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FINAL PROJECT REPORT

Intelligent Heating, Ventilation, and Air Conditioning Controls for Low-income Households

A Low-cost, Connected Device That Understands Consumer Preferences and Performs Adaptive Optimization

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission, and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation, and bring ideas from the lab to the marketplace. The EPIC Program is funded by California utility customers under the auspices of the California Public Utilities Commission. The CEC and the state's three largest investor-owned utilities—Pacific Gas and Electric Company, San Diego Gas and Electric Company, and Southern California Edison Company—were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The CEC is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the Energy Research and Development Division at ERDD@energy.ca.gov.

ABSTRACT

California's pursuit of energy system decarbonization encompasses multifaceted strategies, notably efficient building electrification and the implementation of time-of-use rates. A pivotal component in achieving these goals involves the integration of smart thermostats, offering a potential solution for optimizing heating and cooling loads in buildings while harmonizing energy reduction with occupant comfort. Regrettably, disadvantaged communities face barriers, lacking access and financial means to embrace these transformative technologies that could enhance their energy efficiency.

In order to advance California's overarching decarbonization objectives while upholding principles of equity and social justice, it is imperative to bridge this accessibility gap. Despite advancements in low-cost sensors and wireless communications, making smart home technologies more broadly available, their adoption within lower-income communities has historically been sluggish. This project is expressly designed to confront the technical and market challenges inhibiting the widespread adoption of smart thermostats among residents in California's disadvantaged communities.

The initiative involves a comprehensive approach, encompassing the design, development, and deployment of a smart thermostat meticulously tailored to meet the unique needs of disadvantaged communities. By doing so, the project aspires to not only enhance energy management but also alleviate associated costs for this population. This report explains the intricacies of the project's processes and highlights its outcomes, offering valuable insights and recommendations for the heating and cooling industry. These recommendations aim to facilitate the broader transition to time-of-use rates and building electrification in California, fostering a more inclusive and sustainable energy landscape.

Keywords: Disadvantaged communities, smart thermostats, energy efficiency, building decarbonization, efficient electrification, smart communities

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Executive Summary

Introduction

California’s ambitious decarbonization goals include efficient electrification of buildings to reduce carbon emissions. To effectively transition to time-of-use or dynamic rates, intelligent energy management of heating and cooling loads is necessary.

This project aimed at achieving one of California’s decarbonization goals, which is to promote energy efficiency in disadvantaged communities. California’s low-income residents spend a more significant portion of their monthly income on energy than does the average Californian. Furthermore, research has shown that smart and connected technology adoption by the industry to help residential owners and occupants manage their energy bills is limited. Additionally, many low-income households are either renters or unable to install costly building system upgrades, making behavioral changes and connected and smart technologies the most cost-effective ways to reduce heating and cooling energy use while ensuring occupant comfort.

In recent years, significant progress has been made in low-cost sensor technology and wireless communication, leading to a new era of home and building automation. These advancements have demonstrated potential benefits for energy efficiency and demand response benefits in California markets. However, the adoption and effectiveness of these technologies in low-income communities have been slower than those for market-rate customers.

Project Purpose

This project focused on the potential opportunity for low-income communities to reduce their energy demand and increase bill savings using smart thermostats. To address these issues and promote the wider use of smart thermostats in disadvantaged communities, the project team designed, developed, and demonstrated new prototype thermostats in an apartment building. This prototype was created to answer several key research questions:

1. What emerging technology features can help overcome the digital divide for underserved communities without broadband access?
2. What type of smart thermostat can help solve some of the common commissioning issues due to heating, ventilation, and air conditioning (HVAC) compatibility found in underserved segments such as disadvantaged, affordable housing, and low-income communities?
3. How can a smart product be designed to address the affordability issues of smart and connected home technology?
4. Can intelligent thermostats help customers manage dynamic rates or other utility control signals?

Project Approach

The project team was led by the Electric Power Research Institute (EPRI); the University of California (UC), Berkeley, California Institute for Energy and Environment (CIEE); and the University of California, Davis, Energy and Efficiency Institute. These organizations were responsible for much of the smart thermostat design, development, deployment, and evaluation. Other team members included Impekable, Sierra Circuits, Inc., and Automation Research Group. Linc Housing Corporation provided the demonstration site and feedback on the thermostat and accompanying mobile application. The project team also formed a technical advisory committee, consisting of: electric utility program managers; low-income community builders, developers, and managers; technology providers; and other subject matter experts to guide and inform the project based on the latest technology and program developments.

The team designed and developed hardware requirements for the smart thermostat based on a combination of market research, technology expertise, and other product development activities. Once the hardware reference design was developed, researchers completed a set of laboratory and usability tests to inform mobile application development as well as a final prototype used for field demonstrations. The team considered two sites and selected a two-story apartment building in Santa Ana, California, with studio, 1- and 2-bedroom units. The building was built in 1969 and featured older heating and cooling systems with a combination of non-programmable and programmable thermostats. The apartment manager had been part of the community for more than 15 years, and the project team recruited 35 percent of the tenants, with about 88 percent having smartphones.

Project Results

The project identified several opportunities and barriers to developing a low-cost, intelligent heating and cooling thermostat designed to meet the needs of California’s disadvantaged communities.

The project team successfully designed and developed two low-cost thermostat prototypes to meet an overarching objective of the project, including a clear, easy-to-use smart phone application (Figure ES-1 and Figure ES-2). In addition, the team worked on innovations to make the thermostat battery powered, reduce the cost to about $75 from the average market cost of $169, and develop simple controls on the thermostat.

Additionally, the project provided insights into the technology landscape for intelligent thermostats as a whole. The project’s efforts yielded several key results, including the following:

- There were challenges related to broadband availability, compatibility of heating and cooling systems, and ease of use of the technology. California’s policies promote efficient electrification and a shift to dynamic energy rates, which adds a layer of complexity to intelligent heating and cooling management. As a result, there is a greater need for heating and cooling solutions that not only optimize efficiency but also enable bill management for low-income and affordable housing tenants as well as property managers.

- The prototype design process identified that power management, to meet the requirement of a battery-operated thermostat, heavily influenced the design decisions. The team strategically moved much of the smart thermostat functionality to the mobile application. This approach allowed the team to successfully design a mobile application and Bluetooth communication interface.
- The recruitment process for pilot participants highlighted the importance of local infrastructure in facilitating the recruitment, commissioning, support, and maintenance of an emerging technology project. The team found that sites with robust support from apartment managers and on-site maintenance staff resulted in a high level of interest and engagement from the community.
- Thermostat deployment, commissioning, and usability testing revealed that maintenance staff and pilot participants experienced a learning curve when transitioning from the traditional thermostat to the mobile application for managing heating and cooling controls. Additionally, there were also long-term customer satisfaction considerations, as the Bluetooth connectivity limitations require a user to be in close proximity to the device; this limits the amount of control that the mobile application could provide, essentially causing it to function more like a remote control.

Many tenants of low-income properties identified their main source of internet access as their mobile phones. During site selection, several potential sites had battery-powered thermostats, an important consideration because those sites would require additional commissioning steps for smart thermostats to function properly. Work with the project technical advisory committee identified that technology turndowns due to the incompatibility of smart thermostats to HVAC systems resulted in additional program costs. Sites with on-site maintenance staff and property managers were more receptive to advanced technology demonstration.

Table ES-1: Revisiting Overall Industry Needs to Develop Thermostat Functional Requirements

	Project Inception	Project Completion
Energy Affordability	The energy bill can be a large part of the monthly budget for low-income/disadvantaged residents.	Energy affordability still applies, as challenges and concerns remain about a shift to time-of-use or dynamic rates. It is unknown how low-income property owners, managers, and residents will manage the new energy cost structures.
Digital Divide Based on Income	Reliable customer-provided broadband for the internet of things decreases in proportion to income.	The digital divide associated with internet availability still applies, as challenges and concerns remain about the persistence of broadband connectivity and the associated energy efficiency or demand response capabilities of smart thermostats.

	Project Inception	**Project Completion**
Digital Divide #2 Based on Income	There is limited adoption of smart, connected technology in disadvantaged communities.	Although technology solutions by main market manufacturers are available, they are still at a higher price point than the original project price target of $75 USD.
Cost of Electricity Becoming More Dynamic	Dynamic electricity costs were not included in the focus of the original project, as California rates at the time were based on a tiered rate structure.	As electric utilities become more and more interested in deploying time-of-use rate structures, it is becoming more important to provide the DAC market segment with similar technologies while understanding the differences in building and community infrastructure.
Ease of Use	Technology was geared toward early adoption evolving to meet mass market needs.	Ease of use concerns still apply, with the key question being how to maintain device usability while balancing its functionality and intelligence for California’s disadvantaged communities.
Tools for Developers and Property Owners	Such tools were not included in the original project focus.	The project technical advisory committee indicated that property owners and developers are interested in tools to help manage centralized systems where the property owner pays energy costs, or master-metered properties. At present, there is limited knowledge of the cost-effectiveness of these types of approaches. Technologies are needed that present minimal operational and maintenance costs/requirements.

Source: EPRI

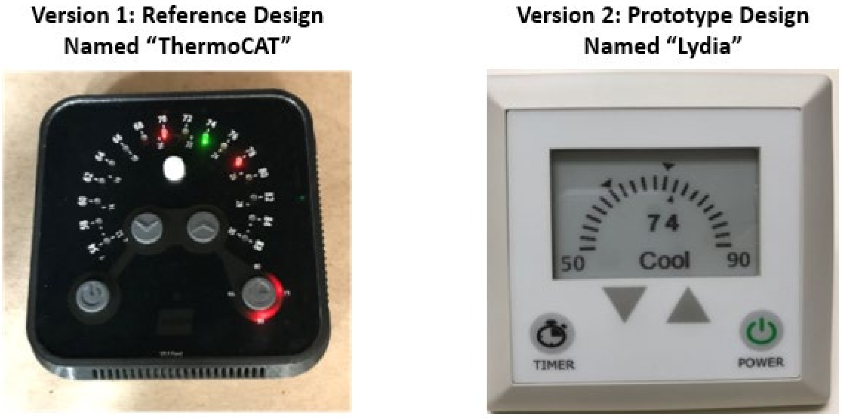
Table ES-2: Results Summary of Secondary Research, Site Selection, and Project Recruitment

	Secondary Research Results	**Santa Ana Field Site**	**Sacramento Field Site**
Site Description	Work with property managers and developers showed that it is important to *not* oversimplify disadvantaged communities into a single population for purposes of data categorization.	This site was a two-story campus layout with studio as well as 1- and 2-bedroom apartments built in 1969.	This site was a two-story fourplex multifamily community built in 1996.

	Secondary Research Results	Santa Ana Field Site	Sacramento Field Site
Heating and Cooling Infrastructure	Work shows that current programs focused on low-income segments identified older heating and cooling systems that are not "plug and play" compatible with smart thermostats, which is a major barrier.	This site features an older heating and cooling system installed during a deep building retrofit in the 1980s. Apartment units have a combination of nonprogrammable and programmable thermostats.	This site features a relatively new heating and cooling system. Apartment units have programmable thermostats.
Program Support Infrastructure	Scaling technical solutions requires strong trade support and community infrastructure.	The apartment manager has been part of the community for over 15 years. Four on-site maintenance workers are dedicated to the community.	The part-time apartment manager is available only in the mornings.
Project Recruitment Statistics	Successful programs and pilots have historically seen recruitment of anywhere from 1% to10%.	The project team was able to recruit 35% of community tenants.	The project team was able to recruit 10% of community tenants.
Availability of Personal Broadband	Studies show variations in the following: 1) personal broadband availability is correlated to household income and 2) a considerable portion of low-income households' main method of broadband/cellular communication is via the smartphone(s).	Survey responses indicate that: 1) the availability of personal Wi-Fi was 61% and 2) the availability of smartphones was 88%.	Survey responses indicate that the availability of personal Wi-Fi was 57%.

Source: EPRI

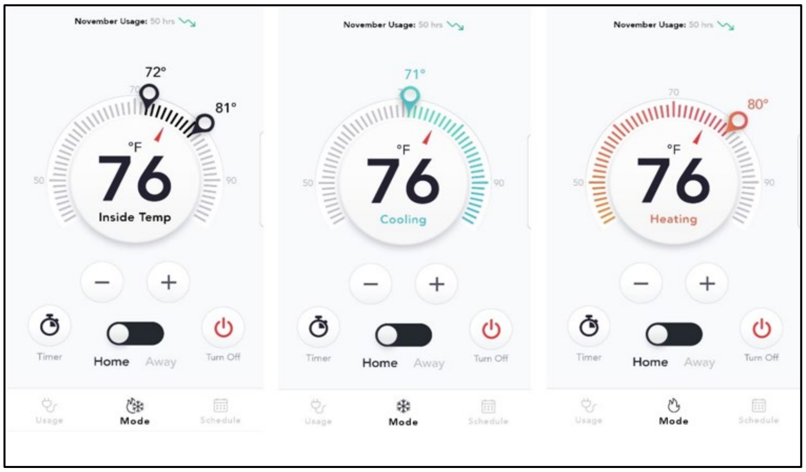
Figure ES-1: Intelligent Thermostat Hardware Developed in Project


Version 1: Reference Design
Named "ThermoCAT"

Version 2: Prototype Design
Named "Lydia"

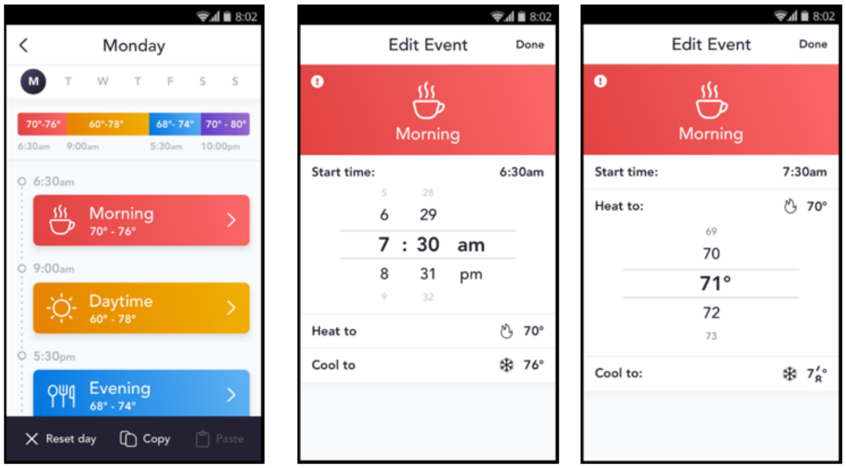
Source: EPRI

Figure ES-2: Thermostat Mobile Application Home Screen in Heat/Cool Modes



Source: EPRI

Figure ES-3: Thermostat Mobile Application Schedule Screens



6:30am Morning 70° - 76°

9:00am Daytime 60° - 78°

5:30pm Evening 68° - 74°

Morning

Start time: 6:30am

Heat to 70°

Cool to 76°

Morning

Start time: 7:30am

Heat to: 70°

71°

Cool to: 7?°

Source: EPRI

A field demonstration using the prototype design showed continued usability challenges based on the historic use of thermostats in the field site community. The project team ran a second set of usability tests and provided recommendations for new and existing thermostat manufacturers wishing to use the designs from this project. These recommendations included the following:

- **Prioritizing immediate actions to the hardware:** To meet battery life and cost requirements, the project team investigated how a simplified user interface (UI) on the hardware side — such as moving all functionality to a mobile application — would affect users. Field and usability tests showed that this approach was not an acceptable solution to most end users due to usability concerns for tenants and a history of using the interface on the device itself.
- **Providing changes to the UI of the hardware and mobile application:** Field testing revealed small suggestions for updating several hardware and mobile application features. These features included renaming some of the hardware functions, changing the hardware UI, and simplifying information on the user screens.
- **Providing push notifications:** Push notifications enable users to be aware of high-price events or other comfort and savings opportunities without having to access the application.

Technology and Knowledge Transfer: Advancing the Research to Market

The project team disseminated project results with multiple activities, including identifying other opportunities to better understand the market and technology landscape and identifying lessons learned from secondary research and technology design and use. All hardware and software developed as part of this project will be made open-source and available on the internet and other open-source repositories. Specific components and knowledge repositories are detailed.

- **Hardware designs:** There are two repositories for the two hardware designs since the original reference design continues previous work by UC Berkeley.
  - The open-source work for the reference design board is available at: http://github.com/hamilton-mote/thermostat-hw
  - The open-source work for the prototype hardware design used for pilot testing is available at: https://github.com/eprissankara73/lydia-board
- **Prototype firmware:** The codebase used to operate the firmware of the final prototype will be made publicly available. The open-source code for the firmware is available at: https://github.com/eprissankara73/lydia-firmware
- **Mobile application:** The codebase and overall mobile application designs include the Bluetooth interface developed as part of this project. The open-source code is available at: https://github.com/eprissankara73/lydia-mobile-app

- **Learning algorithm server code:** The open-source code, along with necessary custom computational and visualization libraries, is provided at: https://github.com/eprissankara73/comfort-band-model

The project team engaged several affordable housing providers in California to better gauge the needs and functional requirements of an intelligent HVAC controller that helps tenants and property managers balance energy bills with occupant comfort. The team shared knowledge of various connected thermostat projects historically, as well as ongoing project presentations at affordable housing energy peer-group events. The project team collaborated with the California Energy Commission (CEC), where thermostat replacement projects were part of the overall efficiency, decarbonization, and electrification strategy. The team also shared lessons learned about barriers to installation, commissioning, customer satisfaction, and acceptance, to improve understanding of smart thermostats as a scalable solution in California's disadvantaged communities.

The project team shared with the electric utility industry the project results that would enable the adoption of intelligent thermostats in disadvantaged communities. Knowledge transfer activities included webcasts, workshops, and other engagement activities throughout the project.

The project team provided a briefing to the California Public Utilities Commission of lessons learned from this project for initiatives such as California Assembly Bill 793 (Energy Efficiency, Quirk, Chapter 589, Statutes of 2015), which discussed energy management tools for residential and small to medium businesses.

Benefits to California

Heating and cooling often represent the largest energy use in low-income housing. Several smart thermostats offer efficient control of heating and cooling systems through learning occupant behaviors, adapting automated thermostatic control to optimize efficiency for those behaviors, and empowering consumers with smart controls using broadband communication. However, many low-income residents cannot afford broadband internet service and thus cannot participate in available energy and bill-saving control functions. In surveys conducted by this project, approximately 20 percent of demonstration site participants identified smartphones as their primary method of broadband connectivity. This figure is similar to national studies conducted on internet access in disadvantaged communities.

In 2018, about 4.5 million low-income residents paid California Alternative Rates for Energy. If a thermostat were to be used at the same rate (10 percent) over four years in California low-income housing, it would provide the following annual energy and carbon savings:

- Approximately 1,000 gigawatt-hours (GWh) per year in cooling and 40 million therms in heating.
- Approximately \$20–\$25 million in annual bill savings by 2024.
- Approximately 1 million pounds of carbon dioxide per year by 2024.

Other potential secondary economic benefits include avoided utility programmatic costs associated with arrears collection, when California ratepayers are not able to pay their electricity bills.

In addition to energy-related benefits, adopting smart heat and cooling control technologies provides secondary benefits such as improved home safety. Research has shown that, because of the poor performance of older space heating systems in low-income communities, tenants sometimes resort to using gas or electric stoves for heating. This poses health and safety risks in these communities that could be avoided with proper heating.

Finally, California's new focus on building electrification and shifting to dynamic time-of-use rates will require additional tools for electric ratepayers to manage dynamic energy rates. Technical, market, and economic barriers associated with adopting smart thermostats in disadvantaged communities present a potential challenge for ratepayers residing in these communities. The development and use of a low-cost thermostat that specifically targets underserved populations could provide economic and market benefits to California and electric ratepayers.

