Energy Research and Development Division
FINAL PROJECT REPORT

IMPROVING RESIDENTIAL PROGRAMMABLE THERMOSTATS

National Lab Buildings Energy Efficiency Research Projects

Prepared for: California Energy Commission
Prepared by: Lawrence Berkeley National Laboratory

DECEMBER 2014
CEC-500-2015-019

PREPARED BY:

Primary Author(s):
Alan Meier
Emmanuelle Revillion

Lawrence Berkeley National Laboratory
1 Cyclotron Road, MS2000
Berkeley, CA 94720
Phone: 510-486-4740 | Fax: 510-486-4673

Contract Number: 500-10-052

Prepared for:

California Energy Commission

Heather Bird
Contract Manager

Virginia Lew
Office Manager
Energy Efficiency Research Office

Laurie ten Hope
Deputy Director
ENERGY RESEARCH AND DEVELOPMENT DIVISION

Robert P. Oglesby
Executive Director

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ACKNOWLEDGEMENTS

This work was supported by the California Energy Commission, Public Interest Energy Research Program, under Agreement No. 500-10-052.

The project team at Lawrence Berkeley National Laboratory would like to thank the sponsor, the Public Interest Energy Research Program of the California Energy Commission, Chris Scruton, and especially our Contract and Project Manager, Heather Bird.

Thanks to the many industry professionals who shared their ideas and feedback for this project. They were individuals; representatives of manufacturers of networked thermostat products; research consulting firms, and especially Doug Frazee of ICF; utilities; international, U.S. and California standards committee members; staff of academic and research institutions; and the Amercian Council for an Energy-Efficient Economy Summer Study; and the Environmental Protection Agency, in particular, Abigail Daken.

Thanks to Emmanuelle Revillion, who collaborated on development of technical presentations for the Electric Power Research Institute and the Environmental Protection Agency.

Thanks to the Lawrence Berkeley National Laboratory (LBNL) staff who contributed to this work including, including Jerri Carmo and Paula Ashley. Thanks, also, to our reviewers for their generosity and time improving this report. Many thanks to Gari Kloss for her invaluable contributions.

This work was supported by the California Energy Commission's Public Interest Energy Research program and by the Assistant Secretary for Energy Efficiency and Renewable Energy, Building Technologies Program, of the U.S. Department of Energy under Contract No. DEAC02-05CH11231.

PREFACE

The California Energy Commission Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

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- Transportation

Improving Residential Programmable Thermostats is the final report for National Lab Buildings Energy Efficiency Research Projects (contract number 500-10-052) conducted by Lawrence Berkeley National Laboratory. The information from this project contributes to Energy Research and Development Division's Buildings End-Use Energy Efficiency Program.

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ABSTRACT

In the last ten years, energy savings accruing to programmable thermostats have been lower than expected and frequently, programmable thermostats have actually increased space heating energy use. Internet-connected thermostats are increasingly being offered by service providers whose primary function is to manage thermostats with the intent of helping consumers use less natural gas and electricity for heating and cooling. Currently, there is no way to compare the effectiveness of different algorithms and services provided by these vendors. Users, utilities, code officials, and researchers cannot presently identify service providers who have developed more effective energy-saving algorithms. This is an important gap because the networked thermostat market is growing rapidly and likely to become the standard in California homes. Furthermore, the extended energy savings potential of "Software as a Service" is significant.

This research created a metric to measure the effectiveness of Internet-based algorithms to save energy in homes. Four different metrics were considered:

- metered savings through field measurements
- estimated savings based on calibrated simulations
- furnace run-time
- savings degree-hours

Thermostat service providers have used variants of all four metrics for internal analysis and research. There is a lack of published results with little actual measured data disclosed. Each approach has drawbacks, although savings degree-hours appears to be the most promising. Savings degree-hours is a simple metric that allows easy comparisons of different algorithms, even when some differences exist among the homes.

Using a basic assumption that networked thermostats save 10 percent per affected home, the statewide savings will be roughly 15 million therms per year or 1.6 trillion British thermal units.

Keywords: connected thermostat, networked thermostat, internet connected thermostat, savings degree-hours, furnace run-time, software as a service, SaaS

Please use the following citation for this report:

Meier, Alan. (Lawrence Berkeley National Laboratory). 2014. ***Improving Residential Programmable Thermostats.*** California Energy Commission. Publication number: CEC-500-2015-019.

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EXECUTIVE SUMMARY

Introduction

The residential programmable thermostat has been in existence for more than 30 years, however, research conducted over the last ten years has shown that savings attributed to them are lower than expected. Frequently, residential programmable thermostats actually increased space-heating energy use. As a result, various initiatives are underway at Energy Star, utilities, and the manufacturers to improve programmable thermostats.

Internet-connected thermostats (networked thermostats) appeared in significant numbers around 2010 with a new type of service provider whose primary function was to manage thermostats to help consumers use less natural gas and electricity for heating and cooling. These service providers developed algorithms optimizing the operation of the home's HVAC system to minimize heating and cooling energy use. The algorithms, still used today, typically take into account the building's mass, insulation, mechanical equipment heating capacity, and outside temperature, enabling the vendor to select optimal times to set-up and set-down the thermostat. Other algorithms draw upon the outside temperature, humidity, occupancy, and location of occupant's mobile phone. Together, the application of these algorithms cuts natural gas use by lowering heating temperatures when the occupants are away or do not want high temperatures. The Internet-connected thermostat service providers claim up to 20 percent reduction in heating energy use.

