifamily Housing
Erin Martin	PG&E	ESA Thermostat Program Manager
Madhu Annapragada	Automation Research Group	HW Design Expert
Marc Shkolnick	Lincoln Electric	Manager of Energy Services
Lukas Hurwitz	Impekable	UI/UX Design Expert
Chris Roman	SDG&E	DR Emerging Technology Lead
Irma DePratti	SDG&E	Low-Income Thermostat Program Lead
John Owen	Seattle City Light	Interest in LI Space
Jeff Hamel	Google Nest	Smart Thermostat Manufacturer
Peter Black	ecobee, Inc.	Smart Thermostat Manufacturer
Ryan May	Intwine Connect	Connected Device Service Provider

TAC Meeting Presentation and Meeting Summary

On January 16, 2019, the project team conducted a TAC meeting with the following three objectives:

1. Present a multi-stakeholder perspective on current product and program gaps for providing intelligent HVAC controls with a specific emphasis on California's DACs.
2. Reassess the utility program and product landscape to better understand if overall project objectives are still applicable or any directional changes are needed.
3. Present current project progress and identify other opportunities to address specific research questions.

General questions and areas of interest by the various stakeholders who attended the call included the following:

- **Interest from CPUC:** Comments during and after the TAC meeting were that the project team should consider 1) lessons learned from implementation of similar programs as well as documentation of implementation opportunities and challenges associated with the Lydia thermostat, 2) interest in DR using alternative methods to Wi-Fi, and 3) how Lydia development aligns with IOU-required smart thermostat TOU evaluations completed statewide.
- **Interest from California IOUs:** Comments during and after the TAC meeting were that this project team should consider including items such as 1) alternative thermostats that solve some HVAC compatibility issues experienced during pilot projects 2) challenges associated with the digital divide, and 3) emphasis on HVAC control systems primarily for multifamily applications.
- **Interest from other utilities across the country:** Comments emphasized that this project should share results with out-of-state teams that have parallel ongoing initiatives or programs/pilots also addressing LI communities.
- **Interest from LI property developers and managers:** This group noted that this project should 1) provide generalized solutions but not overgeneralize the LI building segment and demographic and 2) provide solutions for property managers to help educate tenants and manage centralized HVAC systems.

EPRI Customer Connected Device Workshop (2018)

EPRI hosted a Customer Connected Device Workshop in 2018. The objective was to convene utilities, technology providers, and related stakeholders to 1) exchange ideas, experiences, and best practices, 2) address challenges and enable opportunities when addressing a shared customer space, and 3) understand and evaluate how connected, smart devices can provide value propositions for all members of society.

A session of the Workshop was entitled *Connected Devices for All? Reaching Underserved Markets*. The objective of that session was to hear discussions on how to successfully reach historically underserved markets — such as small-to-medium business and LI customers —

through connected device programs. The session discussed efforts by technology providers, energy companies, and developers in thermostat design, deployment, and assessment alongside secondary research in this crucial market space.

Yeye Zhang of Google presented its Nest Power Project and its goals and objectives to launch the Nest Thermostat E as a learning thermostat with a target market that includes LI communities. The initiative goal is to install one million smart thermostats in LI communities by 2023 through partnering with various channels (Center on Budget and Policy Priorities, 2017). Joey Schmitt of Action Research presented on behalf of NYSERDA, describing its current efforts to design, develop, and implement a LI thermostat program in New York. Oriana Tiell at PG&E presented its plan to release a TOU pilot in which smart thermostats would be installed for LI customers in PG&E's service territory. Members of the PG&E ESA team would periodically update the project team with its results through formal and informal methods of knowledge transfer.