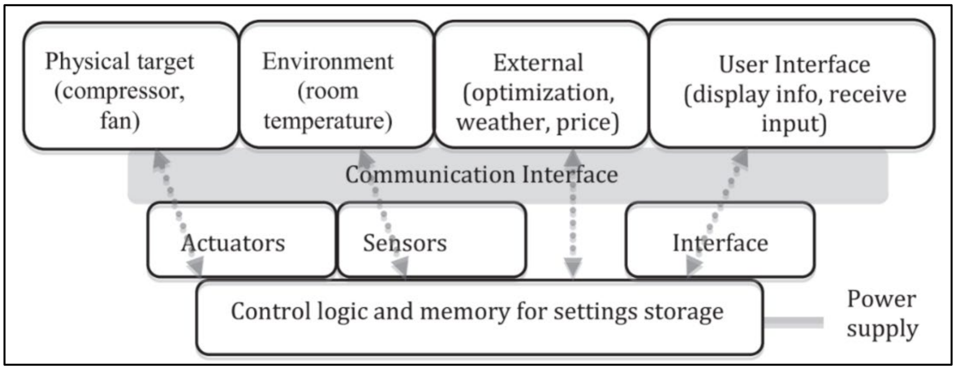
CHAPTER 1: Introduction

The basic function of the typical residential thermostat has been to control space conditioning of the premise. This has remained constant over the past 60 years. Energy management is an emerging use of thermostats, which has been enabled by emerging technologies and functions developed over the last 20 years. Features include one-touch energy-savings, occupancy sensing, access to weather data, display of energy consumption, alerts for maintenance (for example, the battery or filter), and diagnostics (Schwartz, 2010). Remote control using mobile applications is becoming a popular feature as smartphones and internet access continue to become ubiquitous. Since 1978, California building codes have required thermostats with night setback capabilities. The U.S. Environmental Protection Agency (US EPA) established technical specifications for programmable thermostats for its ENERGY STAR® program in 1995 (US EPA ENERGY STAR, 2009). Residential demand response (DR) is another development. Utilities with high power supply costs during certain times of the year (usually in the summer) could communicate directly with thermostats. These thermostats could be used to minimize energy consumption by either adjusting setpoints and/or not allowing space conditioning use during certain periods of time. This method is potentially a more cost-effective way of managing the energy system versus building new generation capacity.

A basic thermostat has four components: 1) a temperature sensor, 2) a switch or actuator to the physical target of heating, ventilation, and air conditioning (HVAC) equipment, 3) a feed-back loop between the two, and 4) some means for the user to change the target temperature.

Thermostats have become increasingly disaggregated into separate components, primarily due to advancements in communications and sensor technologies. Figure 1 shows a schematic of the components of a communicating thermostat. Note that these components may or may not be packaged together. For further information on defining thermostat components, see Appendix A. The temperature sensor may be wireless and communicate with the controller via radio frequency; the user interface (UI) may be a mobile phone, paired with the device itself or a webpage.

Figure 1: Components of a Basic Thermostat



Source: UC Berkeley California Institute for Energy and Environment (CIEE)

Although programmable thermostats have been promoted as devices that can save energy, they differ from traditional energy efficiency (EE) or energy conservation measures, such as insulation or a more energy-efficient appliance, in which simply installing the measure provides a probability of saving energy. In contrast, operating the thermostat (manual or automated) to control an HVAC system affects household energy use and leads to associated occupant impacts. Field studies showed no significant savings in households using programmable thermostats compared to households using nonprogrammable thermostats (Peffer et al., 2011). US EPA reviewed this information and determined that users were not using these thermostats. They concluded that difficulties in programming and a lack of understanding of terms such as setpoint were some of the main reasons that energy conservation functions were not enabled. As a result, US EPA discontinued the ENERGY STAR programmable thermostat program in December 2009. The current versions of smart thermostats make programming easier, potentially through more usable interfaces and access to more convenient mobile and web applications. As new occupancy sensors (physical or through geofencing[1]) and learning/optimization algorithms become more predominant, some programming burdens are also lifted from users (Ford et al., 2016).

Nationally, there was renewed interest in connected thermostats around 2013 with the use of data-driven labeling approaches. In December 2016, US EPA released the final version of a new ENERGY STAR specification covering connected thermostat products. This specification is novel in that it grants ENERGY STAR recognition to a product incorporating both hardware (HW) and service elements. The specification is also the first to rely on analysis and aggregation of field data, rather than a laboratory test, to demonstrate that products can save energy (US EPA ENERGY STAR, 2016). The new specification uses data collected by the thermostats to evaluate their ability to save energy. This project investigates the potential of smart thermostats as well as other drivers discussed in the following section.

Project Drivers

This project targets one of California's strategies to meet its long-term decarbonization plan, specifically EE for low-income (LI) communities. HVAC can be the largest load in residential buildings and possibly the highest efficiency opportunity in LI housing. For example, in a deep efficiency project in an LI community in Lancaster, California (Climate Zone 8), heating and cooling accounted for 50 percent of the energy consumed in a tenant unit (Hammon-Hogan et al., 2016). Improved and intelligent HVAC controls such as those provided by smart thermostats could potentially promote EE at low cost and encourage awareness of energy use by tenants.

California's mild weather and decades-long history of cutting-edge building energy codes is worthy of discussion before describing the development of the smart thermostat. While California enjoys a diverse climate, in general, the mild weather means less energy is spent on heating and cooling end uses — only 4 percent of total end-use energy consumption is for cooling and 27 percent is for space heating (compared to 6 percent for cooling and 41 percent

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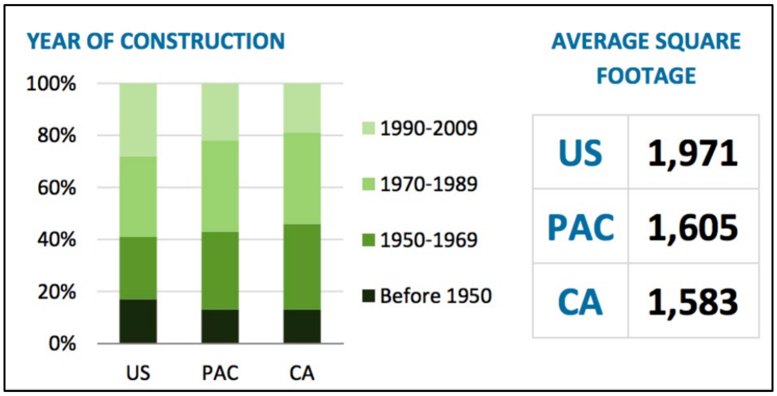
[1] Geofencing can be defined as using global positioning system (GPS) capabilities to identify boundaries. Geofencing is realized using the GPS capabilities of smartphone technologies. Smart thermostats can be paired with users' smartphones to identify when they are approaching their residences. Settings are automated as users enter or leave their residences.

for space heating for the United States as a whole). It is estimated that 14 percent of California homes are not heated, and 40 percent have no air conditioning (A/C) (Palmgren et al., 2010). However, population trends in California show the greatest increase in hotter inland areas. Historically, A/C — in residential and commercial buildings — is the primary contributor to peak demand in California. As the state works toward meeting its decarbonization targets, it will be important to understand the effects on peak demand attributed to efficient electrification of space heating.

Figure 2 shows the year of construction for U.S. homes, Pacific region homes (Alaska, Washington, Oregon, California, and Hawaii), and California homes (EIA, 2013).[2] The energy code governs building envelope (for example, window construction and amount of insulation in roof, walls, and floor), equipment selection (efficiency of space conditioning equipment), and performance goals. Part of this code required setback thermostats (thermostats that adjust temperature setpoints, either through automatic controls or default manual programming) for new homes. Californians are more likely (more than 50 percent) than other Americans (about a third) to have a programmable thermostat, likely due to early development of these building codes. Part of the 2008 California Building Energy Efficiency Standards (commonly known as Title 24) states that programmable thermostats must allow the setting of temperature setpoints for at least four different time periods per day. Recent updates to the building code continue to adopt and promote inclusion of thermostat technologies for both EE and DR opportunities. Also shown is that approximately half of California residential buildings were built before the energy codes and are likely to be poorly insulated.

Figure 2: Year of Residential Construction Nationally, Regionally, and in California



US	1,971
PAC	1,605
CA	1,583

Source: US Environmental Information Administration

North America has seen an increase in “smart” thermostat deployment in recent years. Berg Insight estimates that 7.8 million smart thermostats were installed in North America in 2016 (up from 5.8 million in 2015) (IoT Business News, 2016). While these thermostats vary in function, for the purposes of this project, a smart thermostat (also called an intelligent thermostat in this report) tends to have the following capabilities:

- It allows the customer to remotely program the thermostat (called networked, connected, or communicating thermostats).

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[2] California’s first building energy codes took effect in 1978.

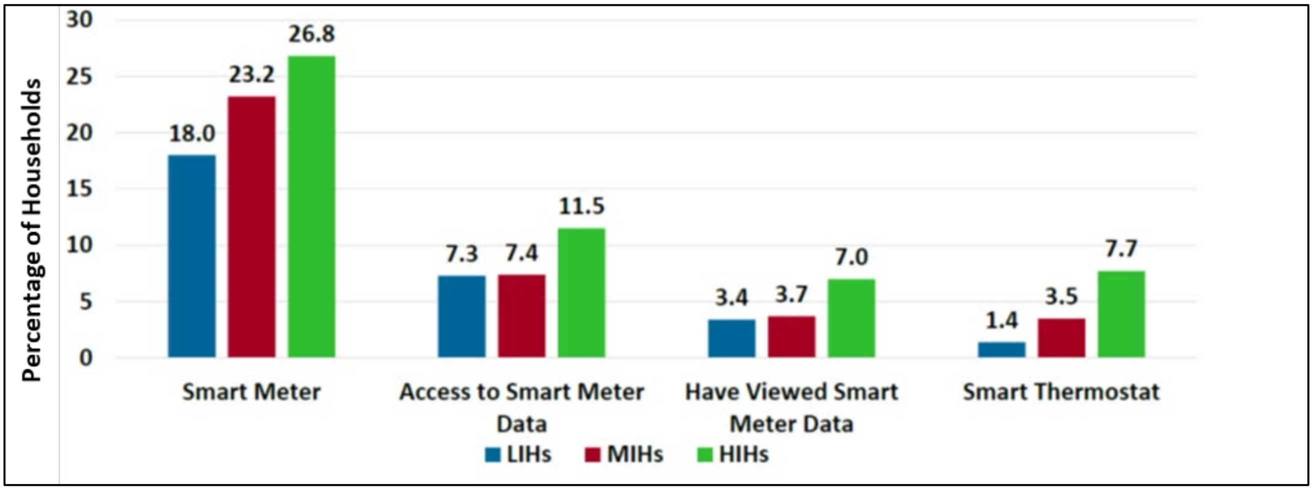
- It enables two-way wireless communication of data.
- It provides advanced algorithms (beyond automation, such as optimization and learning) to improve comfort and reduce energy consumption.

A smart thermostat could also engage occupants by raising awareness about their amount and pattern of energy use.

Smart thermostats allow users to manage home temperature based on the time of day and from a remote location using a tablet, laptop, or desktop computer. A key feature to using smart thermostats as a tool to reduce HVAC energy consumption is their ability to learn and adapt to user behavior. This learning ability potentially helps homeowners reduce energy bills and provide a more comfortable living environment.

Figure 3 details three segments of household income: 1) low-income households (LIHs), 2) medium-income households (MIHs), and 3) high-income households (HIHs) (Chen, 2018). Note that, in all instances, inclusion of smart thermostats as well as access to and knowledge of other potential energy-saving information and technologies varies, depending on household income, with HIHs having greater access than LIHs.

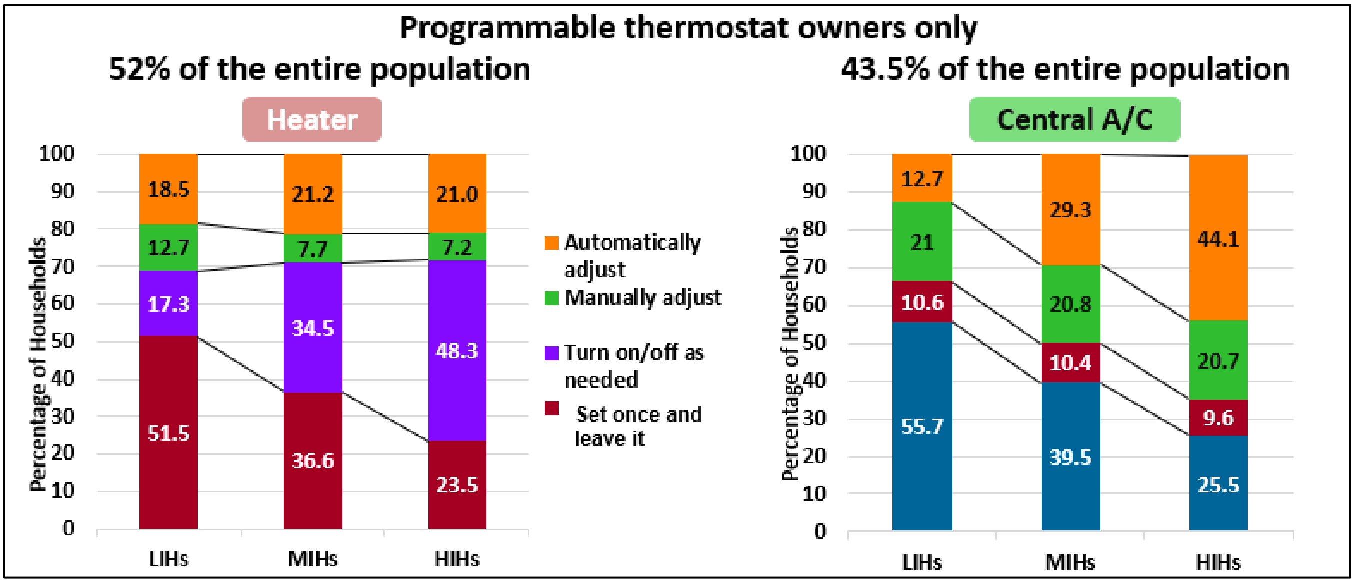
Figure 3: Differences in Access to Smart Grid Technologies (Nationally) Based on Household Income



Source: University of Tennessee-Knoxville

Smart thermostats have a high potential for efficiency in the LI segment, as these households tend to have fewer plug loads and smaller, older dwellings. In addition, as California moves towards meeting its state decarbonization goals, it will be important to enable the adoption of efficient electrification technologies such as heat pumps (HPs). The nature of HP operation to maintain comfort conditions, especially in LIHs that are susceptible to poor insulation, will require improved HVAC control. This improved control will also be more important as continued deployment of distributed energy resources (DER), such as residential solar, has caused the state to move to more dynamic energy rates. However, considerable challenges remain for LIHs related to access to smart thermostat technology and education on intelligent programming and use of the technology (Figure 4) (Chen, 2018).

Figure 4: Surveyed Responses at the National Level of Differences in Programmable Thermostat Usage by Income Level



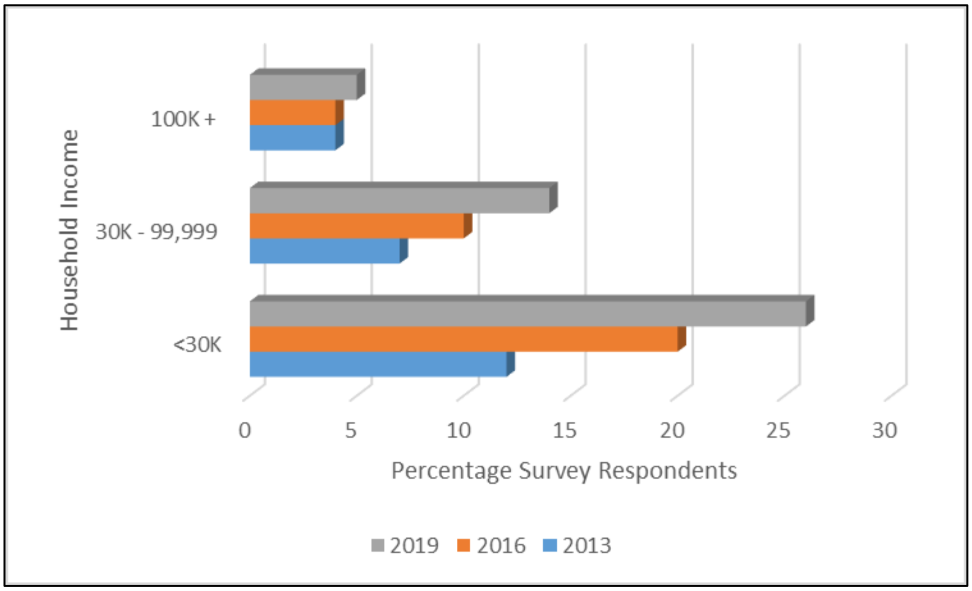
Source: University of Tennessee-Knoxville

Figure 4 shows a national survey of programmable thermostat owners and how they use the thermostat. Variations in thermostat use based on income may cause differences in the realization of energy savings for HIHs versus LIHs. This concept is important to understand when reviewing market penetration of smart thermostats and developing bill-saving algorithms.

California Assembly Bill 793 (Energy Efficiency, Quirk, Chapter 589, Statutes of 2015) (California Legislative Information, 2015) provides incentives to residential customers to purchase energy management technologies and develops plans to educate residential customers about investor-owned utility (IOU) incentive programs. Thermostats offer a low-cost but potentially high-impact way to reduce LIH energy bills. Lack of access to broadband in LI communities may create an efficiency digital divide in which a segment of society is unable to benefit from energy savings due to a lack of infrastructure. This is especially true with the current trend of efficiency measures being delivered through the internet (for example, home energy reports and smart thermostat efficiency programs).

In 2019, 90 percent of U.S. adults reported using the internet at least occasionally (up from 79 percent in 2011), and 81 percent of adults owned a smartphone. In addition, national research shows increased reliance on mobile/smartphones as the primary method to access the internet for LIHs with household income of less than $30,000/year (Figure 5) (Pew Research Center, 2015).

Figure 5: Households Identifying Primary Access to Internet via Mobile Phone



Source: Pew Research Center

That is a 12-percent increase in households that rely on their mobile phone as the primary access mechanism; also, the number of households has doubled in the less-than-$30,000/year income bracket between 2013 and 2019. This illustrates the challenges to using smart devices, including smart thermostats, in LI communities due to inherent challenges in nonmobile-phone access to household broadband.

In addition to a digital divide caused by income level, market barriers such as split incentives[3] present challenges in EE upgrade adoption — including smart thermostats. Utility programs have historically offered "free" tenant measures implemented through property owners to combat split incentives. In California, these programs include measures such as compact fluorescent lights (CFLs) and low-flow showerheads. Some programs, such as the Massachusetts Low Income Home Energy Assistance Program (LIHEAP), include free programmable thermostats (with DR) as part of tenant measures. Beyond LI customers, the same lack of broadband access affects many small commercial customers as well as other demographic segments such as rural customers. In addition, the importance of cost-effective DR can potentially increase grid reliability. However, customers who lack broadband are unable to participate in DR programs.

Project Objectives

Based on the potential opportunity for energy, demand, and bill savings enabled by smart thermostats, the project team developed the following project objectives:

- **Enable energy affordability:** The energy bill is a larger part of the monthly budget for LI and disadvantaged residents.

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[3] Split incentives refer to situations in which the tenant pays the electricity bill, while the building or facility manager is responsible for building upgrades, and neither stakeholder has the incentive to identify, complete, and participate in a demand-side management (DSM) incentive program.