Currently, there is no way to compare the effectiveness of different algorithms and services provided by these vendors. Users, utilities, code officials and researchers cannot presently identify service providers that have developed more effective energy-saving algorithms. This is a significant gap because the networked thermostat market is growing rapidly and is likely to become the norm in California homes. Furthermore, the energy savings potential of this "Software as a Service" is significant. Software as a Service (SaaS) is a software distribution model in which applications are hosted by a vendor or service provider and made available to customers over a network, typically the Internet.

Project Purpose

This research created a metric to measure the effectiveness of Internet-based algorithms to save energy in homes and focuses on space heating with natural gas. This report describes the inquiries and experimentation undertaken in this project and provides results, conclusions, and recommendations for further research.

Project Results

Four different metrics were considered:

- metered savings through field measurements
- estimated savings based on calibrated simulations
- furnace run-time
- savings degree-hours

The thermostat service providers have used variants of all four metrics for internal analysis and research, but have published few or no results. Little actual measured data has been disclosed. Each approach has drawbacks, although savings-degree-hours appears to be the most promising. It is an intuitively simple metric that allows easy comparisons of different algorithms, even when some differences exist among the homes. However, as in all of the cases, further investigation, using real data, in real homes, is necessary.

Project Benefits

The energy savings will occur as a result of the work described in this report in two ways:

1. Networked thermostats will be installed in California homes, leading to savings beyond those obtained with existing programmable thermostats
2. Future energy-saving algorithms will be improved through this research because manufacturers can more easily evaluate effectiveness of algorithms

Future potential energy savings associated with this research were estimated based on the following assumptions:

- Current networked thermostats could save 10 percent per affected home
- Improved algorithms (identified by the metric) could raise savings 30 percent (that is, 3 percent of space heating use)
- Fifty percent of homes have a constant broadband connection
- Only homes with central air conditioning systems would install a networked thermostat (so as to obtain the dual benefits), that is, 49 percent of California single-family homes
- No credit has been taken for reduced electricity use by furnace fan or reduced air conditioning electricity use during the summer.

Based on these assumptions, the statewide energy savings will be roughly 15 million therms/year or 1.6 trillion British thermal units. These savings correspond to roughly $13 million/year in lower bills at current residential gas rates. This estimate is probably conservative because creating this metric to measure effectiveness of the algorithms will also increase consumer confidence in networked thermostats. For example, an Energy Star endorsement of certain thermostat providers could both accelerate consumer uptake and direct purchases towards service providers with more effective algorithms.

CHAPTER 1: Introduction and Overview

1.1 Recent History of Residential Thermostats

The recent history of residential thermostat technology in the United States began in 1995 (Peffer et al. 2011) when the US Environmental Protection Agency (EPA) added programmable thermostats to its Energy Star program. Energy Star specifications required certain features: default energy-saving and comfort setpoint temperatures, cycle rate setting, recovery systems, and a hold or override option. The primary applications for these thermostats were (and continue to be) homes heated by natural gas or oil. Consumers understood that the Energy Star emblem on an appliance indicated energy efficient equipment; manufacturers had to comply with Energy Star eligibility requirements.

Throughout the 1990s the Energy Star specifications grew more complex, adding schedules for weekend/weekday, seven-day, or vacation. More recently, part of the 2008 Title 24 California Building Energy Efficiency Standards requires that programmable thermostats have the ability to set temperature preferences for at least four different time periods per day.

1.2 Usability Problems Associated with Thermostats

In 2009, Energy Star terminated the thermostat endorsement program. There had been few careful studies of the energy savings attributable to these thermostats, such as a before/after comparison. However, a few longitudinal studies found no difference in energy consumption between homes equipped with manual and programmable thermostats (Cross and Judd 1997; Haiad et al. 2004; Nevius and Pigg 2000; Shipworth et al. 2010). Two other studies found that homes relying on programmable thermostats actually consumed more energy than those where the occupants set the thermostats manually, especially residences with heat pumps (Bouchelle, Parker, and Anello 2000). During this entire period, anecdotal evidence accumulated that the thermostats were overly complex and that consumers were unable to operate them in a way that obtained energy savings compared to manually operated thermostats.

Subsequent research has confirmed the suspected usability problems associated with thermostats. Investigations by Meier and others (Meier et al. 2011; Peffer et al. 2011) showed that occupants disabled as much as half of advanced thermostat's controls. They showed that typical users were often unable to perform key tasks related to operation of programmable thermostats. Furthermore, they found that different designs of user-interfaces led to widely differing success rates in accomplishing those key tasks.

Utilities across the globe are exploring time-varying price tariffs to reduce peak electricity demand – driven primarily from space heating (e.g., in hydroelectric-rich New Zealand and Canada) and cooling systems (e.g., in the U.S. and Australia). Time-of-use pricing has created the demand for programmable communicating thermostats that can receive price or reliability signals from the utility. In California, these thermostats were not included in the 2008 energy code, but their capabilities are expected in future iterations. At the federal level, this will most likely start with the new Energy Star specifications regarding climate controls (a subset of programmable thermostats) which will include communication and time of use price level indication. Including controls to deal with time-of-use pricing will add another level of complexity to thermostats. For this reason, future thermostats are likely to have even greater usability challenges.

1.3 Internet-Connected Thermostats

Internet-connected thermostats appeared in significant numbers around 2010. An Internet-connected thermostat – or simply a "networked thermostat" – controls a home's temperature in the same manner as a programmable thermostat; however, the unit also has a two-way communication with the Internet via wifi or an Ethernet connection. The network connection enables a person to control the thermostat from a remote computer or mobile telephone. These two new interfaces offer new opportunities for improved usability. The network connection enables the occupant to review or modify schedules through a more user-friendly website.