- **Digital divide based on income:** As previously discussed, penetration of reliable broadband connectivity becomes less and less reliable as annual household income decreases. Therefore, Wi-Fi solutions become less reliable both to customers and energy companies.
- **Access to smart home technologies:** As less reliable broadband is available in LIH market segments, it is also quite common for these segments to suffer from limited technology availability. For example, in 2018, it was estimated that 90 percent of people who bought a Nest smart thermostat had an annual income of more than $100,000/year (Staples, 2018). As a result, the adoption of emerging technologies to help customers manage energy-related decisions in affordable housing, LI, or disadvantaged communities has been hampered.
- **Energy costs are becoming more dynamic:** California's decarbonization goals will require increased market penetration of renewable and distributed energy resources. Decentralization of the electricity supply will make the cost of supplying electricity more dynamic than it historically has been. This project not only targeted EE in multifamily affordable housing communities but also focused on available tools to help tenants manage time-of-use (TOU) rates as energy costs become more dynamic.
- **Ease of use:** There are demographic as well as psychographic differences between the affordable housing/LI segment versus the early adopters of the smart thermostat and the connected home in general. This project will emphasize the design of a thermostat focused on the affordable housing/LI segment.
- **Bill management tools for developers, property owners, and managers:** Throughout the project, the project team elicited feedback on capabilities where the smart thermostat could enable bill management for property owners, developers, managers, and other stakeholder groups in affordable and LI housing. One item of interest to these entities is centralized systems (for example, in the case of master-metered properties where the owner pays the energy bill) that help manage energy costs and tenant comfort.

With these project drivers in mind, it is important to be reminded of the main research questions as points of field testing and demonstration points of departure:

- What type of available emerging technology features can help overcome the digital divide for underserved customers without Wi-Fi access?
- What type of smart thermostat can be developed to solve commissioning issues due to HVAC compatibility found in underserved segments such as disadvantaged, affordable housing, and LI communities?
- Can a smart product be designed to address affordability issues by targeting a $75 smart thermostat product in the market?
- What type of intelligent HVAC tools can be provided to help customers manage dynamic rates or other utility control signals (such as TOU rates or DR)?

The project focused on the following tasks:

- Conducting market and customer research to better understand the needs for cost containment, comfort, and other factors affecting affordability of the proposed thermostat. Such factors are important, since the connected home industry is an area of rapid technology change.
- Developing requirements for an intelligent HVAC controller (a smart thermostat), which includes a UI for the mobile application and thermostat HW.
- Developing a prototype intelligent HVAC control system for LIHs.
- Evaluating device usability and optimization algorithms in the laboratory and focus group settings.
- Testing the prototype in the field.

To complete the project, the team set forth the following objectives related to thermostat design, development, and deployment:

- Developing a simple, intuitive UI that recognizes and records user preferences for the indoor environment through basic commands.
- Developing an HVAC control unit (thermostat) with built-in automated algorithms. Developers intend to embed efficiency analytics in the unit based on an understanding of consumer preferences.
- Developing a thermostat that would sell in volume for as little as $75 retail.
- Being able to control basic HVAC operations, with humidity-sensing and options based on energy costs.
- Collecting data on runtime, indoor setpoints, indoor temperature, and so forth.
- Having capabilities for data collection and connectivity to utility systems to enable DSM programs such as EE or DR.
- Developing a thermostat that can operate on two or three AA batteries for six months.
- Integrating low power near field communication (NFC) for smartphone pairing.

Key Innovations

When designing the thermostat and the project, the team worked on addressing the following key innovations:

- **Integrating low-power NFC for smartphone pairing:** Due to LIHs being more likely to own a smartphone versus having Wi-Fi access, the project team designed a thermostat that will not rely on Wi-Fi access as its primary communication mechanism. Instead, the project team investigated Bluetooth Low Energy (BLE) as the primary mechanism to enable functional control of the thermostat. BLE was used because it is native to many smartphones; however, BLE *does* require that the phone be located next to the thermostat.

- **Making the thermostat battery operated:** Many smart thermostats require either a common wire (C-wire)[4] to power the thermostat or alternative equipment to draw power for the HVAC system. Alternatives come with additional cost or labor and result in suboptimal HVAC system operation. Similarly, the project team examined development of a battery-powered intelligent HVAC controller with a six-month battery life.[5]
- **Reducing thermostat cost:** Many smart thermostats in the market cost more than $200. With recent interest in providing lower-cost options, companies such as Google Nest and ecobee, Inc. now offer lower-cost thermostats intended for LIHs. However, these thermostats still sell for $169 (Google Nest Thermostat E., n.d.; Ecobee, n.d.).[6] The thermostat developed through this project is intended to be sold for $75.
- **Developing simple controls on the thermostat itself:** Numerous thermostats, especially legacy and programmable types, have been designed with many of the controls on the thermostat. This project examined a unique method of providing many of the controllable options for the smart thermostat in a mobile application versus on the actual thermostat HW.

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[4] A common wire or "C-wire" is provided by newer HVAC systems used to power thermostats.

[5] Six-month battery life was chosen to match the suggested timing for replacing smoke detector batteries.

[6] Refurbished versions of other smart thermostats cost $129.

CHAPTER 2: Project Approach

This chapter focuses on secondary research conducted throughout the project to define and continue to assess whether project objectives matched market needs. The chapter then covers design work and the eventual development of a thermostat reference design used for preliminary usability and laboratory testing. Finally, the chapter summarizes a field test plan to guide the recruitment, installation, and assessment of thermostat performance.

Market Assessment — Opportunities and Barriers to Providing Smart Thermostats in California's Disadvantaged Communities

Secondary research was an important facet of this project. Since technology development in the smart technology space moves rapidly, it was important to understand whether original project objectives were still pertinent to the greater project purpose and meeting California's energy goals. The project team used a two-step process for secondary research throughout the project: 1) researching current smart thermostat market and functions, and 2) gauging market developments to ensure that key innovations would address barriers to smart thermostat adoption, with specific emphasis on adoption for California's LI communities.

Smart Thermostat Research

In recent years, North America has seen considerable growth in smart thermostats installed for residential applications. Smart thermostats can be used for several purposes, the main being improved occupant comfort through increased automation. Self or intuitive programming capabilities provided by these thermostats, when done properly, free occupants from making frequent thermostat changes depending on whether they will be present in the room. This type of programming uses setback temperatures based on either the detected or the learned behavior of the occupant in conjunction with external variables such as HVAC and outdoor and indoor environmental characteristics.

Another capability of programmable and smart thermostats is their use as an energy system resource through participation in DR programs to reduce energy consumption during times when it is expensive to generate electricity. Historically, residential DR programs relied on direct load control switches. These one-way communicating devices were only capable of sending a paging signal through a utility system to cycle residential HVAC systems. Because these devices did not send any information back to the utility system, there was no indication of HVAC performance during a DR event. In addition, if customers chose to opt out of a cycling program, they had to unenroll in the program through a phone call to a utility or third party. These steps potentially lead to decreased customer satisfaction with the utility.

Two-way communication capabilities provided by the new generation of thermostats could mitigate some reporting and customer service issues. Utilities began using smart thermostat pilots and program evaluations across the United States to investigate these benefits. Because these devices presented a new paradigm of consumer-facing technologies, utilities were presented with new opportunities as well as new market delivery channels.

The 2015 United States Energy Information Administration (USEIA) Residential Energy Consumption Survey (RECS) reported that, in the Pacific States,[7] 39 percent of households owned a programmable thermostat, 8 percent of households owned a nonprogrammable thermostat, and 53 percent had no thermostat (USEIA, 2015). According to the California 2003 Residential Appliance Saturation Survey (RASS), only 28 percent of California households set the temperature for A/C during the day, and the presence of programmable thermostats did not appear to dramatically affect setback behaviors (Hammon-Hogan et al., 2016).

In a recent study comparing the energy consumption of California households with manual thermostats versus programmable thermostats, programmable thermostats were set slightly higher (0.7°F –1.2°F [–17.4°C –17.1°C]) than manual thermostats in the cooling season (the summertime, which would save energy). However, these setpoints were not enabled and were in some form of OFF mode. Similarly, programmable thermostats were set at higher temperatures than manual thermostats (that would use more energy) in the wintertime. That same study found that setpoints assumed in Title 24 energy code compliance software (SW) overestimated the cooling setpoint and underestimated the heating setpoints. This would cause households in the study to use, on average, a lower setpoint for cooling (used more energy) and a higher setpoint for heating (used less energy) than the default energy-saving setpoints (Palmgren et al., 2010).

Occupants regularly interrupt the programming by choosing Hold and/or Override functions on their programmable thermostats. Both these functions are modes that suspend the programmed schedule. An override allows the user to temporarily change the desired temperature, deviating it from the programmed setpoint until the next scheduled time programmed. The Hold mode is a permanent change; putting a programmable thermostat in Hold mode functionally transforms the programmable thermostat into a manual thermostat. A study conducted by a thermostat manufacturer examined the operating mode of installed programmable thermostats in households within four energy companies — two in New York and two in Southern California. Of the more than 35,000 monitored thermostats, 53 percent were in Hold mode. The households within the service districts of San Diego Gas & Electric Company (SDG&E) and Southern California Edison Company (SCE) showed a higher percentage (65 percent) in program mode, although it was unclear why (Haiad et al., 2004).

A new generation of connected thermostats tends to simplify the user interaction with 1) more intuitive interfaces, 2) additional interfaces, more familiar to the user, 3) automatic responses to sensor triggers (mostly occupancy) to adapt setpoints without the need for manual schedule adjustments, and 4) automatic learning of occupancy and setpoint patterns, to save energy and improve comfort at the same time.

Even though the technology has improved compared to older technologies, it is still unclear how residents interact with these smart systems and the degree to which they value automation over direct control. The project team collected summary statistics on third-party evaluations of smart thermostat pilots and programs across the United States. These studies

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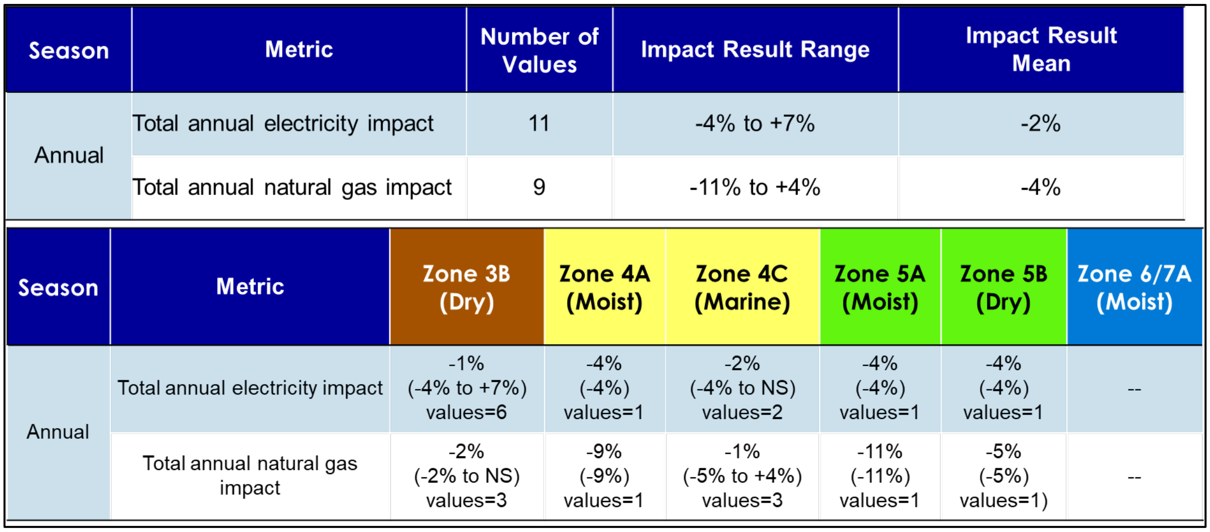
[7] Pacific States as defined by the EIA include California, Oregon, and Washington.

varied in climate, overall research questions, number of thermostats, targeted market, and thermostat manufacturers (Figure 6) (Clarin, 2017).

Figure 6: Smart Thermostat Energy Efficiency Evaluations Summary (as of 2016)



Season	Metric	Number of Values	Impact Result Range	Impact Result Mean
Annual	Total annual electricity impact	11	-4% to +7%	-2%
	Total annual natural gas impact	9	-11% to +4%	-4%

Season	Metric	Zone 3B (Dry)	Zone 4A (Moist)	Zone 4C (Marine)	Zone 5A (Moist)	Zone 5B (Dry)	Zone 6/7A (Moist)
Annual	Total annual electricity impact	-1% (-4% to +7%) values=6	-4% (-4%) values=1	-2% (-4% to NS) values=2	-4% (-4%) values=1	-4% (-4%) values=1	--
	Total annual natural gas impact	-2% (-2% to NS) values=3	-9% (-9%) values=1	-1% (-5% to +4%) values=3	-11% (-11%) values=1	-5% (-5%) values=1)	--

Source: EPRI

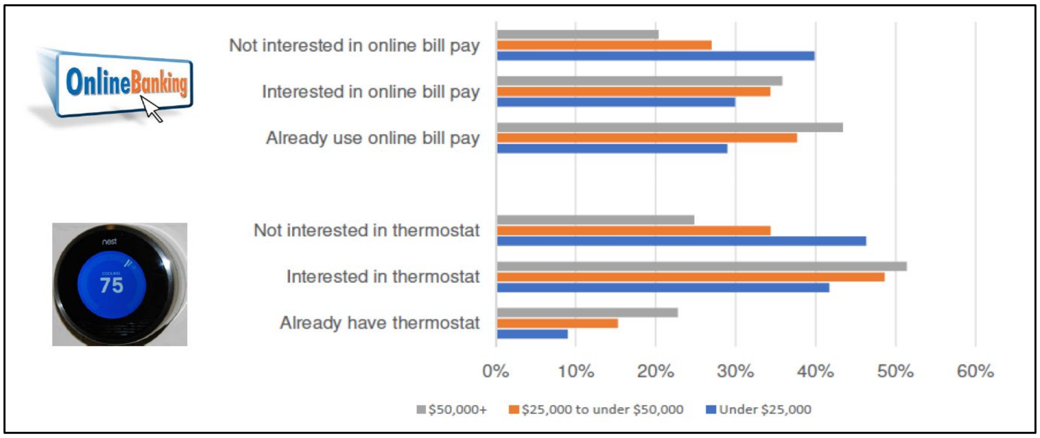
Although there seems to be savings potential, in some instances thermostat deployments have increased energy consumption when examined through a programmatic/scaled lens. It is important to understand the background conditions of each of these pilots and programs before assessing their extensibility to California and the LI community market segment.

In addition, since 2018, smart thermostat manufacturers have shown an interest in providing their products to LIHs and disadvantaged communities. Leading smart thermostat manufacturers such as Google Nest with its Nest Power Project (Nest Power Project Initiative, n.d.) and ecobee with its ecobee3 lite have indicated an interest in providing a similar thermostat at a reduced cost to be more affordable and in providing refurbished products with similar manufacturer warranties to LI communities. Manufacturers have also begun establishing partnerships with community-based organizations (CBOs) that could provide better avenues to influencing adoption in LIHs or disadvantaged communities.

Previous Efforts Providing Programs for Low-Income Communities

As discussed in Chapter 1, access to EE and other DSM programs has historically been challenging to LI populations nationally (Figure 7) (Merckley, 2018).

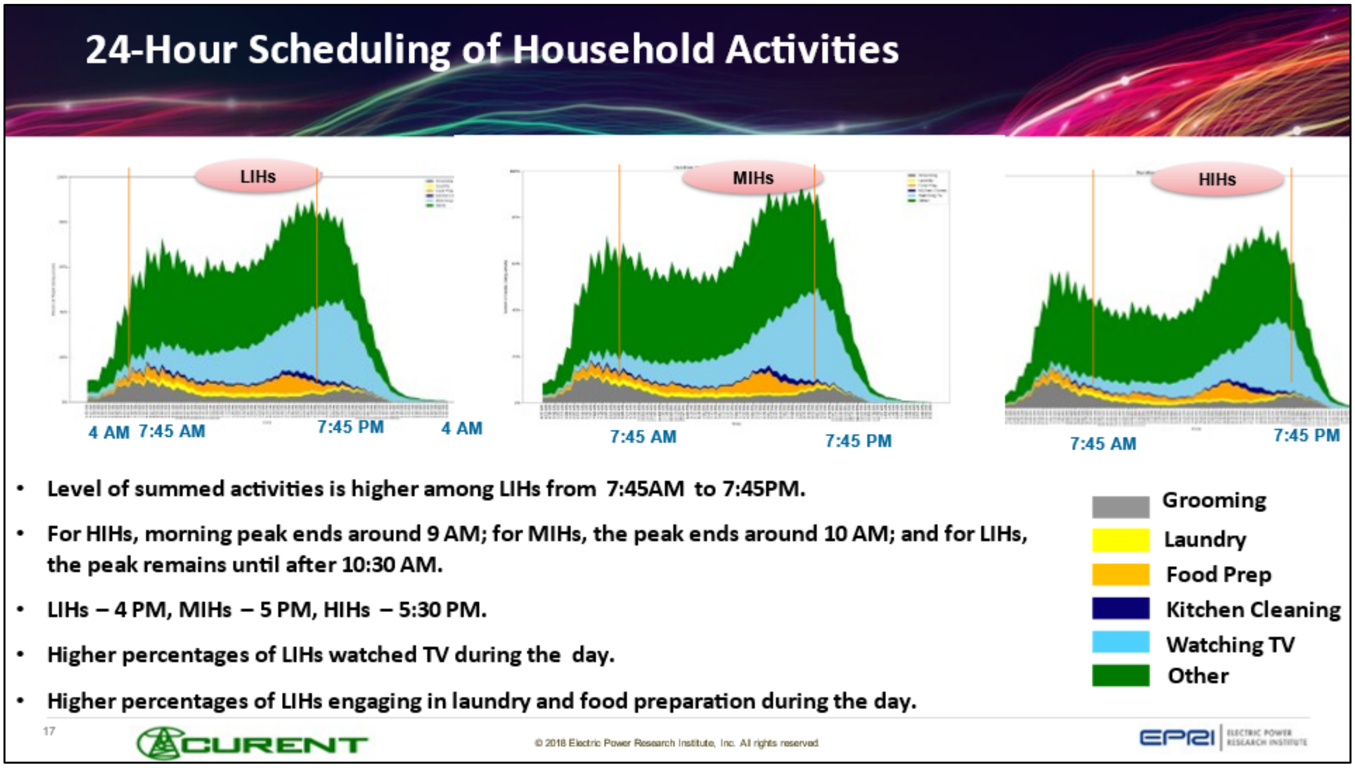
Figure 7: Interest in Smart Thermostats and Online Bill Pay for Energy Services Based on Household Income



Source: Smart Grid Consumer Collaborative

There are differences in not only ownership but also access and interest in smart technology and internet-dependent services. In LI communities, it may be necessary to rethink typical recruitment strategies that are successful in current smart thermostat programs. Previous work shows that access to CBOs or other no-provider ambassadors may be a more effective way to reach LI customers (Merckley, 2018). In addition, it is hypothesized that occupancy and usage patterns could potentially be different based on household income level (Figure 8) (Chen, 2018).

Figure 8: Differences (Nationally) in Activity and Schedule by Income Level



24-Hour Scheduling of Household Activities

- Level of summed activities is higher among LIHs from 7:45AM to 7:45PM.
- For HIHs, morning peak ends around 9 AM; for MIHs, the peak ends around 10 AM; and for LIHs, the peak remains until after 10:30 AM.
- LIHs – 4 PM, MIHs – 5 PM, HIHs – 5:30 PM.
- Higher percentages of LIHs watched TV during the day.
- Higher percentages of LIHs engaging in laundry and food preparation during the day.

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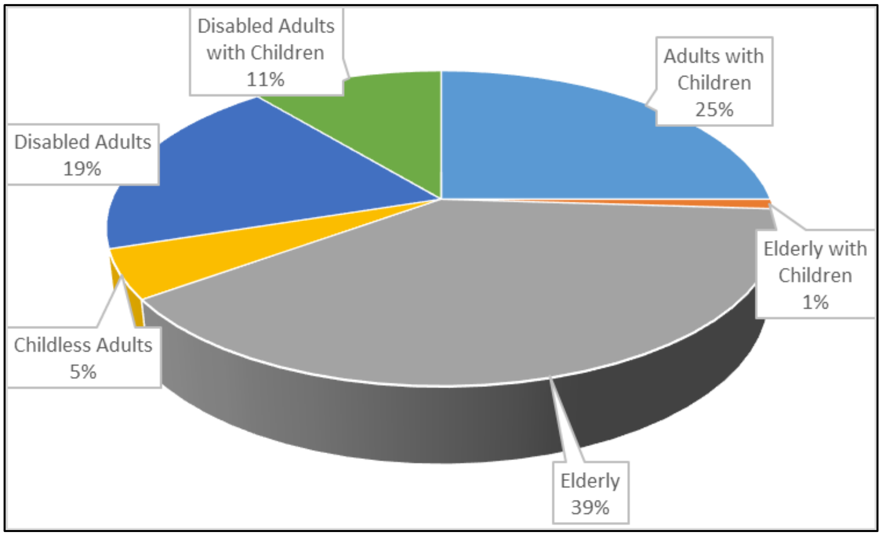
Source: University of Tennessee-Knoxville

Additional challenges in providing emerging efficient technologies and programs to LI communities include: 1) access to capital to afford upgrades, 2) structural deficiencies of existing building stock, causing increased project costs, 3) split incentives in rental properties, 4) awareness of incentives or other programs available, 5) timing of fiscal budgets and availability of resources and incentives, and 6) multiple programs where access to resources becomes challenging to manage. These issues make it challenging to provide EE upgrades at scale in LI communities.

However, it is important to understand and address the LI community landscape. LIHs are quite heterogeneous and vary significantly by race and ethnicity. LIHs also tend to have a language other than English spoken at home (ChildTrends, n.d.). LIHs in California with children are more likely to be led by a single parent (45 percent versus 20 percent in higher-income households). Other large constituents of California's poor and LI sectors are retirees, the elderly, and persons with disabilities (Figure 9) (Sussman-Stillman & Banghart, 2016).

Figure 9: Low-Income Households in California Receiving Federal Assistance



Source: National Center for Children in Poverty

It is important to provide access to technologies that improve efficiency, especially to LI communities in the state, because energy costs are typically a higher portion of LI family monthly budgets (Center on Budget and Policy Priorities, 2017). California, with its historically aggressive EE goals, is above the median as it pertains to the percentage of energy bills that an LI family pays in proportion to a baseline median family in the same area. It is important to keep monthly energy costs in mind, as this could have residual effects such as LI residents foregoing medical or dental care (Drehobl & Ross, 2016). In addition, children in homes experiencing energy insecurity are 82 percent more likely to be at risk of developmental delays (Children's Healthwatch, n.d.).

Thermostat Design

This section focuses on developing thermostat design requirements, including HW requirements, interfaces with mobile phones to enable connectivity, thermostat algorithms, and DR capabilities.

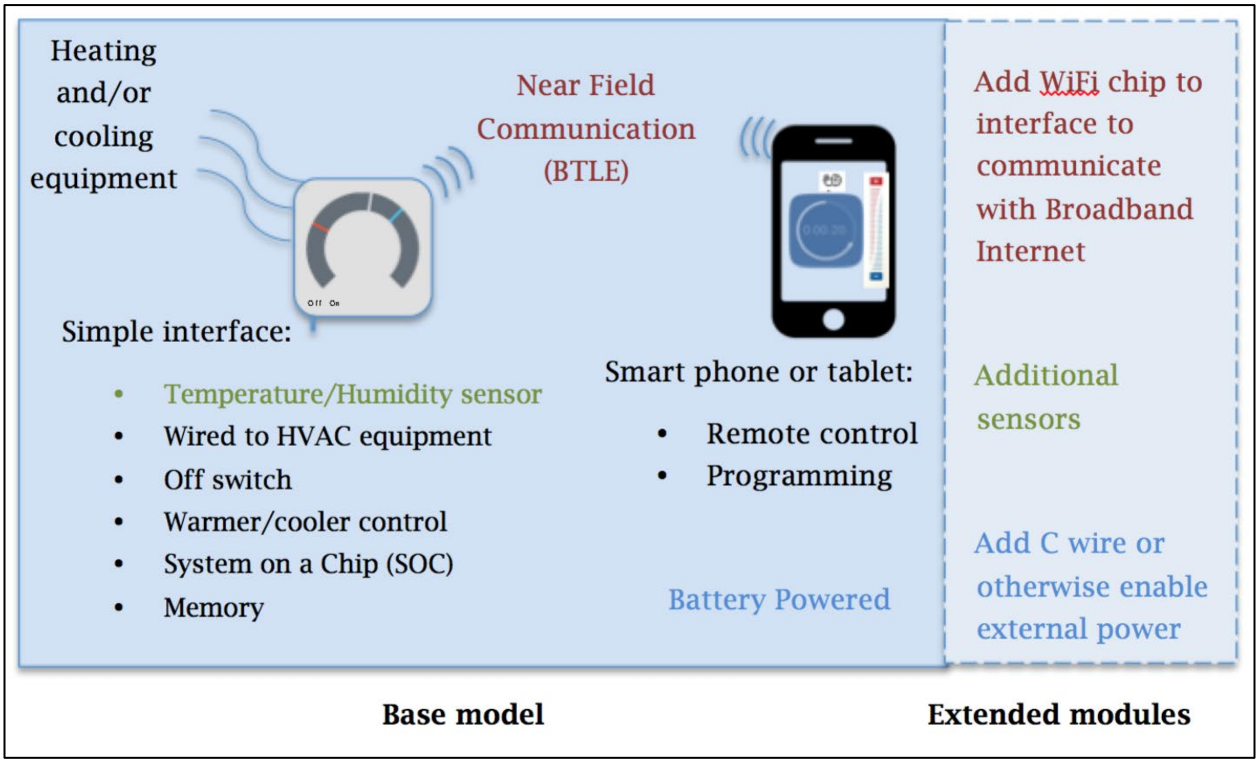
Design Requirements

The basic architecture of the low-cost smart thermostat is a usable and simple thermostat on the wall connected to HVAC equipment that, at minimum, can communicate via NFC, such as BLE (also called BTLE), to a more sophisticated interface on a smartphone or tablet. The following section explains the thermostat design and summarizes significant efforts in completing a reference design.

Thermostat Architecture

The disaggregated or modular nature of this thermostat design allows for additional options, such as direct Wi-Fi, auxiliary sensors (temperature, occupancy, carbon dioxide) that communicate via BLE or Wi-Fi, and external power (Figure 10).

Figure 10: Modular Architecture of Thermostat



Source: University of California, Berkeley, CIEE

This thermostat architecture is informed by several design choices regarding connectivity, power, interface, equipment controlled, and sensors. For additional details on the overall thermostat architecture, see Appendix A.

User Interface

Previous work shows that improving usability may increase use and adoption of smart thermostats that can encourage energy-conservation behavior. Current research also indicates that smart thermostats with energy saving features — such as automatic temperature offsets based on occupancy measurements — can provide substantial energy savings. The UI then takes on the important function of engaging the user as well as collecting data on user preferences. Based on a combination of secondary resources, usability studies (Perry et al., 2011), and a heuristic evaluation of five thermostats (Peffer et al., 2013), this section outlines new functions as well as several design guidelines to improve thermostat usability. Suggested design features include the following:

- Energy consumption feedback (information to help users understand the connection between temperature settings, HVAC use, cost, and the environment).
- Occupancy sensing (whether by near or distant passive infrared sensors, or geofencing through a phone).
- Intelligence in the form of learning algorithms to recognize patterns (for example, occupant preference in temperatures and characteristics of HVAC and house) as well as optimization for controlling equipment and determining appropriate setbacks.
- Voice-activated thermostat controls, especially for seniors and the disabled (such as ecobee thermostats with embedded Amazon Echo).
- A "boost button" (an additional time period of space conditioning), similar to the plus-1-minute button found on microwave ovens, provides some flexibility to a program due to a temporary and/or impromptu change in schedule (Rathouse, & Young, 2004).
- A timer to turn heating or cooling on or off for a specific amount of time (Kempton et al., 1992.
- An estimation of the time needed to reach the desired temperature.

With these functions in mind, the project team created UI design guidelines based on historical experience, thermostat designs, and mental models. In summary, the general recommendations include: 1) ensuring that main options are visible on the home screen, 2) using a wide and shallow decision tree to minimize the number of screens, 3) considering not covering up any HW buttons, 4) ensuring a consistent and clear display hierarchy, and 6) incorporating feedback mechanisms such as error prevention.

Persona Creation

Persona creation is a primary step in product development. Personas help to gauge the needs and "pain points" of the intended users of a product before release, thereby helping to prioritize important tasks and consider solutions from a user's point of view. Research indicates that the most important benefits of persona creation are prioritizing product requirements, prioritizing audience requirements, and challenging assumptions (Miaskiewicz & Kozar, 2011)

With UI and usability design guidelines in mind, the project team began to develop the reference design considering functional and usability requirements.

Mental Models

Mental models are one way to segment or predict a set of thought processes to better understand or predict how a potential user may operate a device. The project team established three distinct mental models for the thermostat UI, ranging from fully manual control to fully automated and optimized control (Table 1).

Table 1: Mental Models Used for Thermostat Development

Mental Model	Fully Manual	Statically Automatic	Smart Automatic
Targeted customer segment (maintain comfort)	People who enjoy fiddling with their thermostat, variable schedules of occupancy	People with a regular schedule of occupancy (for example, at work or at home all day, including seniors, invalids, or children)	People who are comfortable with "intelligent" systems changing setpoints
Energy-saving opportunity	Low use of heating and/or cooling due to cost, mild climate, insulated house	Regular use of heating and/or cooling due to climate and house/HVAC characteristics	Any condition
When to use	Use during swing seasons (fall and spring)	Use during extended cold or hot weather (for example, the middle of summer or winter)	Any time

Source: EPRI

There are three mental models discussed here:

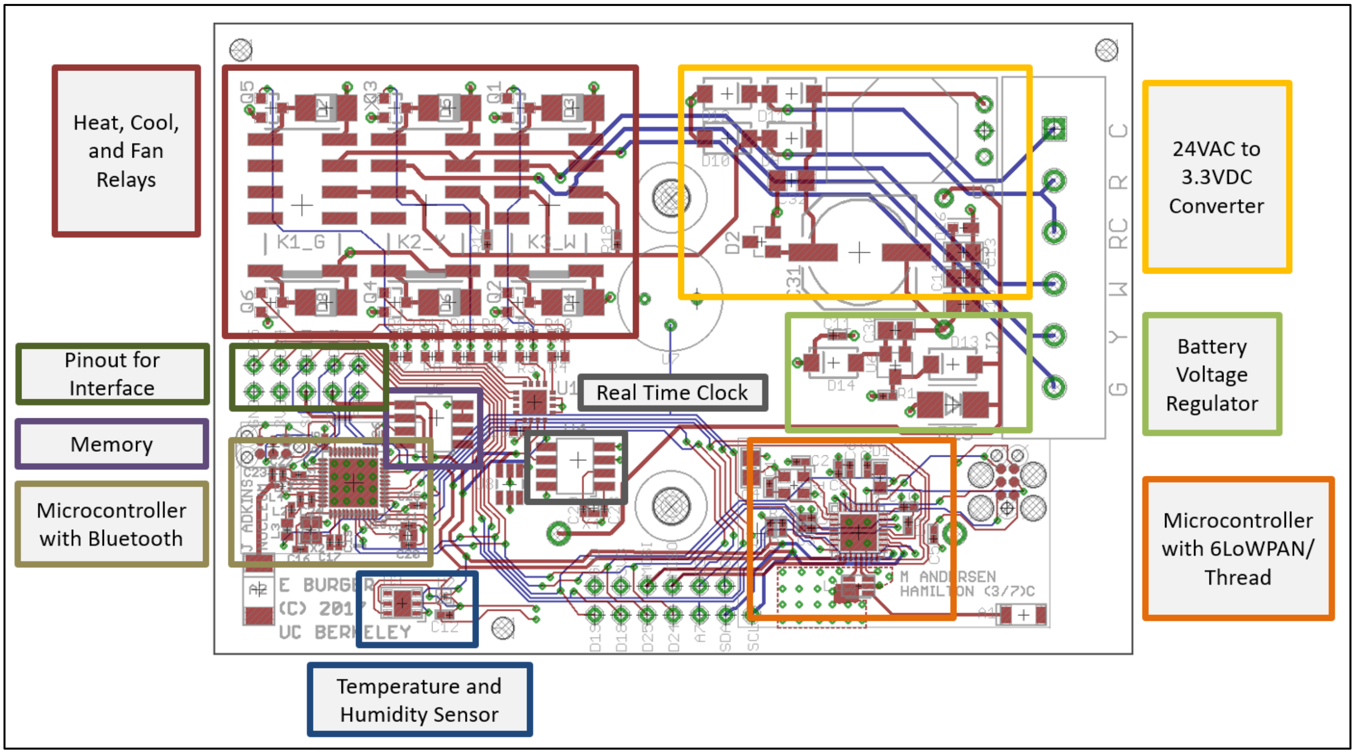
1. People with fully manual thermostats enjoy "fiddling" with a thermostat, primarily using the on/off and timer functions because of 1) the user's personality (a person who wants to be in control) or schedule (variable schedule), 2) context (less use of HVAC equipment because of a highly insulated house or a mild climate), or 3) season (during swing seasons, where the outdoor daily and weekly temperatures vary quite broadly).
2. Statically automatic describes a regular schedule, primarily using the schedule of the thermostat to automatically turn on and off heating and cooling equipment based on a timed schedule of occupancy. Users in this category may have a regular schedule (home all day, work regular hours) and may have narrow temperature requirements (senior or invalid). Statically automatic describes the regular use of HVAC equipment, either due to occupancy, house dynamics, or weather; hence, this model may be appropriate for deep into winter and summer seasons when temperature variations are more predictable.
3. Smart automatic thermostats are appropriate where the user wants little interaction with the thermostat; thus, the thermostat "learns" the occupancy schedule, house and HVAC system characteristics, and weather and can modify the setpoints accordingly.

These design aspects were used to develop an HW reference design detailed in this chapter. Additional details on UI design are in Appendix A.

Hardware Reference Design

The LI thermostat reference design is based on the University of California (UC) Berkeley California Institute for Energy and Environment (CIEE) Hamilton (UC Berkeley CITRIS and the Banatao Institute, 2020) and Nucleum motes. These mote configurations were intentionally developed to be low-cost, low-power solutions for large deployment of small, use-case-specific sensor systems. The project consolidated both the Hamilton and Nucleum motes onto a single printed circuit board to save space and combine the functionality of each mote for the thermostat reference design (Figure 11).

Figure 11: Overview of Printed Circuit Board Footprint and Layout of Hardware Requirements



Source: EPRI

For more information on the HW reference design, see Appendix A.

Bluetooth-to-Thermostat Interface

Enabling integration of the thermostat to a mobile phone/tablet requires a physical layer communication medium. While market-ready high-end thermostats typically use Wi-Fi connectivity, high availability of Wi-Fi-based broadband connectivity is not typical in the low- and reduced-income market segment; overall broadband connectivity is estimated at 82% of U.S. households, including broadband via smartphones (Marketing Charts, 2018). A better option for connectivity (across older and newer phone models) is BLE protocol. Table 2 compares classic Bluetooth and BLE protocols in terms of physical layer characteristics (EE Times India, 2013). The lower power and low current draw make BLE suitable for communications on a limited basis (low throughput and low data rate).

Table 2: Comparison of Bluetooth and Bluetooth Low Energy (BLE)Technical Specifications

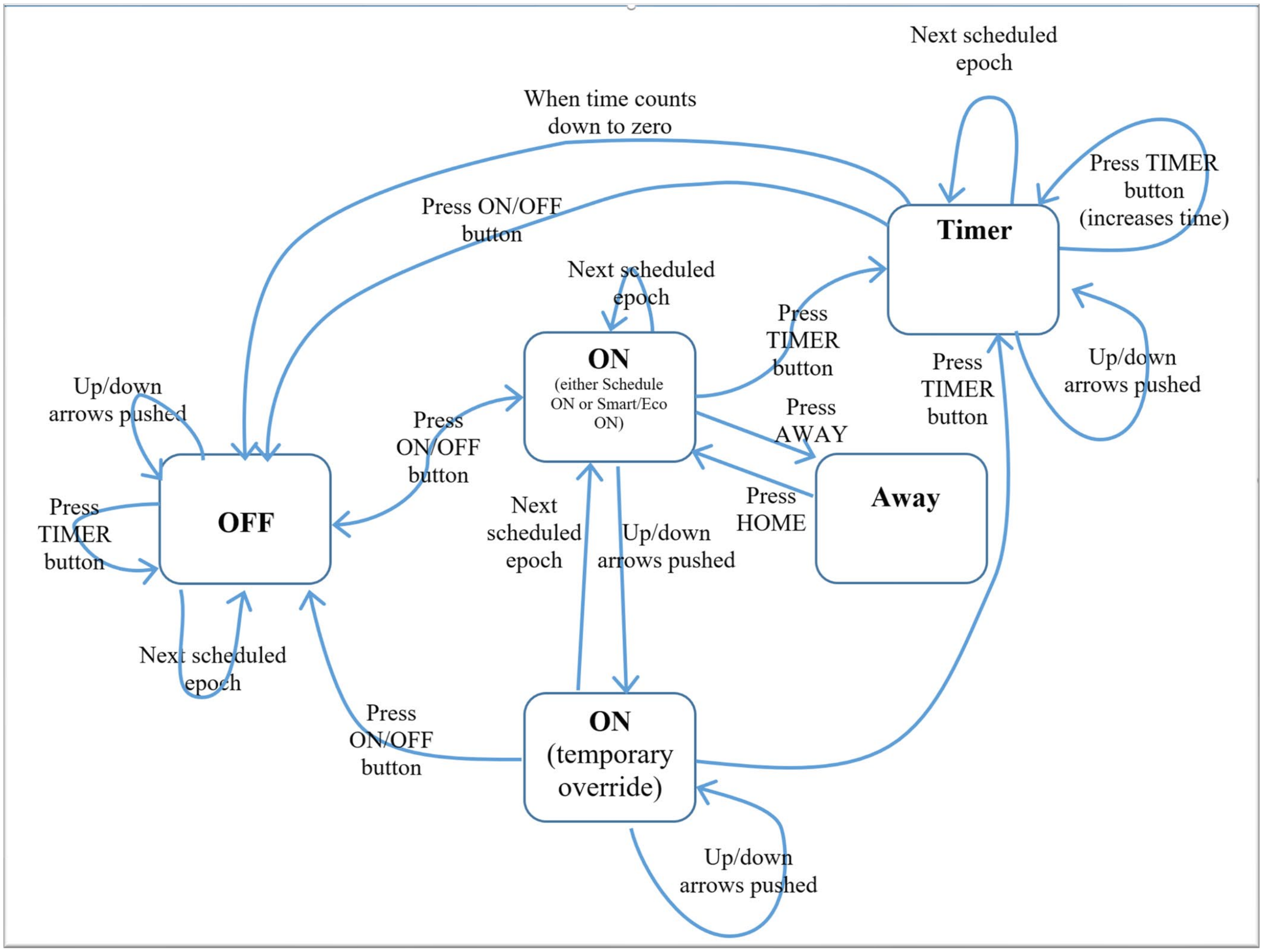
Technical Specification	Classic Bluetooth Technology	Bluetooth Low Energy Technology
Radio Frequency	2.4 GHz	2.4 GHz
Distance/Range	10 m	10 m
Over-the-Air Data Rate	1–4 Mbit/s	0.2 Mbit/s
Application Throughput	0.7–2.1 Mbit/s	0.2 Mbit/s
Active Slaves	7-16,777,184	Unlimited
Security	64/128-bit and application layer user defined	128-bit Advanced Encryption Standard (AES) and application layer user defined
Robustness	Adaptive fast frequency hopping, forward error control fast acknowledge	Adaptive fast frequency hopping
Latency (from a Non-Connected State)	Typically 100 ms	6 ms
Total Time to Send Data	100 ms	<6 ms
Government Regulation	Worldwide	Worldwide
Certification Body	Bluetooth Special Interest Group (SIG)	Bluetooth SIG
Voice-Capable	Yes	No
Network Topology	Scatternet	Star Bus
Power Consumption	1 was the reference	0.01–0.5 W (depending on use case)
Peak Current Consumption	<30 mA	<15 mA
Service Discovery	Yes	Yes
Profile Concept	Yes	Yes
Primary Use Cases	Mobile phones, gaming, headsets, stereo audio streaming, automotive, PCs	Mobile phones, gaming, PCs, watches, sports and fitness, healthcare, security and proximity, automotive, home electronics, automation, industrial

Source: EE Times India

Thermostat Algorithm Development

Thermostat control and overall algorithm development was based on maintaining customer comfort while reducing energy bills. To support the thermostat operation as it relates to the onboard functions (ON/OFF, timer) and the mobile phone integrated functions (Scheduling, Away mode, DR), an expanded state machine[8] was constructed and programmed through the embedded onboard processor. Figure 12 shows the state machine for the HW unit by itself and the state machine for the integrated HW/mobile functionality. Additional information on the thermostat algorithm development can be found in Appendix A.