An Internet connection also makes it possible to collect far more data about settings and system operation than in a stand-alone thermostat. Most units collect and are able to transmit thermostat setpoints, actual temperatures, and furnace run-time.

Networked thermostats rapidly evolved beyond simple remote control and web-based management. Many aspects of a programmable thermostat's functionality have been transferred to the Internet. Companies that specialized in home automation have added a comfort function to their home management interface to remotely control an Internet-connected thermostat from the TV or other display. Likewise, security companies such as ADT have included thermostats in their networks. When the occupants leave the building (and arm the burglar alarm), a message goes to the thermostat and allows the most energy-saving settings to be immediately implemented.

A new type of service provider appeared whose primary function is to manage thermostats with intent to help consumers use less natural gas and electricity for heating and cooling. A partial list of thermostat service vendors is given in Table 1. The combination of the networked thermostat with the service provider's algorithms to manage thermostat settings through the Internet is an example of "Software as a Service" (SaaS).

Table 1: Selected Vendors of Networked Thermostats and Their Business Models

Thermostat Vendor	Headquarters	Business Model
Nest	California	Primarily hardware sales
Ecofactor	California	Service
Ecobee	Ontario, Canada	Hardware and service
Energy Hub	New York	Service
Honeywell	Minnesota	Hardware and service

Source: LBNL

These vendors developed algorithms to optimize the operation of the home's HVAC system to minimize heating and cooling energy use. The algorithms typically take into account the building's thermal mass, insulation, and furnace capacity, occupants?, time of use? and outside temperature. These algorithms allow the vendor to select optimal times to set-up and set-down the thermostat. Other algorithms draw upon information collected from other sources, such as outside temperature, humidity, occupancy, and location of occupant's mobile phone. Together, these algorithms cut natural gas use by lowering temperatures when the occupants are away or do not actually want such high temperatures. The thermostat suppliers claim up to 20 percent reduction in heating energy use.

The delivery of these services depends on the provider and the technology, but many business models exist. For example, the Nest thermostat contains most of the software services, so the company derives most of its revenues from sale of device. Ecofactor sells no thermostats and provides only services (often through third-parties, such as utilities, which may package them as part as an efficiency or Demand Response program). The business model is based on a monthly service charge. Ecobee sells a package of thermostat and services. Many firms have begun working with utilities to manage air conditioning (AC) demand; this creates another business model.

At present, there is no way to compare the effectiveness of different algorithms and interfaces. Users, utilities, code officials and researchers cannot presently identify service providers that have developed more effective energy-saving algorithms.

The networked thermostat is a rapidly-growing market segment and is likely to become the norm in California homes. They will become especially attractive as time-of-use pricing spreads. In colder parts of California and the nation, the networked thermostat will be installed to conserve space heating energy. In California, the initial justification for installation may be to manage AC costs but, once installed, the networked thermostats will also extend to gas space heating. At the same time, the energy savings claimed by the thermostat providers rival those of many engineering improvements to homes and their heating systems. To date, there is no recognized procedure to evaluate and compare the energy savings of these services.

1.4 Objective of this Study

The objective of this research is to create a metric to measure the effectiveness of Internet-based algorithms to save energy in homes. The focus is on space heating with natural gas; however, the same thermostat will also be controlling air conditioners. Networked thermostats are likely to become a common technology for controlling heat in California homes – if not the most common – so it is important to identify the most successful metrics. A consistent test procedure will assist in the design of efficiency programs and help inform consumers. The metric could also help vendors improve algorithms through internal comparisons and analyses.

This report therefore describes the lines of inquiry and experimentation that were undertaken in this project. It ends with results, conclusions, and recommendations for further research.

1.5 Benefits of this Research

About 8 million California single-family homes use natural gas for space heating and the average consumption is 184 therms/year (Kema, Inc. 2010). However, only 73 percent of the homes have central heating systems and it is assumed that half of all California homes have a robust broadband connection suitable for a networked thermostat. Thus, total natural gas consumption available for saving with networked thermostats is about 520 million therms/year. (This is probably a low estimate because single-family homes with a central furnace use more than the average.)

The energy savings from the work described in this report occur in two steps:

1. People install networked thermostats in California homes (this is already happening)
2. Energy-saving algorithms are improved through this research by the following actions:

    a. Regulators, operators of utility programs, Energy Star, and other stakeholders recognize providers with most effective algorithms through an Energy Star endorsement or inclusion on a list of approved services eligible for rebates

    b. Providers of networked thermostats improve their algorithms (by using a recognized metric for internal development)

We estimate the potential energy savings with the following assumptions:

- Current networked thermostats could save 10 percent per affected home
- Improved algorithms (identified by the metric) will raise savings 30 percent (that is, 3 percent of space heating use)
- Fifty percent of homes have a constant broadband connection
- Only homes with central AC systems install a networked thermostat (so as to obtain the dual benefits), that is, 49 percent of California single-family homes
- No credit taken for reduced electricity use by furnace fan or reduced AC electricity use during the summer

Based on these assumptions, the statewide savings will be roughly 15 million therms/year or 1.6 TBtu (trillion British thermal units) (Table 2). This estimate is probably conservative because the creation of a metric to measure effectiveness of the algorithms will also increase consumer confidence in networked thermostats. For example, an Energy Star endorsement of certain thermostat providers could both accelerate consumer uptake and direct purchases towards providers with more effective algorithms. Also, the fraction of homes with a constant, reliable broadband connection is likely to be much higher in the next few years.

Table 2: Assumptions Used in Estimating Savings From the Development of a Metric to Measure Effectiveness of Algorithms to Manage Networked Thermostats.