Figure 12: State Machine for Mobile Integrated Thermostat Functions



Source: EPRI

Demand Response Capabilities

To enable energy services with the thermostat involving participation in DR programs, the thermostat was enabled with DR capability through the companion mobile app. DR events were provisioned through a mobile app server. The mobile app received upcoming DR events and scheduled it in the HW unit. Figure 13 shows the schema for provisioning DR events.

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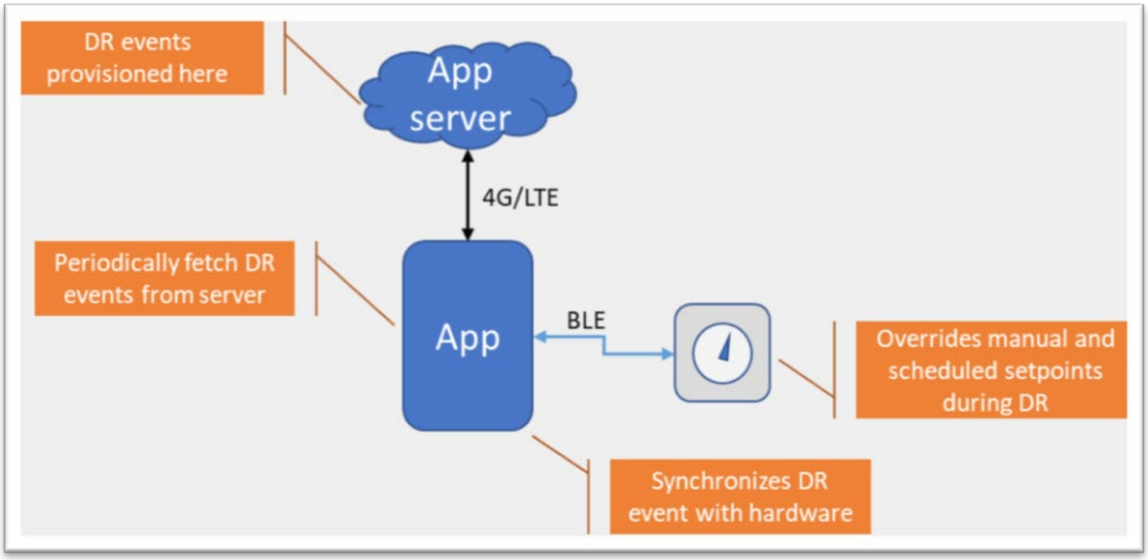
[8] A state machine shows device or system state transitions based on current states and given inputs.

Figure 13: Demand Response Capability Enabled Through a Mobile App



Source: EPRI

With thermostat design components completed, a field test plan was created to recruit, install, train, and test the thermostat in LI communities.

Field Test Plan

The following section discusses an overall usability test plan, project recruitment plan, and overall impact evaluation strategies. Note that this is a summary of the work performed as part of this project. For additional information, see Appendix B.

Usability Testing

The purposes of usability testing were to: 1) assess the degree to which prospective users could accomplish basic tasks with the thermostat HW while troubleshooting and examining any difficult user interactions, 2) draw implications for design iterations, and 3) develop training materials to help during the project period of performance (PoP). To do so, in-person usability testing with pilot-ready HW and mobile applications was necessary.

Think-aloud protocols, a procedure that requests test subjects to think out loud as they perform specific tasks, was used to help understand the thought processes of the test participants. Two researchers were needed, one to record the test via video and another one to direct and time tasks. It is important to note that sample sizes were split based on household size (number of people residing in one household), and multiple members of the same household could participate in each session. Recruitment of participants was targeted to those fluent in English. When there was an excess of volunteers, priority was given to selecting participants with a range of ages and household compositions (for example, with and without children), and ranges of experience with thermostats.

To recruit participants, the site partner’s managerial staff acted as the liaison with occupants. Sessions were scheduled on a single day at each test site. Participants were asked to complete five tasks: 1) read the current temperature, 2) turn on the thermostat, 3) change the thermostat temperature, 4) set the time, and 5) turn the thermostat off. Appendix B shows the script used for usability testing.

Participant Recruitment

The recruited group of participants consisted of affordable housing tenants residing in two main properties provided by the project's affordable housing team member. Sites were selected using criteria that included but was not limited to 1) variations of on-site support from property managers, 2) the presence of an on-site maintenance staff member(s), 3) sites in two different California climate zones, and 4) different affordable housing property layouts (Table 3).

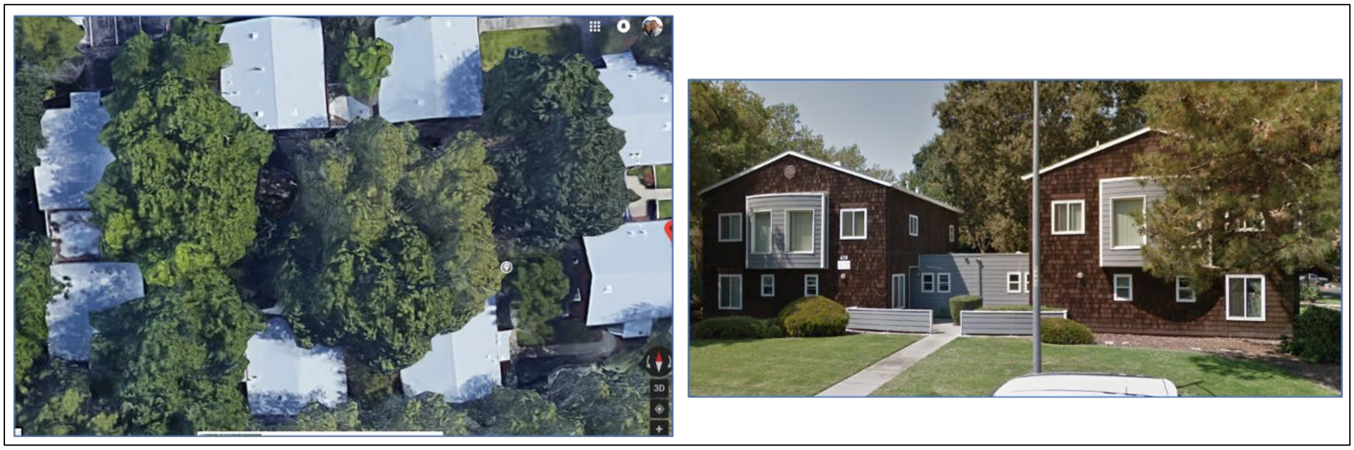
Site providers agreed upon recruitment of pilot participants. Note that, although both sites are multifamily housing properties, the properties have different style buildings, vintages, and campuses. Figure 14 and Figure 15 show aerial views of the two communities, while Figure 16 and Figure 17 show the existing HVAC systems and thermostats.

Table 3: Summary of Project Communities

Property Description	City	# of Units	CA Climate Zone	Year Built
2-story 4-plex multifamily community	West Sacramento	40	12	1996
2-story campus layout w/ studio and 1- and 2-bedroom apartments	Santa Ana	274	8	1969

Source: EPRI

Figure 14: Aerial View (Left) and Street View (Right) of the West Sacramento Site

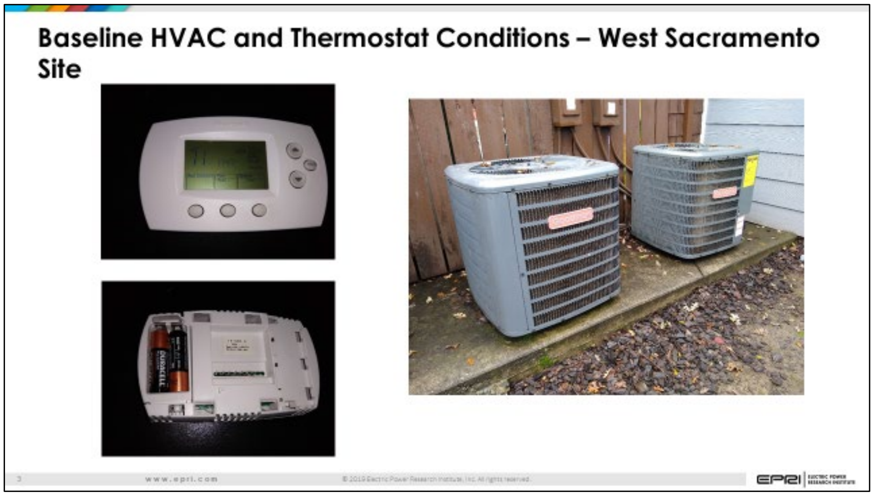


Source: EPRI

Figure 15: Aerial (Left) and Street (Right) View of the Santa Ana Community

Source: EPRI

Figure 16: Existing Thermostat and HVAC System at the West Sacramento Site



Baseline HVAC and Thermostat Conditions – West Sacramento Site

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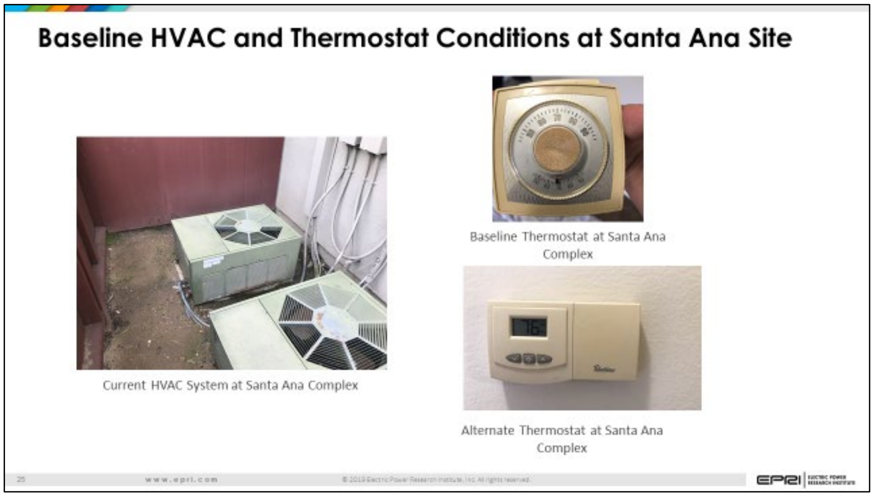
Source: EPRI

Figure 17: Existing Thermostat and HVAC System at the Santa Ana Site



Baseline HVAC and Thermostat Conditions at Santa Ana Site

Baseline Thermostat at Santa Ana Complex

Current HVAC System at Santa Ana Complex

Alternate Thermostat at Santa Ana Complex

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Source: EPRI

Although the West Sacramento site had a relatively new (SEER 13) HVAC system, both sites had a non-programmable thermostat or a programmable thermostat that was battery operated. The project team investigated both sites. Although both HVAC system setups did present options to install non-battery-powered smart thermostats, additional steps were needed to enable smart thermostats, which could have led to more installation failures and reduced adoption when considering product scalability.

Maintenance and management staff of a multifamily building play a critical role in tenant satisfaction during a technology rollout or demonstration. Maintenance and management were also different at the two sites (Table 4).

Table 4: Management and Maintenance Staff Summary in the Two Communities

Community	On-Site Apartment Management?	On-Site Maintenance Staff?
West Sacramento	Sometimes. A part-time apartment manager is available in the morning.	Yes, although staff supports several communities in the area.[9]
Santa Ana	Yes. The apartment manager has been part of the community for over 15 years.	Yes. Four maintenance staff members are dedicated to the community.

Source: EPRI

The project team worked with property managers to provide a recruitment flyer detailing project specifics and to acquire a signed data sharing agreement extending through the period of project performance. The intent was that, if tenants were interested in participating in the project, they would: 1) sign the project consent agreement and 2) fill out the survey. See Appendix C for the customer agreement and recruitment flyer.

The required pilot customer characteristics for this project were for the participant to 1) be a customer of PG&E, SCE, or SDG&E, 2) pay their own bill, 3) reside in one of the approved affordable housing communities as identified by the host sites and the project team, and 4) plan to be tenants for the next 12 months.

It is important to note that certain eligibility criteria were *not* included that are typical of smart thermostat programs. These criteria included:

1. **Unit/home ownership:** Usually, smart thermostat programs require that pilot participants own their homes for participation. This is usually due to split incentive issues associated with providing HVAC upgrades. This project addressed these concerns in two ways: 1) providing a product at a relatively low cost, such as a smart thermostat, and 2) providing functionality that helped tenants by managing electricity bills.
2. **A preference towards single-family detached home:** Due to interactive energy effects and HVAC compatibility concerns, typical smart thermostat programs usually focus on single-family detached communities. As many HVAC systems found in

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[9] The dedicated maintenance staff member did change during the project PoP.

existing California multifamily communities, especially older buildings, have no easy mechanisms for powering a smart thermostat, this project addressed these challenges by providing a smart thermostat that was battery powered.

3. **A subscription to internet service or Wi-Fi compatibility:** Typically, connected devices that include smart thermostats rely on broadband connectivity. This is one of the main challenges to smart thermostats in affordable or rural housing — a high reliance on broadband connectivity to enable smart, connected device functionality. Because one of the major features of this thermostat is alternative mechanisms to Wi-Fi, this was not a main screening criterion for this evaluation.

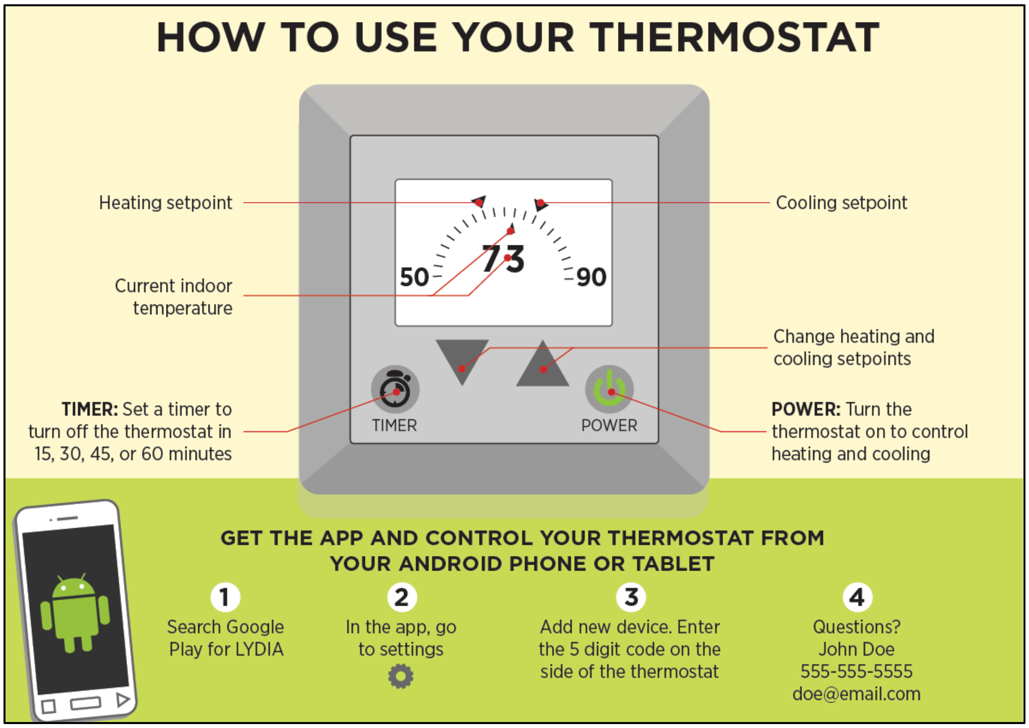
However, it is important to note one unique selection criteria: eligible participants had to have an Android phone to participate in Phase 1 of the study. This was primarily for development expediency. The Android platform was chosen over other competing mobile phone platforms because Android phones are provided as part of the California Lifeline Program (CPUC, n.d.).

Commissioning, Installation, and Maintenance

After recruitment, the project team developed several steps to schedule, commission, install and maintain the thermostat during the project's PoP. After the project team confirmed the enrollment agreement and the target apartment units, the team worked with the property manager to schedule and provide notification to residents about access to the apartments for installation. To install the thermostat, the project team worked with the property manager on each site to identify whether a preferred HVAC contractor or the site's on-site maintenance staff should be responsible for installation. Although installation of a smart thermostat is perceived to be simple and straightforward, it is important to better understand implementation challenges faced not only by tenants and technology but also by the various trades needed to facilitate market transformation, including on-site maintenance and managerial staff in disadvantaged communities.

During this time, the project team helped train the maintenance staff to install the thermostat, download the mobile application, and provide basic training for the tenant. The maintenance staff also provided a quick start guide that pilot participants could use for basic thermostat functions. The maintenance staff was interviewed to ensure that members understood the technical and operational challenges of installing the thermostat and other challenges encountered during the installation and commissioning process. An information flyer was left behind in the apartment to inform the residents on how to use the wall unit and download the mobile application (Figure 18).

Figure 18: User Guide Left Behind After Thermostat Installation



HOW TO USE YOUR THERMOSTAT

Heating setpoint

Cooling setpoint

Current indoor temperature

Change heating and cooling setpoints

TIMER: Set a timer to turn off the thermostat in 15, 30, 45, or 60 minutes

POWER: Turn the thermostat on to control heating and cooling

GET THE APP AND CONTROL YOUR THERMOSTAT FROM YOUR ANDROID PHONE OR TABLET

1. Search Google Play for LYDIA
2. In the app, go to settings
3. Add new device. Enter the 5 digit code on the side of the thermostat
4. Questions? John Doe 555-555-5555 doe@email.com

Source: EPRI

In addition to leave-behinds, the project team developed how-to videos available through media delivery channels to show consumers how to use specific new products and technologies. The first video demonstrated how to use the thermostat itself (see https://drive.google.com/file/d/102yAqLwH92BiO691ic6zezUQJrPYBtzk/view). The second video demonstrated how to use the thermostat app (see https://drive.google.com/file/d/1gcAKQkaLoumt9t9cMLvRR4P8m1x6NlwH/view).