Assumption	Amount	Units
Unit energy consumption (UEC)	184	Therms/year
Stock (millions of homes)	7.8	Homes (millions)
Fraction of homes with furnace fans	0.73	-
Fraction of homes with constant broadband connection	0.5	-
Total energy use (millions)	524	Therms
Savings fraction attributable to networked thermostat algorithms	0.1	-
Increased savings fraction arising from use of metric and improved algorithms	0.3	-
Potential energy savings	15.7	Millions of therms/year

Source: LBNL

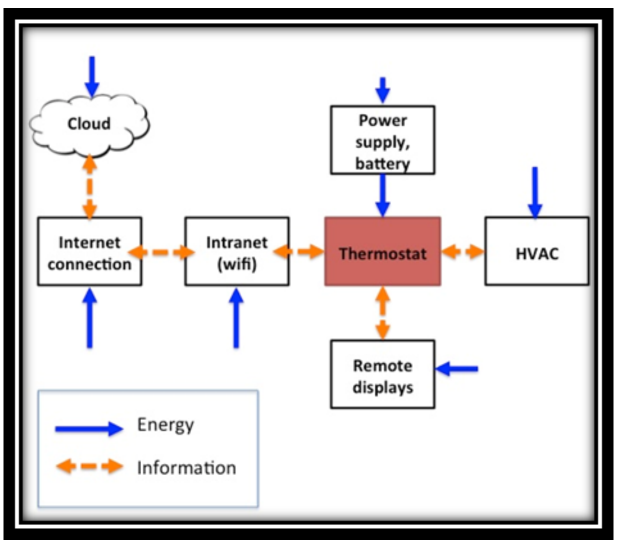
CHAPTER 2:
Analysis

2.1 Technical Objective

The technical objective of this project is to develop a metric to test the effectiveness of thermostat control algorithms to save energy. For this project, the highest priority is saving natural gas used for space heating, so the primary objective is a metric that captures the behavior of algorithms controlling heating systems. The metric must be flexible enough to be applied in most common operating environments, that is, combinations of sensors, controls, and communications networks.

The networked thermostat exchanges information and induces energy use upstream and downstream. The information and energy flows are illustrated Figure 1. Note that a broad array of information might flow from the Internet, such as weather, cell-phone location, and status of burglar alarm. Additional in-home information might flow directly through the wifi router (although this flow is not depicted). This information could originate from a wifi-enabled smoke detector (which also measures temperature or movement).

Figure 1: Energy and Information Flows Associated With a Networked Thermostat.



Source: LBNL

The metric under investigation in this report addresses only the HVAC energy use. In general, the upstream energy flows induced by the thermostat will be small, but should not be ignored entirely. The information flows depicted in the above schematic, however, suggest where external data might flow to support the thermostat control algorithm.

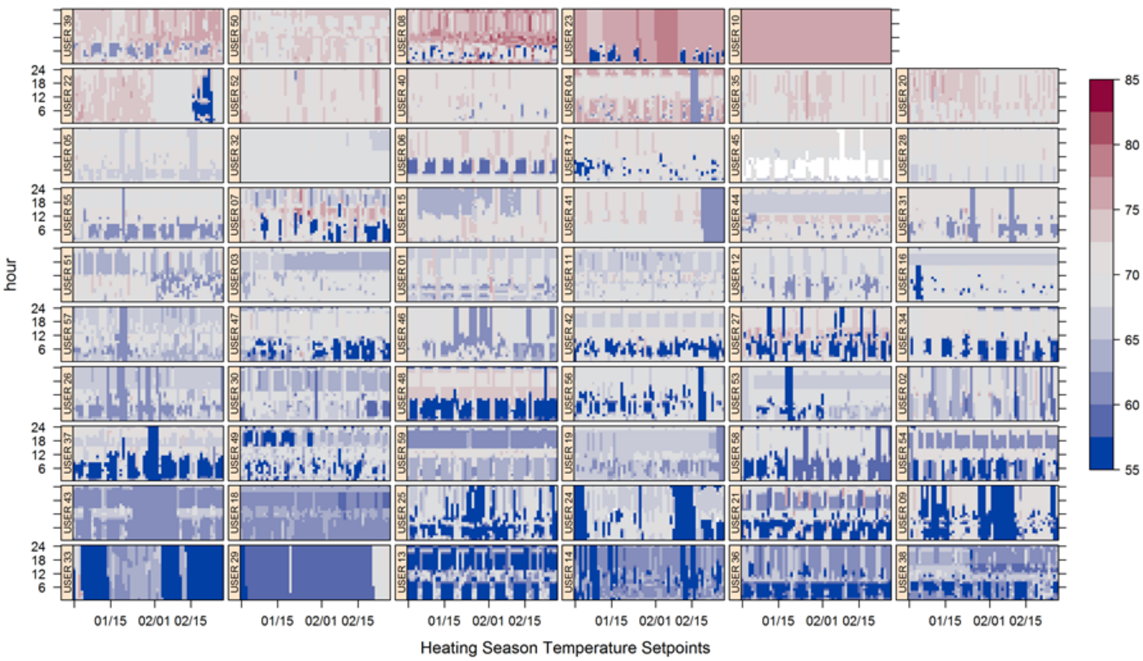
2.2 Typical Data Inputs for Networked Thermostats

The networked thermostat receives information (and ultimately transmits it to the service provider) from diverse sources depending on the operating environment and the vendor's configurations. The thermostat itself collects setpoint and temperature information. It will also know the schedule. All thermostats are connected to HVAC systems, so they receive system status information, such as, operation of the furnace, AC, and perhaps the fan and back-up heat (for heat pump status). Like some sophisticated programmable thermostats, the networked thermostat may also have access to local humidity and outside temperature. A networked thermostat differs from an unconnected thermostat in that it may receive further local information from motion sensors, which detect movement near the thermostat.

The thermostat service provider has access to other data about the home and its operations that will affect heating and cooling energy use. The provider can obtain the outside temperature and humidity from various Internet weather services, along with forecasts of weather. If the thermostat provider is linked to the security system provider – e.g. an alarm company that has already purchased a thermostat provider – then the thermostat provider will know if the occupants have left the building and armed the alarm. If the thermostat provider is linked to the cellular phone provider, then it can use geolocation services to know how far away the residents are from the home.

The thermostat provider is also able to capture and store much more data than can be processed by an unconnected thermostat. This data stream can easily exceed six channels at 15-minute intervals. The ability to collect, store, and analyze this data gives the provider new insights into each home's energy consumption habits, as well as possible approaches to reducing energy use. When the provider collects data from many homes, it can search for additional patterns and approaches to saving energy. Figure 2 illustrates two months of winter thermostat setpoints in 59 homes. Such data would be expensive to collect from conventional thermostats, yet this is now being collected from millions of American homes.

Figure 2: Winter Thermostat Setpoints in 59 Homes



Source: Urban, Bryan, and Roth (2014).

Each thermostat provider's technical and business model is distinct, drawing upon a unique collection of information. Nest's model draws upon information collected by its own thermostat and, soon, data from Nest smoke detectors. Energy Hub's units draw information from security systems (because the company is linked to an alarm company). Each company independently builds algorithms to manage its customer's thermostats. Ideally, the metric should be able to capture the success of algorithms that lead to lower heating energy consumption through any combination of sensors, interfaces, and algorithms associated with a networked thermostat.

2.3 Typical Algorithms Used To Reduce Heating Energy Use

Each provider uses a combination of algorithms to reduce a home's heating and cooling use. Some of these algorithms are described below with respect to space heating.

Take into account a home's thermal inertia for night setbacks. The provider calculates the home's thermal constant, that is, the time it takes for the house to heat up or cool down. Based on this knowledge and the occupant's schedule, the algorithm switches off the heating system earlier than actually scheduled and coasts towards the setback temperature.

Optimize morning set-ups. The home's thermal constant, furnace capacity, and outside temperature are considered in order to switch on the heating system early enough to bring the indoor temperature to the desired temperature at the desired time (but no earlier).

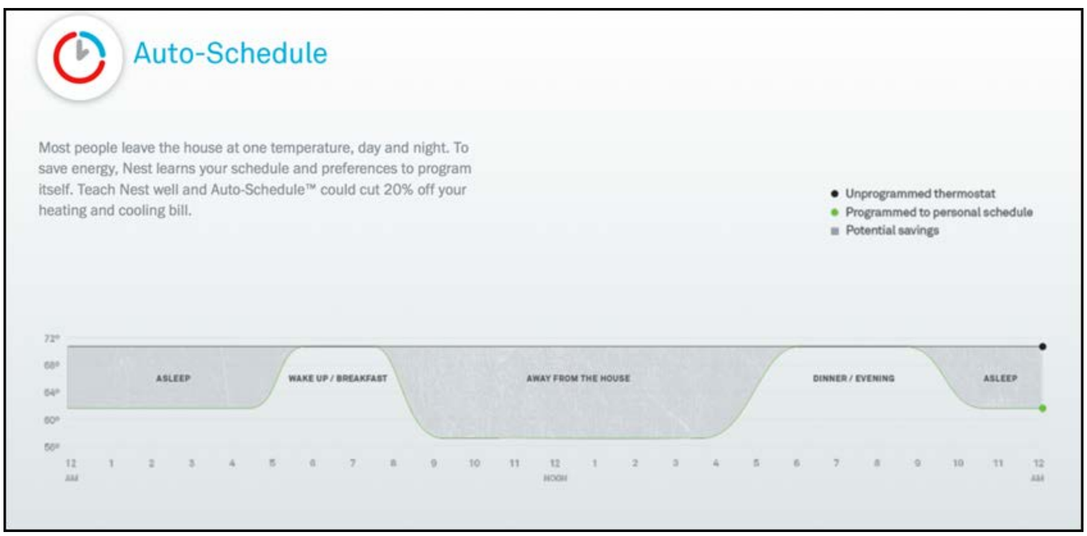
Lower temperature when no occupancy is detected. The algorithm draws upon a motion sensor to decide if occupants are present. If none are sensed, then the system switches to a lower temperature.

Lower temperature when occupants are known to be out of the house. This information might be determined by the arming of the burglar alarm or location sensing from a mobile telephone.

Manage system behavior so as to maximize operating efficiency. The algorithm may select heating system cycling intervals to minimize off-cycle losses or part-load inefficiencies. In dual-fuel heating systems (such as oil/heat-pump systems) or heat pumps with electric resistance back-up, the algorithm may manage the system to maximize use of the most efficient heating fuel. This kind of management could conflict with the HVAC system's own controls, so the extent of variability is limited.

With the exception of the last algorithm, the ultimate result of these algorithms is lower indoor temperatures, ideally occurring when the occupants are away or don't have a preference. This scenario is illustrated in Figure 3. (Note that the assumed baseline is a constant indoor temperature.) Lower indoor temperatures correspond to reduced heating energy use (although there are a few exceptions where this relationship fails, such as with certain dual-fuel heating systems).