After installation, it was the responsibility of the property manager and the on-site maintenance staff to maintain and support the thermostat during the project PoP. As this is common practice for tenants in these communities, the project team wanted to not meddle in common maintenance practices and to respect trust lines for tenant support in these communities. Support contact numbers from the project team were given to the maintenance staff members.

Impact Evaluation: Quantification and Verification of Energy Impacts

To quantify and verify impacts of this project, the team took a five-pronged approach to attempt to meet overall project objectives:

1. **Collect data at three levels:** The project team looked at qualitative results gleaned throughout the project and coupled them with two types of data — thermostat-level data collected from the unit itself and data from smart meter readings.
2. **Understand system usability:** As previously discussed, usability testing was completed before device deployment. Such data were coupled with qualitative data

obtained via survey deployment during and after the project PoP as well as quantitative data collected from sensors and interactions with the thermostat.

3. **Leverage existing and parallel initiatives:** The project team assembled a technical advisory committee (TAC) comprising utility companies and LI property developers and managers and planned to leverage existing and parallel demonstration efforts to better complement, as opposed to overlap, existing research efforts.
4. **Understand implementation issues:** The project team documented and discussed potential implementation concerns and tracked implementation issues before, during, and after deployment. As discussed in the previous test plan philosophy, the project team examined ways to leverage current efforts by utility members of this project's TAC working in parallel on LI or affordable housing smart thermostat initiatives.
5. **Revisit project drivers:** The project team understood that connected devices are in a period of rapid technology change. The project team will continue to revisit project drivers to tailor research to questions prevalent in the space today.

For detailed information on the impact evaluation strategy, see Appendix B.

Summary

This chapter: 1) summarized secondary research conducted to better understand technology developments and energy company programmatic activities being conducted in the thermostat space, 2) discussed the approach to designing a smart thermostat, and 3) addressed the overall field test plan, which included plans to recruit, commission, support, quantify, and verify project impacts. Several steps were taken for all three activities to complete thermostat development, recruit a target set of participants, and provide evaluation methods to quantify project impacts. The goal was to provide recommendations for thermostat production as well as extensibility and applicability in the targeted LI market segment. Chapter 3 focuses on the results of thermostat deployment, commissioning, and analysis completed as part of this project.

CHAPTER 3:
Project Results

This chapter summarizes results and lessons learned as a result of design, recruitment, commissioning, installation, and evaluation plans. The chapter is divided into two sections: the first section focuses on thermostat design work (HW and SW development), while the second section documents field test impact evaluation results to quantify and verify functional testing.

Reference Design Testing for Prototype Development

The first round of testing focused on laboratory and usability bench testing of the HW reference design. The results of this work were intended to establish HW adjustments and inform usability before the thermostat would be installed in the field. Main outcomes of reference design HW testing included the following:

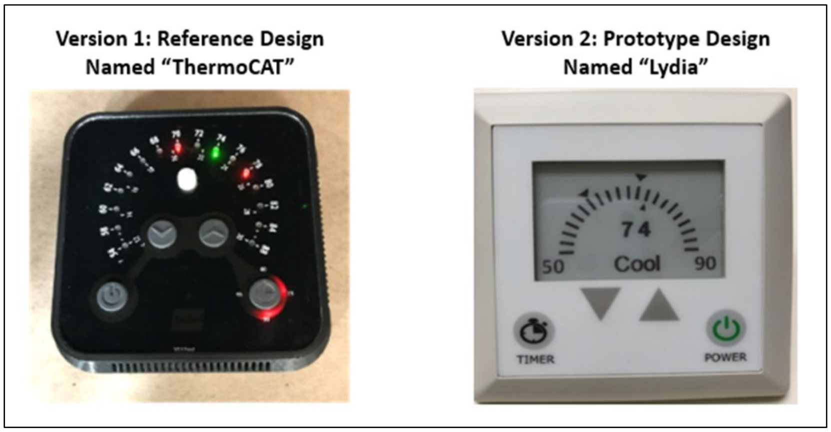
- **Validation of short battery life:** During the two-day testing period, the AA battery ran out several times. This indicated that the battery life would not be able to support the power consumption of this prototype if applied to daily use.
- **Confusion about temperature setpoint:** Half of the participants were unable to independently complete the task of "changing temperature" even if most of them recognized the up/down buttons. More than 80% of the participants expressed some level of confusion about the heating and cooling setpoints displayed in a pair as red lights. Participants did not realize that the cooling setpoint (the red light on the right) had to move past the current temperature (the green light) to trigger the A/C cooling ON.
- **Difficulty in understanding ON/OFF thermostat state:** Participants had difficulty understanding what ON meant for the thermostat and for the A/C equipment. Although participants easily performed the task of "Turn thermostat ON," it was not clear to them what being ON meant — whether it was actively controlling temperature or it meant the A/C was ON. Furthermore, the prototype had a green light ON to display the current temperature even when the thermostat was in the OFF state, which led to the misperception that "Green light ON means the thermostat is ON."
- **HVAC state:** It was difficult for participants to tell whether the HVAC would be heating or cooling only, given the lighting indicators of the current temperature and setpoints. In the task of changing temperatures, because of the confusion of the two setpoints summarized above, participants could not tell whether the A/C would start cooling and what temperature it would cool down to.
- **Problems with button design:** The low contrast on buttons made it difficult for some participants to identify the buttons. For example, some participants confused the timer button and the power button (both on the bottom of the screen with the same size and similar round shape); some tried to twist instead of push on the buttons, and some misperceived that the sensor "knob" in the center of the screen was a button.

Laboratory and usability testing of the reference design led to some changes from the HW design to the prototype that would be tested in the field.

Prototype Design and Development

The new design version (referred to as "Lydia" or the "prototype design" in this report) incorporated lessons learned from HW reference design testing. Figure 19 shows the HW unit and mobile application of the new version compared to the preliminary reference prototype.

Figure 19: Hardware Reference Design Versus Prototype Used for Field Testing


Version 1: Reference Design Named "ThermoCAT"

Version 2: Prototype Design Named "Lydia"

Source: EPRI

The main changes from reference to prototype design include:

- **E-paper for screen display:** To address the short power battery life, the prototype version applied the e-ink or e-paper to display information, including current temperature, setpoints, timer ON/OFF, and HVAC states of heating/cooling. The design rationale behind the choice of e-paper was that the power consumption of e-paper is significantly lower than light emitting diodes (LEDs) because e-paper mainly consumes energy only during screen updates. Besides the power conservation, another benefit of e-paper is that it enables developers to design the display with more flexibility (drawing number digits, words, shapes, and so forth) during the research iterations. The downside of e-paper was that screen update response time had to account for the e-paper update mechanism and additional e-paper functionality. These issues presented design decisions between functionality and cost.
- **Use of BLE:** The next upgrade of the reference design that enhanced the prototype was the use of a BLE module as opposed to a basic Bluetooth chipset, for example from Nordic Semiconductor. The main driving force for this decision was the reduced cost and time to market, which also affected the total system cost. Another advantage of the Bluetooth module is the well-designed and tested radio frequency HW interfaces, providing value at a reduced cost to the product system. Another upgrade to the Bluetooth system was to implement a Bluetooth general attribute (GATT) protocol, which minimizes power consumption between the smartphone and HW and allows maximum flexibility of data transfers. The data transfer was initiated by the smartphone

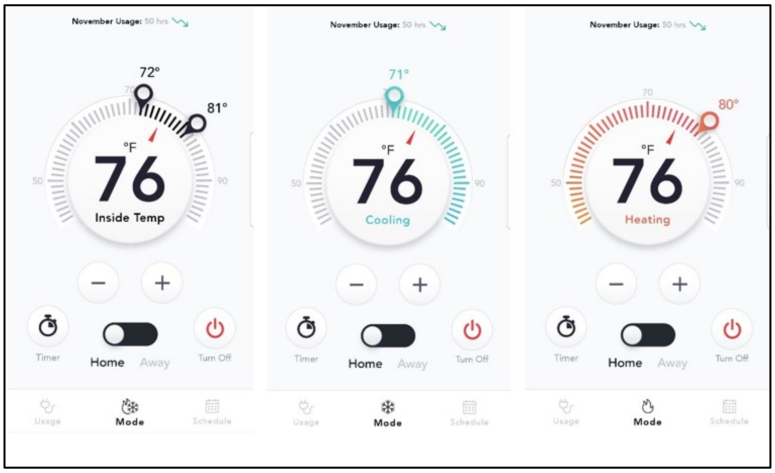
app, but the Bluetooth protocol was terminated by the HW once all data had been transferred and verified.

- **Design of the temperature subsystem:** The core of the thermostat functions was based on temperature, which required careful design of the temperature subsystem. The first design decision considered was to move the main temperature sensor away from all active components and chips that consume current. Towards this end, the main temperature sensor was installed on an end of the board devoid of any other components. The next design decision was to install a secondary temperature sensor on the center of the board with the maximum active components. The coupling of these two features allowed more accurate temperature determination algorithms to be implemented in SW without HW redesign. Another aspect of the prototype was to position proper holes on the enclosure that would directly be above the temperature sensor region, to allow proper detection of ambient temperature.
- **Setpoints display differentiated from current temperature:** To address the communication of setpoints and current temperature, the prototype version presented the current temperature in the center of the screen using numeric digits and tick marks on the inner side of the scales, while the setpoints were presented as tick marks on the outer side of the scales. The wall unit still maintained both setpoints to communicate the "comfort band" concept to the users (A/C would not turn ON if the room temperature was within the comfort band). More distinguishable features were used in the cell phone application, including color coding, switching to show only one setpoint if in Heat only or Cool only mode, and so on. Further description will be provided in the next subsection of the app interface.
- **Explicit indication of A/C states and ON/OFF states:** To address the communication of ON/OFF and heat/cool states, instead of making users infer whether the HVAC was ON from the setpoints/current temperature position relationship, the screen showed the Heat or Cool state in words. For the thermostat control ON/OFF, the screen shut down to an empty display when the power was OFF.
- **Highly distinguishable buttons:** To address the low contrast on the buttons, refined shapes and patterns were used to increase the contrast and better communicate the functions they stood for.

Mobile Application Development

In the prototype design iteration, a smartphone application (referred to as an app in this chapter) was developed. Specifically, the smartphone application was designed to enable the following four user-facing functions: 1) control modes, 2) Home and Away modes, 3) Scheduling, and 4) usage feedback (Figure 20).

Figure 20: Three Control Modes on Home Screen



Source: EPRI

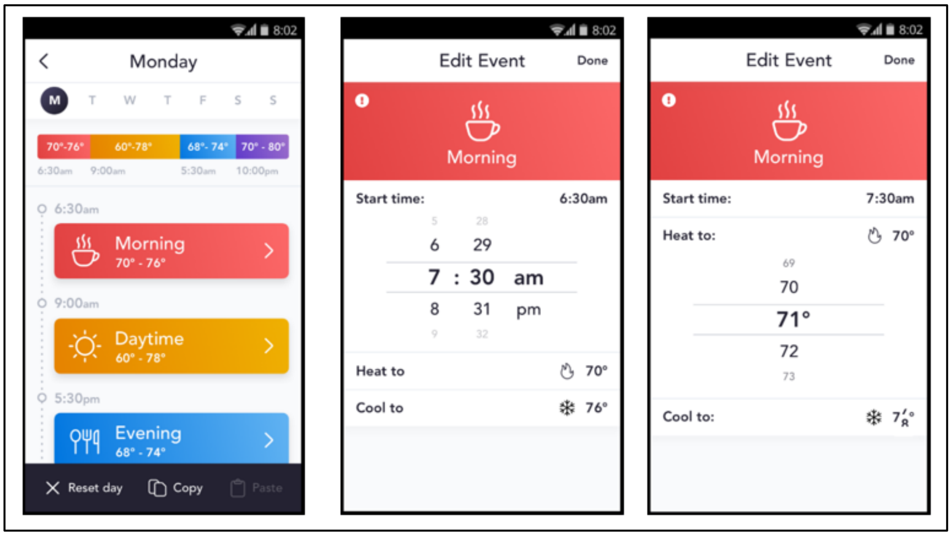
Home Screen

- **Control modes:** Figure 20 shows the three control modes the application allows: 1) Heat+Cool, 2) Heat only, and 3) Cool only. In the Heat only and Cool only modes, the screen displays only the heating setpoint or cooling setpoint to avoid confusion. When the HVAC is ON during heating or cooling, red or blue is used to indicate the HVAC state besides using text. In the mobile app, setpoint markers also allow users to drag along the temperature scale to set the target temperature.
- **Home and Away modes:** The application provides an additional Away mode, which offers a potentially quick and easy way for users to switch to a temperature setting that is different from the Home mode. This function was designed not only for a quick switch to a low consumption setting before leaving home but also to build in the potential for a quick response to utility signals (for example, DR reminder, high peak price alert, and so on.)

Schedule Screen

The "Schedule" screen was designed for users to program the setpoint temperature schedules for the seven days of a week. Figure 21 shows the screen on which the scheduled events of a day are shown in time order. Users can click on the event or add an event; this leads them to the configuration screen, where they can set up the time of the event as well as heating/cooling setpoints.

Figure 21: Schedule Screens Enable Event Summary and Editing

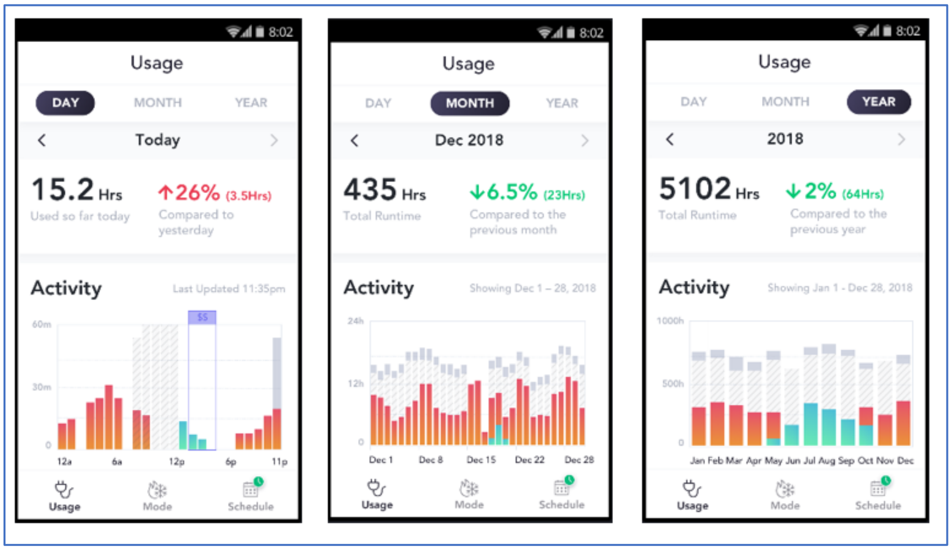


Source: EPRI

Usage Screen

The "Usage" screen provides users with information feedback based on their HVAC runtime (Figure 22). Users can select a view based on day, month, or year. On the top of the screen, where users can notice it, brief and quick information on total runtime and comparison with the previous usage period was displayed. More detailed information of hourly, daily, or monthly usage was available on the screen. The hourly information board also highlighted the hours that have high peak prices, which signals the users to avoid high usage in those hours.

Figure 22: Usage Screens Include HVAC Use Feedback



Source: EPRI

Project Recruitment, Installation, and Training

Once a final mobile application and prototype was developed, the project team began the recruitment of potential project participants at the West Sacramento and Santa Ana sites. To recruit households for installing and functionally testing the wall unit and mobile application, property managers surveyed residents (Appendix C) in the two sites to collect information about the type (brand and operating system) of phone in use, whether the resident owned a tablet, if there was personally provided internet, and the preferred language in the household.

The first wave of recruitment consisted of fliers sent to individual units, followed by a two-week period during which tenants would sign a project agreement and answer the survey. After the first wave of recruitments, the West Sacramento site recruited a total of four tenants in the first week (10 percent of the entire population), while the Santa Ana site recruited a total of 100 tenants in the first two weeks (36 percent of the entire population).

Although the project team never surveyed tenants directly, they hypothesized that the maintenance and management support infrastructure summarized in Table 4 in Chapter 2 was the main driver in the difference between the recruitment rates at the two sites. An engaged property management staff resulted in greater recruitment of potential project participants. To increase participation on the West Sacramento site, the project team conducted a weeklong door-to-door recruitment for tenants in West Sacramento. Through that effort, an additional 20 participants (50 percent of the entire population) agreed to participate in the project. West Sacramento participation eventually included 24 total participants (60 percent of the entire population), although a considerable amount of recruitment effort was needed to achieve that recruitment level.

After recruitment, the project team assessed the survey responses on 1) smartphone or tablet ownership, 2) internet access, and 3) preferred language. The main outcomes of the survey were:

1. A higher penetration of tenant smartphone ownership over internet access: The West Sacramento and Santa Ana sites had more survey participants who indicated that they owned a smartphone versus having personal internet access.
2. Approximately 20 percent of responses showing that primary broadband access was via a smartphone: These tenants indicated that they had no personal internet.
3. A high response of "not-English" being the preferred language: At both sites, more than 40 percent of survey responses indicated a preference for a language other than English.

As a result of the recruitment and survey work, the project team decided to use the following field testing and deployment strategy.

- **Focus field testing on the Santa Ana Site:** Project support from managerial and maintenance staff provided a better infrastructure to support potential challenges that accompanied emerging technology deployment. As a result, it was determined that, to minimize project risk, it would be best to deploy the thermostats at one site. The project team would provide the Santa Ana site maintenance staff with education, training, and background materials for thermostat commissioning.

- **Stagger field deployment:** Instead of undertaking one mass deployment, the project team chose to stagger thermostat installations, to: 1) provide an opportunity to discuss and understand the lessons learned from the phases of deployment and 2) provide the thermostat development team with opportunities to make necessary code changes. The deployment strategy, along with the number of participants in the Santa Ana site, is discussed in the next section.

For detailed information provided to the maintenance staff and the overall field deployment strategy, see Appendix C.

Field Testing and Usability Impacts

During field testing, the project team was able to train maintenance staff members, who found it relatively straightforward to install the thermostat HW itself. The mobile application was a challenge to some, since this was new to them. In the first 10 installs, there were technology turndowns (90 percent success rate), primarily due to responsiveness of the screen display — a design element to minimize power draw of the thermostat enabling a six-month battery life. The thermostat data indicated that, of the thermostats installed (n=20), first week usage implied that: 1) tenants were able to activate HVAC units via the app, 2) usage varied from considerable usage to turning the app on and off, 3) the home screen was the only screen that was used, and 4) no users set a thermostat schedule or accessed the usage screen.

The prototype unit was able to control heating and cooling via physical buttons on the thermostat unit. Residents, accustomed to seeing the temperature settings change instantly, would occasionally over-adjust the temperature, since they assumed that their initial button presses had not registered. Some residents had difficulty in shutting off the system. In any case, the lack of immediate feedback for some physical button presses led residents to the conclusion that the thermostats were not working properly.

Residents where physical thermostat units were installed were also shown how to install the accompanying mobile app, either from infographic leave-behinds (see Appendix C for a picture of the infographic leave-behind) or by a direct prompt by the project team member or the Santa Ana community maintenance staff. Residents were initially interested in the prospect of being able to control their home's heating and cooling via smartphone and mobile application. However, pilot participants who were able to install the application found further difficulty in pairing the application with the thermostat. Once connected, the HW display delay explained earlier also added to the less-than-desirable user experience.

Approximately one month after these prototypes were installed, on-site apartment maintenance staff informed the project team that all prototype thermostats had been removed at the request of the residents. The challenge for adoption was the overall assumption that HW functionality would not be a critical component and would allow for trade-offs to enable: 1) alternative methods of connectivity, 2) battery-powered functionality of smart devices to permit compatibility with HVAC systems that do not have C-wires, and 3) a targeted project price point while understanding the limitations of using "off-the-shelf" and approved HW.[10] Initial tests showed that power conservation measures that resulted in slower response times of the HW display caused customer dissatisfaction and lack of persistent use of the thermostat. In the interim, continued efforts were taken to track updates made to the thermostat and the application during that time.

Prototype Usability Testing

In the absence of a full demonstration, the project team agreed that the best method to provide a final prototype thermostat design was to continue usability testing on the prototype. During this stage, the mobile application and the prototype HW were tested for usability. Final usability testing on the prototype design was completed on a subset of potential project participants. In summary, usability strengths of the prototype design included the following:

- The design iteration enabled users to easily perform basic thermostat tasks — turn ON/OFF, identify current temperature, and identify means of raising and lowering setpoints.
- Users were able to identify use cases for the ON/OFF functionality that might result in energy savings compared to their current habits.
- Most users liked the phone application and its design and reported that they would use it if deployed.

Several usability weaknesses were also identified:

- The e-paper screen design was perceived as tedious for users due to the lags in response time.
- Users were confused when interpreting two setpoints that were displayed.
- Users could not identify use cases for Timer and Away functions.
- Limits to remote control via Bluetooth disappointed some participants.

Additional design suggestions particular to EE-related features include:

- **Updates to the usage screen:** Most participants generally appreciated the usage screen, but simplifying the information is recommended, such as visualizing only the heating/cooling usage and excluding the Away and OFF stats. The monthly comparison view (compared to previous month or the same month last year) might be more meaningful than a daily comparison. Comparison to previous day, neighbors, or goal setting did not appear to be significantly motivating.
- **Dual setpoints (comfort band):** The presence of both heating and cooling setpoints confused most participants. It was difficult for participants to understand the concept of comfort band in relation to turning on the A/C or heater. The confusion occurred in the task of setting target temperatures and the subsequent task of scheduling. The test

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[10] Project timeline considerations limited the team to pre certified components. Although additional certification of custom components would have resolved some of the demonstration challenges, additional project time and a higher budget would have been required.

result suggested that showing a single setpoint of the Heat only or Cool only mode is preferred to the dual setpoints of Heat+Cool mode, and the Heat+Cool mode should not be the default setting of the UI.

- **Schedule:** The confusion of dual setpoints continued in this task. The "Heat to" and "Cool to" language in labeling the setpoints confused users; as one participant noted, "It's winter, so why would we be cooling?" Participants were also confused by the absence of event end times when setting up schedules because they typically prefer to set up specific time periods rather than scheduling an entire day. 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.

Additional information on results from usability demonstrations can be found in Appendix C.

Lessons Learned From Demonstration and Deployment

The following section details the main lessons learned from prototype development and deployment with the attempt to summarize outcomes. The main goal is to provide a final smart thermostat product with open-source code and suggestions for entities interested in continuing product development.

Table 5 compares the design concepts generated in this project with two mainstream concepts, according to the design requirements applied in this project.

Table 5: Comparison of Design Concepts Across Project Prototypes and Commercially Available Thermostats in Terms of Customer Facing Requirements

	Project Delivered Design of Wall Unit and Phone App	Market Available Basic Nonprogrammable Thermostat	Market Available Smart Programmable Thermostat
Controls basic HVAC operations	X	X	X
Embeds efficiency analytics based on consumer preferences	O		X
Capable of selling for $75 retail in volume	X	X	
Connectivity to utility signals	X		X
Operates on the power supply available in LI neighborhood	X	X	
Sufficient power life to avoid frequent change of power battery	X	X	X
Provides UIs for energy feedback/engagement	O		X

X: The design concept has achieved the requirement to the extent of market acceptance (it may not be the best, but it's good enough to have buyers and maintain users). O: The design concept has the capability built in but needs further implementation with empirical data and testing.

Source: EPRI

Evaluation of the market provides two main conclusions:

- **Current market solutions (affordable but not smart, or smart but expensive):** Basic nonprogrammable thermostats currently appeal to decision makers and maintenance staff in California LIHs. This type of thermostat meets the basic needs of HVAC controls and usability with affordability and power supply compatibility requested. However, these thermostats are not designed for advanced EE enhancement functionality, such as EE analytics, connectivity to utility signals, or interface for energy feedback/engagement. Smart programmable thermostats, on the other hand, include the advanced functionality that enables EE analytics, feedback, and engagement. However, the high price, uncertainty of power compatibility, and uncertainty of Wi-Fi availability in disadvantaged neighborhoods undermine smart thermostat feasibility for the LI communities evaluated.
- **Design prototype (wall unit + app):** The project delivered a design prototype that was installable, affordable, and potentially smart but not yet as user friendly as some commercial products. The prototype remedied the issue of power condition by enabling operations using AA batteries with a reasonable power life. The design implemented the functional components for HVAC control and utility signal connectivity. A smartphone application interface was developed to improve and enrich UI capabilities for engaging EE behavior. This prototype was an installable and functional thermostat that embraced both smart EE features and affordability. Drawing upon price points as low as programmable/noncommunicating thermostats that meet all functional criteria defined in the beginning of the project will result in decreased functionality and value proposition, especially in terms of the HW.

Smart Thermostat Design Decisions Under the Constraints in Low-Income Housing

Smart thermostat design decision trade-offs are challenging in this project, balancing functionality, affordability, and usability.

- Power requirements were strong constraints in this project. In the prototype design, the e-paper saved power consumption, but the delayed response time caused negative user experience. Improving the e-paper display size and response speed would increase the material cost.
- Wi-Fi availability was another constraint to the design decisions. This project developed the Bluetooth approach to enable communication between the mobile app and the HW wall unit controller. Consequently, the application could improve user experience, compensate for HW weakness, and enable advanced functions. However, the need for a user to hold the phone close to the device to communicate with the unit and the inability to remotely control the unit from outside the home when the homeowner did not have Wi-Fi may be inconvenient. Previous bias towards using the HW itself to control thermostats also made the design challenging to adopt, as much of the functionality was pushed to the mobile application.

Field Deployment Lessons Learned

During the design development, the project team conducted several field activities, including recruitment, tenant surveys, and installation of a small number of pilot device units. The field activities provided valuable lessons for future device deployment or related program implementation.

First, on-site property staff play an important role in connecting the design team with the residents. The property with on-site management and maintenance staff showed significantly higher customer engagement. Second, users tended to compare the usability experience with their status quo baseline. For example, the residents in one community site had been accustomed to the temperature presentation in numeric digits, which led to some disappointment at the temperature presentation on the scale in the prototype. Residents are generally receptive to the prospect of new technology that might improve the level of control over their living area climate and comfort level but only if the user interaction is *not* a significant departure from the experience they are familiar with. This means that, if the previous thermostat unit was primarily controlled via physical buttons on the device, then its replacement should at least offer this functionality.

Production Thermostat Design Recommendations

The project team developed a future-state design that considered lessons from each of these stages of development and testing. The intent was to provide this future state design and potential improvements in such a way that interested parties can incorporate lessons learned from this project into their existing thermostat design or pick up where this project left off.

Additional design considerations to improve usability of the thermostat include: 1) presentation of a setpoint range over a single setpoint, 2) renaming the timer function to something more suggestive (for example, Heat/Cool Boost), and 3) creating default setback settings for users that are switching to Away mode. Additional HW and mobile application suggestions are detailed below.

Hardware Unit

Critical design choices on the thermostat HW are driven by power consumption considerations, in particular, the need to support non-C-wire-enabled HVAC systems. This requires battery backup with an expected lifetime of six months. The battery life requirement significantly impacts the HW design, with two major contributors to power draw in the HW unit: display and connectivity. While e-paper is an excellent choice for ultra-low-power displays, there is a trade-off on responsiveness of display changes. Usability challenges identified during the demonstration and usability testing show the need to prioritize immediate response to the user on the HW itself. Additional alternatives to consider are summarized below.

- **Alternatives to the e-paper display:** The e-paper display was chosen for power draw considerations as well as cost requirements set forth in the beginning of this project. However, slow response time caused usability challenges. The prototype version uses an off-the-shelf module that has higher latency and current draw than desired. A custom e-paper module that potentially resolves the latency and power consumption issues could be designed in production levels.[11] In addition, low-power liquid crystal display (LCD) or ultra-low-power memory in pixel (MIP) LCD displays could potentially be used, although both of these options increase cost and require considerably more power to operate.

- **Alternatives to BLE connectivity:** The prototype version uses a pre certified module for Bluetooth and Wi-Fi functionality. Cost can be considerably reduced by approximately $5 per thermostat by using a system on a chip (SoC) and certifying the full product. Another attractive option involves the use of other communication protocols such as long range (LoRa), the ability to provide wide area networking that can be set up and maintained by a third party (such as utility/energy providers, multifamily housing owners, and so forth). However, the expense of a LoRA chip and LoRA infrastructure (wide area routers) increases the total cost of ownership and operational costs. Bluetooth Classic allows for higher throughput and data transfer rates that may contribute to improved usability but come at the expense of higher power consumption.
- **Alternative to the HW enclosure:** The prototype version uses an off-the-shelf enclosure. A custom, injection-molded enclosure common in production-level development would have reduced costs by approximately $5 per thermostat.

Mobile Application

Critical design choices on the mobile application were driven by usability considerations determined by results of prototype testing. These included: 1) shading the main screen, except the power button, when the thermostat was OFF, 2) creating a banner or cue across all screens indicating that an Away mode was active, 3) providing push notifications regarding peak pricing, and 4) simplifying information on the usage screen.

Summary

The project team successfully completed initial usability testing and developed a working prototype and mobile application that met project goals. Challenges in usability — with pilot participants comparing the usability experience with their status quo baseline — resulted in an initial pilot in which the thermostats were eventually uninstalled from the pilot site. However, many opportunities and barriers to overall adoption and extensibility of the project’s main objective of providing intelligent HVAC controls for California’s LI communities were identified. Final design recommendations were also given based on this information plus market scouting during the project.

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[11] This approach was not considered, as this would have required additional compliance testing and budget to source custom HW at the pilot testing phase.

CHAPTER 4: Technology/Knowledge/Market Transfer Activities

The project team conducted several activities to disseminate overall results. Although development of a thermostat and associated field demonstration was a compulsory component of the project, the team worked through and identified other opportunities to understand the market and the technology landscape throughout the project and present these results. It is important to monitor the landscape to provide better conclusions and recommendations at the end of this project, as this consumer market moves quite rapidly.

Knowledge transfer for this project can be divided into four main activities:

- **Open-source resources:** Details where all files will be publicly accessible. This includes all HW as well as mobile application and SW files completed as part of this project. The intent is to provide accessible information if a group or organization would like to continue thermostat development.
- **Technical advisory committee (TAC) and workshops:** The project team conducted several multi-stakeholder sessions, both reporting and receiving feedback on project progress.
- **Knowledge transfer to California disadvantaged communities:** The project team continually assessed opportunities and challenges to providing intelligent HVAC controls to California's disadvantaged communities.
- **Knowledge transfer to the electric utility industry:** The project team ensured that information received from the electric utility industry was processed and considered, and all subsequent knowledge gained was transferred back to the industry. The goal was to better understand current opportunities for and barriers to the scaling of intelligent HVAC controls to disadvantaged communities.

For additional information on overall knowledge transfer activities completed as part of this project, see Appendix D.

Open-Source Resources to Allow Replication of Lydia Hardware and Software

The project team plans to maintain all HW designs, SW specifications, and other materials associated with this project in an open-source format. The goal here is to assist any thermostat manufacturer, developer, or other entity that may be interested in continuing smart thermostat development. It is also a possibility that functions such as the ON/OFF button and alternatives to Wi-Fi connectivity could be examined by current and prospective thermostat manufacturers as part of their designs. The following section will focus on how these specifications will be kept "open" after the end of the project.

To provide ample opportunity for the industry to start from the existing prototype and work towards a commercial product, the project team has made many of the assets developed in this project publicly available via open-source licensing.

- **HW designs:** Two HW designs were created as part of this project: a reference design employed in initial usability testing and a prototype design tested for usability and deployed in the field. Note that there are two repositories for the HW design, as the original reference design continues previous work on the Hamilton Board conducted by UC Berkeley's CIEE.
  - The open-source work for the Hamilton board (used to develop the reference HW design) is available at: http://github.com/hamilton-mote/thermostat-hw
  - The open-source work for the Lydia prototype HW design that was used is available at the Lydia wiki page at https://github.com/eprissankara73/lydia-board
- **Prototype firmware:** Codebase used to operate firmware of the final prototype is publicly available. The open-source code for Lydia firmware is available via GitHub in the Lydia firmware repository at https://github.com/eprissankara73/lydia-firmware
- **Mobile application:** Codebase and overall mobile application designs are publicly available, including the BLE interface developed as part of this project. The open-source code for the Lydia mobile app is available at: https://github.com/eprissankara73/lydia-mobile-app
- **Learning algorithm server code:** The open-source code for the intelligent algorithm that predicts a band of thermostat setpoints (as opposed to a single setpoint) is available at: https://github.com/eprissankara73/comfort-band-model

The provided open-source package includes all details that will allow any individual or company to manufacture the system as implemented or to undertake customization. The licensing for these repositories is through the MIT License Open Source Initiative®, which allows for modification and commercialization.

Technical Advisory Committee and Project Workshops

The project team held several sessions to disseminate results and receive feedback on the direction of the project. Results are summarized below.

- **Project TAC:** The project team assembled a TAC encompassing various stakeholders. The last TAC meeting to guide this project was held on January 16, 2019. In addition to TAC meetings and webcasts, the project team identified other opportunities during the project to discuss current results.
- **EPRI Advanced Energy Community (AEC) workshops:** EPRI AEC workshops invite members of national labs, the US Department of Energy, product manufacturers and service providers, DAC property developers and managers, and energy companies across the country to discuss topics relevant to AECs. In 2018, the AEC workshop focused on energy affordability, and lessons learned from the smart thermostat project were discussed during workshop activities.

- **EPRI Customer Connected Device Workshop:** Similar to the AEC workshops, this workshop invited a multi-stakeholder discussion on current topics in the connected device space. A specific session called "Connected Devices for All" discussed activities and programs completed by utility programs in California (PG&E) and outside California (NYSERDA) and by the private sector (Google). Finally, the project team discussed Lydia and current progress.

Technology Transfer to California Disadvantaged Community Builders and Developers

The project team worked with various stakeholders to identify opportunities and barriers in providing intelligent HVAC controllers to help California disadvantaged communities. The team worked with community tenants and maintenance staff members to understand challenges with thermostat installation, operation, and commissioning. Throughout the project, the team worked on understanding challenges to disadvantaged communities and also on supporting and maintaining deployments of intelligent HVAC controls at scale. The project team has worked with other California disadvantaged community builders, developers, and managers, eliciting feedback on the need for intelligent HVAC controls that were potentially not serviced by connected devices on the market at the time.

These discussions were intended to better understand current drivers, opportunities, and barriers from the perspective of those who develop, manage, and maintain LI properties. Developers such as the Fresno Housing Authority, BRIDGE Housing, Mutual Housing California, Stewards of Affordable Housing for the Future (SAHF), and Self-Help Enterprises all provided feedback during the project's PoP.

The main lessons learned during these technology/knowledge transfer activities included the following:

- **Interest in tools to help tenants manage California's the shift to TOU rates:** Stakeholders were very interested in technology scouting that could help tenants, management staff, and maintenance staff manage California's TOU programs. As a result, the project team included TOU management features as part of the Lydia app.
- **Smart tools and products that help property managers and complex managers control/manage centralized HVAC systems:** Conversations with developers and managers, especially those who own master-metered properties,[12] indicated that they were interested in evaluating master-metering and centralized HVAC systems. Although this was not part of the project, the project team, led by EPRI, is investigating field demonstrations and data collection associated with smart thermostat technologies and services available in the market today.
- **Demand charge management using intelligent HVAC controls:** In addition to centralized HVAC controls, master-metered property managers indicated a desire to investigate how to leverage an aggregated group of smart thermostats in a community

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[12] Master metered is a term where several units, tenants, or buildings share a common energy bill that is paid by one entity, typically an overall owner or manager.

to enable demand charge management using precooling or prewarming[13] (EPRI, 2016) functionality that is sometimes provided by smart thermostats or other product and service providers. Usually, this accompanies an interest in battery storage systems for demand charge management. Property developers and managers — especially in California LI and disadvantaged communities — are challenged by interconnection requirements and overall battery storage financing and costs. As a result, these stakeholders are interested in using smart thermostats to shift energy consumption to minimize property demand charges that can potentially be a considerable portion of their monthly electricity bill. The project team led by EPRI is investigating additional field demonstrations to use an aggregate set of thermostats to enable demand charge management for LI and disadvantaged California communities.

As part of this effort, the project team plans to continue engagement with several LI disadvantaged community property managers and sites even after the end of this project's PoP. Example initiatives and projects follow.

Continuing Demonstration Activities — Intelligent HVAC Controls for California

Although the project team has decommissioned the thermostats developed as part of this project, the team plans to continue examining various options to demonstrate intelligent HVAC controls. In some such projects, HVAC control is the main driver, while, in others, HVAC controls are part of a set of technologies being demonstrated.

During the project PoP, an affordable housing manager approached the team to identify opportunities for battery storage for demand charge management. The project team has installed and is beginning to collect data on a 64-unit two- and three-bedroom property in Firebaugh, California (Climate Zone 13) (Figure 23).

Figure 23: One Building (Left) and Aerial View (Right) of Firebaugh Community

Source: EPRI

The community — a 16-building master-metered campus housing migrant farm workers — upgraded its evaporative coolers with electric HPs in 2019. The property is typically unoccupied in the wintertime. Conversations with the property management, maintenance,

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[13] This report will define precooling/preheating as using a combination of smart thermostat controls and a building's inherent or embedded thermal mass as a method to shift space conditioning usage, thus minimizing it at a certain time period.

and HVAC contractors identified that, in the summer, some occupants decreased their setpoints to 50ºF (10°C). This action dramatically increased HVAC consumption and electricity costs for the property manager, primarily due to considerable demand charges, peak energy use, and peak day pricing. The project team, through another CEC grant, is leveraging existing tools to potentially enable demand charge management strategies for this community.

Finally, the project team has connected with affordable housing stakeholder forums such as SAHF's energy working group to conduct a lessons-learned workshop focusing on adoption and deployment of intelligent HVAC controls in disadvantaged communities. In particular, property managers and bill payers are looking at smart thermostats as alternatives (or complements) to battery storage to enable demand charge management in California's master-metered communities.

Technology Transfer With Utility Industry

Throughout the project, the project team presented current developments and final results to energy companies across the United States, with specific emphasis on California IOUs. Avenues of knowledge transfer included the following.