Figure 3: Graphical Depiction of Savings from Thermostat Setbacks



Source: Nest thermostat   nest.com

2.4 Approach

This project explored different formulations of a metric. No strict criteria were used to evaluate each formulation but they were generally assessed with respect to several requirements. The approach must be technically robust when applied to a single home and it must also be programmatically robust in that the metric can be easily applied to thousands of homes. Four approaches were considered:

- Energy savings indicated by utility meter
- Calibrated simulations
- Furnace run-time
- Savings degree-hours

Brief assessments of the first two approaches, utility meter and simulations, are presented because they have been evaluated (to some extent) elsewhere. More detailed assessments of furnace run-time and savings degree-hours are presented here because they are new.

2.5 Energy Savings Indicated by Utility Meter

The ultimate goal of the networked thermostat is to save energy. Thus, it is reasonable to establish a metric directly based on energy savings. Unfortunately, several obstacles make this approach inappropriate for widespread use. These obstacles are described below.

The scenario envisioned for metering energy savings involves several steps:

1. Identify the home and measure the home's gas use and thermostat settings for one heating season (or less);
2. Install networked thermostat and continue measurements;
3. Normalize energy use for differences in weather and operating conditions (such as temperature settings); and
4. Calculate the energy savings attributed to the networked thermostat.

The metric is energy savings, which might be therms/year or MBtu (thousand British thermal units)/year. This metric could be applied to the performance of a networked thermostat in a single home or, in the case of a program with many homes, a Randomized Control Trial (RCT).

This metric is attractive for many reasons. First, the metric reflects the stated goal of the networked thermostat, that is, to save energy. A high value corresponds to greater energy savings. The metric also accommodates all types of algorithms (driven by thermal models, occupancy, outdoor temperature, etc.) because it takes into account only the ultimate impact (energy savings). A consumer can easily estimate the cost-effectiveness of the service with this metric.

A variant of this metric would be percent reduction in space heating use. Expressing the metric in terms of percent reduction in space heating would make the results more widely applicable with respect to home size and climate.

From the perspective of evaluating savings, a drawback of this approach is that the uncertainty in the normalizations (typically around 10 percent) may be as large as the anticipated energy savings (often less than 10 percent). The uncertainties are likely to increase when shorter monitoring periods are selected.

The metered savings metric is attractive and possibly the most convincing, but the procedure has numerous practical problems that make it unattractive for routine testing. These include:

- lack of access to utility data for programs
- no pre-retrofit year
- may need a second control group
- long evaluation period
- high cost of evaluation

These kinds of evaluations are only realistically feasible through cooperation with the utilities serving those homes. A metric based on metered energy savings may be useful for a one-off evaluation for programs and larger assessments of network thermostats rather than frequent quantification of different providers' algorithms and their updates.

2.6 Calibrated Simulations

Another metric for measuring the effectiveness of different algorithms could be based on calibrated simulations. This technique was proposed by Urban and Roth (2014) in a proprietary study for Nest. The metric is a form of energy savings, though simulated.

The thermostat setpoint history of each home is collected for a year (or other suitable time period). This information is then entered into a simulation model for a prototype home and simulated for an average year. The output from the simulation is the predicted space heating energy consumption under specified conditions. The metric can be obtained by simulating the house a second time, but with standard thermostat setpoints. The difference in energy consumption between the two simulations is the metric of energy savings.

The simulations can be further customized if additional characteristics of the home are known. For example, the prototype can be adjusted to reflect actual floor area (or even the actual floor plan and building design), furnace characteristics, and internal loads.

This approach is attractive because the resulting metric is energy savings. One drawback is that it requires two simulations for each home. Nowadays, this requirement is computationally feasible; indeed, most thermostat providers already apply considerable computation time to each home in order to extract coefficients for their algorithms. A second possible drawback is that average local weather data for each home must be obtained to simulate its energy use. This is not essential, though, because standard locations could be used.

The simulation also inserts an extra layer of complexity, making tracing the actual impacts more complicated. This uncertainty could be minimized if all thermostat providers applied the same simulation tool; however, this may be difficult to monitor. In the end, there remains an uncertainty caused by simulations and the issue that the outcomes are not physically linked to real homes.

A final drawback of simulations is their ability to capture situations where the algorithms draw upon more "exotic" sources of information (security system status, geolocation data, etc.) to modify temperatures and equipment operation? These aspects cannot be easily included in a simulation. More field investigations are needed to verify the robustness of the calibrated simulation approach.

2.7 Furnace Run-Time as a Proxy for Energy Savings

Several networked thermostat providers estimate energy savings by examining the elapsed time of furnace operation. Furnace run-time is an intuitively attractive metric for evaluating energy savings because a reduction in run-time corresponds directly to reduced energy use. The actual fuel use can be calculated if the furnace's capacity (input rating) is known.

$$fuel\ use = RT\ x\ furnace\ capacity$$

$where,$

$RT = furnace\ runtime$

The furnace run-time depends on the thermostat's usability, climate, thermal characteristics of the home, and the furnace's capacity relative to the heating load. The energy savings corresponds (approximately) to the difference in run-times.

$energy\ savings = furnace\ capacity\ x\ (RT_{initial} - RT_{CT})$

$where,$

$RT_{initial} = furnace\ run\ time\ prior\ to\ intervention$

$RT_{CT} = furnace\ run\ time\ with connected\ thermostat$

This approach would be nearly ideal because it links thermostat usability directly to reductions in energy consumption and costs.

This approach has three major drawbacks:

- Energy consumption does not necessarily scale with equipment operating time

- Networked thermostat providers do not know the furnace (or AC) input capacities in the homes they serve
- Networked thermostat providers do not have operating data for pre-installation conditions

The first drawback deals with the metric, while the other two are programmatic.

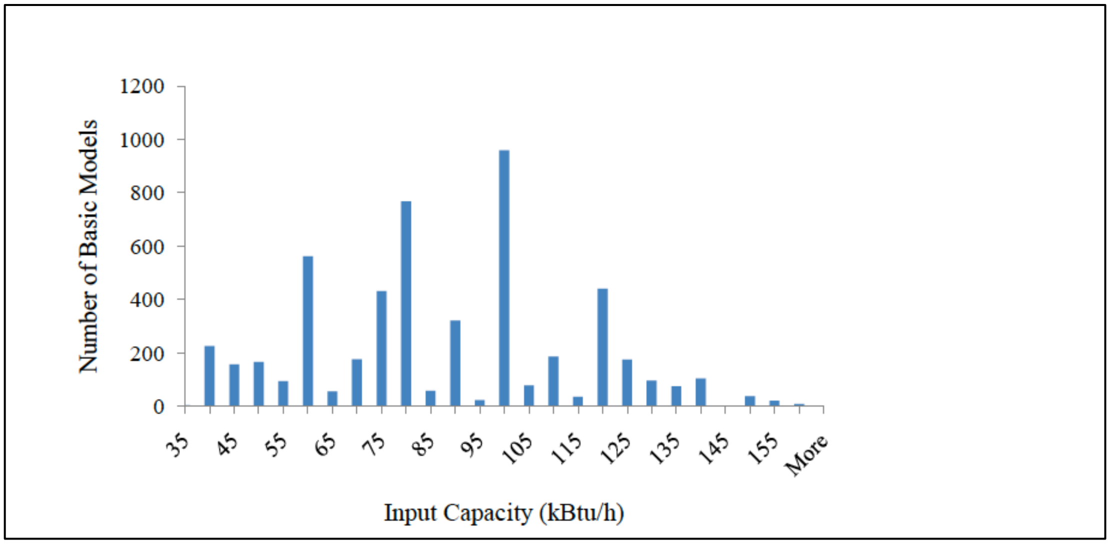
Energy consumption does not scale with equipment operating time. An increasing fraction of heating and cooling systems operate in several modes. For example, gas furnaces have two stages and heat pumps have resistance heating modes. Variable-speed compressors will become more common in ACs and heat pumps (they already have nearly 100 percent saturation in Japan). For fuel-fired heating equipment, operating time does not include electricity consumed by fans and controls. As a result, the simple relationship between equipment operating time and energy consumption will fail. Suppliers of networked thermostats acknowledge these problems and admit that they are still investigating solutions.

The non-linear scaling effects are likely to be modest for small changes in operation. When a furnace operates 5 percent fewer hours, for example, the reduction in energy use is also likely to be very close to 5 percent. However, larger run-time changes may not correlate so closely to energy use.

Networked thermostat providers do not know the furnace input capacities. The lack of information about furnace capacities means that they cannot convert furnace run-time into energy consumption. This problem could be solved if the networked thermostat providers surveyed a representative sample of their customers and obtained furnace and AC capacity data.

Alternatively, networked thermostat providers could use an arbitrary furnace capacity based on California assumptions. Many different sources of data would be suitable; for example, a DOE study surveyed the capacities of gas furnaces in homes. In the figure below, the most common input capacity is 100 kBtu/hour. A similar survey may be available for California homes.

Figure 4: Distribution of Gas Furnace Models by Input Capacity



Source: U.S. Department of Energy (2011).

Many of the uncertainties associated with varying capacity and efficiency still apply in both approaches. Various assumptions regarding fuels and auxiliary use could be applied, but the resulting factor, converting run-time to energy consumption, would be close to arbitrary.

Networked thermostat providers do not have comparable equipment run-times for pre-installation conditions. An estimate of energy savings requires equipment run-times before the installation of the networked thermostats. There is no obvious control or reference case from which to estimate energy savings.

A hypothetical reference run-time could be constructed for each home. The reference case would require an assumption for the home's temperature settings and an algorithm to convert temperature into run-time. One service provider, Ecobee, generates a "before" condition by estimating a home's furnace run-time based on thermal parameters observed after the networked thermostat is already installed and operating. Ecobee derives these thermal parameters by curve-fitting the relationship between average daily indoor-outdoor temperature difference and furnace run-time (and perhaps some other factors). Ecobee uses this relationship to extrapolate the run-time for operation at a hypothetical 72 degrees Fahrenheit set point (the "before" condition). Ecobee then sidesteps the uncertainties in translating equipment run-time into energy consumption by calculating a percentage reduction in furnace operation. Ecobee claims that the percentage reduction in furnace run-time corresponds to percentage savings in energy.

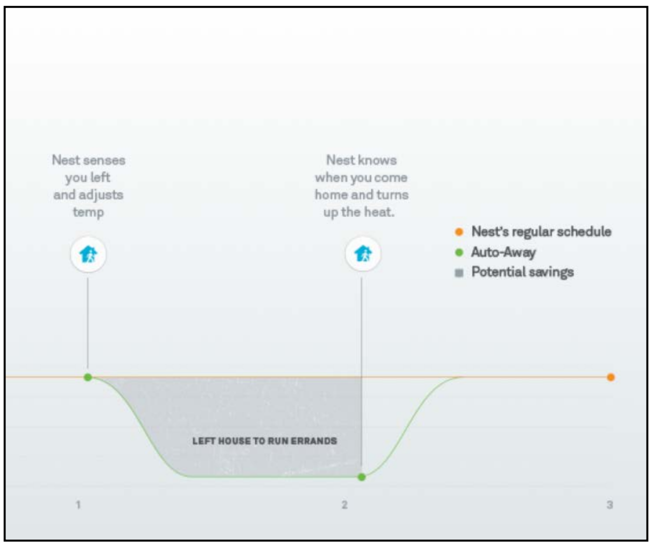
Ecobee's approach relies on a proprietary formula for inferring furnace run-time at the 72 degrees Fahrenheit reference temperature. Other networked thermostat providers use a similar curve-fitting approach but apply different assumptions about time steps, heat loss, thermal mass and internal loads for this inference—the algorithms are their "secret sauce." The different proprietary conversion formulas create a kind of black-box in the conversion of measured indoor temperatures into furnace run-time.