- EPRI held webcasts focused on lessons learned from designing, developing, and implementing affordable housing DSM programs. For example, on June 26, 2019, EPRI hosted a webcast on lessons learned from designing, developing, and implementing efficiency programs for healthy and affordable communities. The webcast brought together LI and affordable housing program managers to share lessons learned on designing, developing, and financing affordable housing programs nationwide (see Appendix D for materials presented during that webcast).
- The project team also spent time discussing lessons learned and eliciting feedback from EPRI's utility advisors on Lydia itself as well as improvements in developing DSM programs for LI communities. Much of the feedback and interest has been captured in other sections of this report.
- The project team paid special attention to California utility and state program stakeholders interested in the project for both the thermostat and the functions itself, such as: 1) battery-operated thermostats to solve some of the HVAC compatibility issues that cause technology turndowns,[14] 2) challenges with the "digital divide" question, and 3) a technology/infrastructure that can be used in multifamily applications and how best to launch those programs. In addition, these stakeholders were interested in an opportunity to engage and learn from other stakeholders to better understand topics such as:
    - Lessons learned from implementation of thermostat programs in disadvantaged communities.
    - Interest in enabling DR programs and the challenges of implementing such programs for LI customers through alternative methods not involving Wi-Fi.

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[14] A technology turndown is an instance when a DSM program plan involves installation of a device or system that is ultimately not compatible with the existing infrastructure.

  - Ensuring alignment with California IOU statewide efforts in providing thermostat programs for TOU management in LI communities.

Summary

In addition to identifying HW and SW specifications and the format in which they will be available after the project ends, it is important to understand lessons learned during secondary research, engagement of TAC members, and demonstration and deployment of smart thermostats. The project team engaged stakeholders through plans to address the fundamental issue of intelligent HVAC controls for California's LI citizens. A summary of knowledge transfer activities the project team plans to continue follows.

- **LI property managers and developers:** The project team intends to continue to engage LI property managers and developers on tools to help manage California's shift to TOU rates. The team has installed smart thermostats in two California disadvantaged communities and plans to collect data from these installations over the next one to two years. It is important to understand the challenges that property developers and managers face in disadvantaged communities so the project team can plan to work with specific task forces moving forward.
- **Technology transfer to the utility industry:** The project team continues to engage with both utility R&D and DSM programs nationwide to share lessons learned from the implementation and results of its smart thermostat program for LI housing. Specific focus will be given to California-related pilots and programs such as California's statewide TOU rate management for LI residential customers. It is important to understand pilot hurdles to scaling the program to larger market segments.
- **Technology transfer to DAC staff members:** The project team disseminated information on barriers to scalability of installing, supporting, and servicing the mass-market adoption of tools such as smart thermostats to help customers reduce energy bills. There needs to be a significant value proposition for all parties to support the adoption, operation, and maintenance of new technology, including addressing the digital divide enabling smart technology. It is important to understand baseline conditions, general inertia, and potential challenges in convincing maintenance staff to learn how to install, train, operate, and maintain this new technology. For example, during the thermostat installs in Firebaugh, a training issue resulted in incorrect operation of the HVAC system and a desire by some to return to the status quo thermostats. It will be especially crucial that all parties receive the appropriate supporting documentation to ease potential "adoption inertia" and ensure persistence of the technology offering.
- **Open-source design requirements and specifications:** The project team did not engage a manufacturer to agree to mass-market production of the ThermoCAT or Lydia reference design. Rapid technology progress has resulted in products from large smart thermostat manufacturers that have the potential (through lower price points and market and utility DSM programs) to target LI disadvantaged communities. However, because the products are still relatively new to the market (less than two years old), there is little empirical evidence of the energy impacts of these products at the time this

report was written. As a result, the project team ensured that all aspects of this project — HW specifications, SW, BLE interface code, and so forth — remain in an open source so that a manufacturer can either pick up development efforts where the thermostat is now or take a component of the design and implement it within its existing offering.

The project team understood the importance of not only transferring the results of emerging technology development in the design of a smart thermostat but also gauging the industry and the market to understand the appropriateness of the project objectives. This information is included in the conclusions and recommendations chapter of this report.

CHAPTER 5: Conclusions and Recommendations

The project team successfully developed a prototype of a low-cost intelligent HVAC control system, named Lydia, which prioritizes lower costs and power consumption in a battery-powered unit. The project team also developed key innovations, such as enabling data transfer through BLE as well as the comfort band — a heuristic algorithm used to learn the customer's comfort area of setpoints to establish preferred temperature tolerances with energy savings.

In summary, the learning curve barrier, especially when replacing a non-programmable analog thermostat, is quite high. Tenants usually compare usability to a baseline, in this case interfacing with the thermostat at the HW unit. In this project, the biggest project point of departure was to minimize usability in the HW itself. Otherwise, the project identified the following conclusions and recommendations concerning intelligent HVAC controls in California's disadvantaged communities.

Conclusions

The project team focused on two areas of results and associated recommendations: 1) lessons learned from secondary research, and 2) lessons learned from prototype development and field testing.

Availability of Wi-Fi or cellular-based broadband access in LI housing forces design trade-offs. Retrofitting older and low seasonal energy efficiency ratio (SEER) models of HVAC systems with intelligent controls introduces another set of design trade-offs to maintain product affordability. This particularly affects two areas:

- **Trade-off data collection:** The frequency and amount of data collected through the HW unit needs to be carefully balanced against the availability and bandwidth limitations of Wi-Fi and cellular broadband connectivity options. Connectivity issues affect intelligent algorithm development, which relies on training data sets.
- **Trade-off battery life:** To support operation of the HW unit, the prototype design used a pair of AA batteries in lieu of requiring C-wire availability. This design choice reduced the frequency of changing batteries. However, the connectivity option was restricted to BLE, which significantly reduces the quantity and frequency of data that could be collected.

The project team has added many supporting R&D results that help address the growing smart thermostat market segment. One key concept of the intelligent HVAC control system is the notion of a comfort band — essentially the range of temperature in which occupants do not need to turn on their HVAC system. By driving the temperature controls towards this band as opposed to a single setpoint value, the thermostat can intelligently save on HVAC usage. However, given that the comfort band is dependent upon occupant preferences, determining this range requires data from the HVAC system as well as room temperature, setpoint data, and HVAC system status. The project team developed a heuristic algorithm based on the type of data collected from the Lydia system (room temperature, setpoint, and HVAC system status). Algorithms like these are foundational to a "learning" thermostat, and, by publishing a heuristic algorithm, the project team hopes to democratize the knowledge.

The project team successfully developed a new GATT protocol for thermostats as part of the project. The GATT protocol is specifically defined for BLE and constrains the amount of information exchanged between entities communicating over GATT to reduce the amount of energy needed to accomplish this communication. Using the protocol defined in this project, a mobile phone and its wide-area connectivity via cellular (4G/LTE) can be leveraged to backhaul data to a data store, where data can be used for various purposes, such as developing the customer's comfort band.

The project team included an integrated DR capability for the thermostat, which incorporated a scheduling mechanism for DR that overrode user settings for those who had opted into a utility's DR program.

An intelligent HVAC control system for California's disadvantaged communities is a gap in the industry today. The project has discussed the need for an intelligent HVAC control system that specifically addresses residents living in LI and reduced-income communities. The market for such products exists in two segments:

1. An upstream segment comprising utilities, energy service providers, community choice aggregators, and DR aggregators that need to use the intelligent HVAC control system as a lever for energy-efficient behaviors and utility-driven energy management for downstream customers
2. A downstream segment comprising residents who are looking for HVAC control systems that allow them to be comfortable while also reducing their HVAC-driven energy use and consequently their electricity bills — especially as California shifts to TOU rates

Additionally, formal human factors and usability testing of the HW unit and the mobile application were performed. The project team identified several facets of the prototype with potential for technology transfer and adoption by industry players towards the development of a commercial product. One key design choice in the overall intelligent HVAC control involves enhancements to the user experience that can be delivered using a well-designed mobile application that accompanies the simplified HW unit. Users liked the mobile app design and indicated that they would use the application. This result is also supported through data collected from the limited field deployment.

Users found the UI elements of the HW unit intuitive, especially the ON/OFF button, current temperature display, and buttons for raising and lowering setpoints. However, a key design choice that was implemented, namely, the Timer button, was not found to be particularly intuitive. This weakness was not adequately addressed by the mobile app with button behavior that was identical to the HW unit. The project team recommends changes to the mobile app to provide additional information on the timer function to make the timer options more user-friendly.

It was shown, however, that a highly usable mobile app does not replace a slow HW unit. Users found the lag induced by the slow response of the HW unit to be tedious. While the mobile app can help alleviate some of the slowness, the responsiveness of the overall system is still subject to the speed of response from the HW unit. One major reason for the HW unit's limited responsiveness was the use of e-ink technology to reduce thermostat costs while improving the battery life.

Recommendations

Development of an HVAC controller to help LI citizens in California was the main objective of this project, and lessons learned from product development are described in this report. Still, additional research is necessary to better achieve the project's overall objectives. Recommendations for future research include the following.

- **Addressing the digital divide:** Accessibility to broadband connectivity in LI communities is a challenge when it comes to realization of energy-related benefits that smart technologies can potentially provide. This includes improved access to broadband as well as several alternatives to broadband, such as the BLE methods explored during this project.
- **Providing tools to help customers and community managers manage TOU rates:** Throughout the project, California's shift to dynamic energy rates is something that LI property owners, managers, and developers are monitoring. Continued exploration into tools and solutions to help Californians shift to TOU rates, with specific emphasis on disadvantaged communities, will inform future project deployment.
- **Continuing collection of operational data:** Continued collection of operational data from demonstrations and deployments can provide a better industry understanding of how scaled field placements can be extended to larger populations. Operational data also enable the development of algorithms to help reduce overall bill impacts.
- **Assessing market-ready technologies:** A knowledge transfer activity associated with this project was the deployment of smart thermostats available in the market today. Since many of these technologies are relatively new to the market, it is important to collect empirical data on these technologies with a specific focus on LI market segments.
- **Holistically assessing barriers to adoption:** This project not only evaluated product development but also considered all necessary stakeholders, including apartment managers, trades, maintenance staff members, and contractors, who all have a hand in overall technology adoption. Secondary research also found alternative "trust circles" that may need to be considered when providing LI programs. Understanding programmatic opportunities and barriers is one way to maximize the likelihood of extensibility of the overall program strategy.

CHAPTER 6:
Benefits to Ratepayers

The project aimed to demonstrate how the smart thermostat industry can meet the needs of underserved population segments that face the hurdles of split incentives[15] and lack of access to broadband services, such as many small business owners. The project also provided valuable insight on consumer requirements for EE products in LI communities and how to improve the reach of other programs for LI customers.

HVAC is often the largest electrical load in LIHs, and one of the greatest causes of HVAC inefficiency is the occupant settings of the thermostat. Several high-tech thermostats offer efficient control of HVAC systems by learning occupant behaviors, adapting automated thermostatic control to optimize efficiency for those behaviors, and empowering consumers with smart controls using broadband communication. However, many LI residents cannot afford broadband internet service and cannot therefore participate in energy saving control functions available for smartphone apps. As the industry continues to address the digital divide, an intelligent HVAC control system for LIHs will reduce the need for broadband service by combining intelligent learning functions with Bluetooth and Wi-Fi communication SW and HW, enabling the consumer to directly control the thermostat via the thermostat’s dashboard or via a smartphone app used in the residence.

Various studies have indicated that smart thermostats can potentially optimize indoor setpoints based on preferences and can reduce the energy used for cooling by 10 percent and for heating by 5 percent. EPRI research indicates that the average energy used for cooling an 842-square-foot apartment in Lancaster, California, is about 300 kWh per month, or about 1,500 kWh over an entire year (Hammon-Hogan et al., 2016). Ironically, this energy consumption nearly matches the cooling energy used by an average single-family home in Sacramento, given the correspondence with the average heating and cooling energy use and even with smaller square footage. LIHs constitute 21.1 percent of all households in California, which correlates to an energy use of 1,530 GWh in cooling, 730 GWh in heating, and 470 million therms of gas usage. As California moves towards its state decarbonization targets, it will be important to understand how advanced efficient electrification technologies such as HPs will be adopted and how building electrification will require new and improved thermostat controls.

EE and efficient electrification investments can positively affect disposable income for LI customers. There are an estimated 4.5 million LIHs statewide (Sadhasivan & Chang, 2019). EE and DR program investment in California is approximately $900 million. Savings realized by LI customers who do not currently have access to smart thermostat technology will almost fully flow back into the California economy in terms of new purchases or investments. Therefore,

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[15] Split incentives is a term used to describe how DSM program adoption and participation often does not occur in rental properties due to a tenant paying the electricity bill and a building or facility manager being responsible for building upgrades. The result is neither stakeholder is “incentivized” to identify and participate in a DSM incentive program.

the proposed thermostat could potentially act as a $50 million annual stimulus investment for the California economy (Alcorn et al., 2013).[16]

In addition, the cost of the California Alternative Rates for Energy (CARE) discount affects all California ratepayers. By reducing the amount of energy used by CARE rate customers, all California ratepayers reap the benefits. Based on CPUC estimates in 2018, California CARE rate programs provided around $1.3 billion in subsidies and served more than 4.5 million homes in the state. Reducing household energy use in LI housing by 4 percent (SCE, 2017) (based on HVAC versus total energy use for gas and electric) results in an overall savings of $44.6 million a year for California ratepayers.

By developing and demonstrating smart thermostats with a functionality and a price point applicable to the LI market segment, this project can help expand the potential for EE and DR in California. The LI community has historically had difficulty capitalizing on innovations in energy-saving and demand-reducing technologies due to barriers of information, building infrastructure, connectivity availability, and first cost. The potential result of affordable smart thermostats could be greater capitalization on energy saving features by all communities.

This project has developed functional specifications, UIs, and prototypes of smart thermostats based on focus groups and surveys of LI residents that could reach an intended price point of $75 if manufactured at scale. All functional requirements will be kept open source, HW and SW, so that a manufacturer can continue development of the thermostat or take promising elements of the thermostat and incorporate them into its particular designs. Moreover, the application of these devices can extend beyond the LI segment to a variety of market segments, with a specific focus in environments that: 1) do not have easy or reliable access to the internet for any reason and 2) involve antiquated HVAC systems and building infrastructure that make it cost prohibitive to perform considerable HVAC upgrades.

In addition to the thermostat development itself, the CEC's Electric Program Investment Charge (EPIC) funds have enabled forums for current California IOU initiatives to interact with other LI programs in the nation to discuss lessons learned in designing, developing, and deploying smart technology and programs.

Knowledge transfer was also enabled through connections made with LI property developers and managers in the state, both project partners and those recruited to join the TAC. Such connections are resulting in additional smart-thermostat-related activities with disadvantaged communities throughout California. Without the intervention of EPIC grant funds, these market segments would potentially not naturally deploy smart thermostats.

At the time of this project's commencement in 2015, LI smart thermostats were currently in the proof-of-concept stage. Smart thermostats themselves were still nascent to the industry, with considerable interest, but most technologies were still being sold for over $200. As of 2018, large thermostat manufacturers such as ecobee and Google Nest Labs developed smart thermostats at a lower price point. A combination of market movement and stakeholder

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[16] This assumes that: 1) 25% of annual end-use consumption is attributed to end uses in disadvantaged communities, and 2) 10% market adoption occurs over a four-year period (such as market rate adoption). An SCE work paper on smart thermostats — temporarily approved in the Database for Energy Efficiency Resources (DEER) — documents heating and cooling savings per California IOU.

connection enabled by this project has created an opportunity to install these thermostats in California disadvantaged communities to serve current-use cases. For example, engagement with disadvantaged communities has led to installation of market-available smart thermostats for demand charge management — a use case that appeals to current LI and DAC property owners and managers, especially those in which the property owner pays the electricity bill. These same communities are very interested in tools such as smart thermostats that would help their tenants manage TOU rate changes. These efforts match up with the current statewide activities. Lessons learned from this project also match correspondence with California IOU program managers who were members of the project TAC.

The "digital divide" is a considerable deterrent to DSM opportunities. Even in current DSM programs, persistence of consumer-owned broadband connectivity is a challenge. This project has demonstrated a proof-of-concept method where DR and technology updates are enabled through the Bluetooth protocol. With larger adoption of smartphones versus personal internet, inclusion of BLE-enabled DSM functions could potentially reach additional DR participants seeking energy bill reduction opportunities.

Benefits from implementation of the proposed thermostat could accrue to other segments, such as small commercial customers distributed across the small office, retail, and foodservice segments. Assuming 50 percent applicability in small businesses and assuming that 30 percent of energy use in these segments is consumed by small businesses, the total energy usage for the target market is 900 GWh of electricity for cooling and 30 million therms of gas for heating. Such a scenario makes savings of 90 GWh of electricity and 5 million therms of gas possible. Additional energy savings for this segment could total $16 million a year.

EPIC grant funding was leveraged to engage key stakeholders, including IOUs (both from emerging technologies and LI departments), device manufacturers (which ultimately produce the product), and LI property owners. The engagement of these stakeholders ensured that the project and the associated thermostat development were in line with what is needed in the industry and the community. It was important to engage a large stakeholder group, as the connected device industry is subject to rapid technology change.

The market reach of smart thermostats may even extend beyond the LI segment to other market segments in California. The resultant monthly bill savings can have a stimulus effect on the California economy, since money not spent on utility bills can be spent on other economically beneficial goods and services or be allocated towards savings and investment.

The results of this project, under the direction and auspices of the CEC, will be made available to the public, including industry trade groups, manufacturers, utilities, academia, and the public at large. Results will be disseminated through a variety of means, as approved by the CEC, which may include conference presentations and proceedings, articles in peer-reviewed journals, and release of project deliverables.

GLOSSARY AND LIST OF ACRONYMS

Term	Definition
A	Amp
A/C	Air conditioning
AC	Alternating current
AEC	Advanced Energy Community
API	Application programming interface
App	Application
BLE (or BTLE)	Bluetooth Low Energy
C-wire	Common wire
CA	California
CARE	California Alternative Rates for Energy
CBO	Community-based organization
CEC	California Energy Commission
CFL	Compact fluorescent light
CIEE	California Institute for Energy and Environment (University of California, Berkeley)
CPUC	California Public Utilities Commission
DAC	Disadvantaged community
DC	Direct current
DEER	Database for Energy Efficiency Resources
DER	Distributed energy resources
DOE	U.S. Department of Energy
DR	Demand response
DSM	Demand-side management
EE	Energy efficiency
EEPROM	Electrically erasable programmable read-only memory
EIA	U.S. Energy Information Administration
EPA	U.S. Environmental Protection Agency
EPIC	Electric Program Investment Charge
EPRI	Electric Power Research Institute
ESA	Energy Saving Assistance
FRAM	Ferroelectric random-access memory

Term	Definition
GATT	General attribute
GPS	Global Positioning System
GWh	Gigawatt-hour
HP	Heat pump
HVAC	Heating, ventilation, and air conditioning
HW	Hardware
I/O	Input/output
IoT	Internet of Things
IOU	Investor-owned utility
LDO	Low dropout (regulator)
LEAP	Low-Income Energy Assistance Program
LED	Light emitting diode
LI	Low-income
LIMF	Low-income multifamily
LIH	Low-income household
LoRa	Long range (proprietary wide area network technique)
LSB	Least significant bit
MIH	Medium-income household
MPC	Model predictive control
MSB	Most significant bit
N	Counter used for variable counting
NFC	Near field communication
NYSERDA	New York State Energy Research and Development Authority
PC	Personal computer
PG&E	Pacific Gas and Electric
PIR	Private information retrieval
PoP	Period of performance
R&D	Research and development
SAHF	Stewards of Affordable Housing for the Future
SCE	Southern California Edison Company
SDG&E	San Diego Gas & Electric
SEER	Seasonal energy efficiency ratio
SIG	Special interest group

Term	Definition
SUS	System Usability Scale
SW	Software
TAC	Technical advisory committee
TOU	Time of use
UC	University of California
UI	User interface
USD	United States dollars
UVLO	Undervoltage lockout (circuit)
USB	Universal Serial Bus
V	Voltage

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