In summary, a usability metric based on reduced furnace run-time is feasible. However, it requires many assumptions or obtaining data that may be expensive, time-consuming, and unreliable.

2.8 Savings Degree-Hours as a Metric

The principal strategy for reducing a home's space heating consumption is to lower the thermostat setting. Any combination of usability enhancements and intelligent algorithms that a networked thermostat can apply to lower the indoor temperature while keeping the occupants thermally satisfied is a success and should contribute to the networked thermostat's overall effectiveness. This includes taking into account a building's thermal mass and outside temperature to lower or raise settings in advance of when the temperatures are actually desired. If the networked thermostat has an occupancy sensor, it might squeeze further temperature reductions by prematurely switching down settings when no occupancy is sensed (Figure 5).

Figure 5: Additional Energy Savings From a Connected Thermostat



Source: nest.com

Other examples are shown in Figure 5. The more tricks the better. One metric of a networked thermostat's overall effectiveness is the cumulative extent to which a networked thermostat lowers a temperature beyond what the occupant would have set, taking into account the number of hours and the number of degrees below the occupants' original setting.

The drawback of comparing the networked thermostat's settings to the occupants' is that there is no information about what the occupants' settings would have been. In other words, we lack a control for that home.

Fortunately, an absolute reference temperature can serve as the control. The reference temperature could be a single temperature (Ecobee uses 72 degrees Fahrenheit) or a thermostat schedule that includes night setbacks. The cumulative deviation of each house from the reference temperature, measured in degree-hours, would be the metric of a networked thermostat's success in wringing out savings through more intelligent control.

Thus the metric "savings degree-hours" (SDH) would be:

$$Savings\ degree\cdot hours, SDH = \sum_{all\ heating\ hours}^{winter} (T_{ref} - T_{obs})$$

$$T_{ref} = reference\ thermostat\ setting$$

$$T_{obs} = observed\ thermostat\ setting$$

Writers of algorithms would seek to maximize SDH by applying as much intelligence as possible into the device, using enhanced user interfaces, feedback, and exploiting external information. They are constrained by the occupants; if the occupants aren't comfortable, they will raise the temperatures. It is worthwhile working through examples of situations to understand the impact of different strategies and effectiveness of networked thermostats.

To include cooling, a second reference temperature would be necessary (say 72 degrees Fahrenheit). It's also necessary to reverse the temperatures to maintain positive savings degree-hours for successful thermostat management. Combining heating and cooling SDH gives:

$$SDH = \sum_{all\ heating\ hours}^{winter} (T_{ref} - T_{obs}) + \sum_{all\ cooling\ hours}^{summer} (T_{obs} - T_{ref})$$

Inserting the hypothetical reference values, the SDH would be:

$$SDH = \sum_{all\ heating\ hours}^{winter} (72 - T_{obs}) + \sum_{all\ cooling\ hours}^{summer} (T_{obs} - 72)$$

Additional Trefs may be used for daytime/nighttime conditions, but this may introduce new, unpredictable, dynamics.

The SDH metric will not always correlate with energy savings. Three examples illustrate situations where this may occur. A networked thermostat may achieve reduced HVAC energy use through more efficient operation (and not through lower temperatures). For example, in a gas furnace with two stages; the algorithm may select a staging plan that optimizes SDH rather than energy efficiency. In a second example with heat pumps, the algorithm may select the less-efficient resistance back-up heat in order to shorten recovery times and maximize SDHs. In the third example, a networked thermostat may recognize that outside air in summer is cool enough to replace AC compressor operation and circulate outside air. This strategy reduces energy consumption but leaves inside temperatures (and SDH) unchanged. Nest claims to use this strategy.

2.9 What is a Good SDH Score?

One advantage of the SDH is that the metric is a kind of score that can permit algorithms to be compared. What makes a "good" SDH score? This will depend on the choice of reference temperature. Nevertheless, it is possible to estimate typical SDHs with a few assumptions.

Assume that the reference temperature setpoint is 72 degrees Fahrenheit maintained for four months. An important strategy for saving energy will be a night setback. If the setback is to 65 degrees Fahrenheit for 8 hours, 120 days per year, we can easily estimate SDH for heating conditions.

$$SDH = 120\ days\ x\ 6\ \hbar ours\ x\ (72 - 65) = \ 5040\ savings\ degree\ \hbar ours$$

So, SDHs will be on the order of 5000 degree-hours. These suppositions need to be confirmed with field data.

CHAPTER 3: Conclusions and Recommendations for Further Research

In this project, researcher addressed a new type of energy-saving technology: a service to manage residential thermostats delivered through the Internet. This service is a collection of data-driven algorithms that manage the thermostat, generally lowering the temperature when people are away or don't have a preference. The service is important because this approach has obtained space heating reductions as large as 20 percent, which is more than many hardware-based technologies have achieved. Furthermore, the service has a very low cost of delivery--and the marginal cost is nearly zero--so it is potentially extremely cost-effective. Consumer uptake of the technology is likely to be driven mostly on the AC end, either by utility demand response programs or the consumer desire to avoid summer bill shock.

Yet, no recognized procedure exists for measuring the effectiveness of the algorithms. The policy question is, how should utilities, Energy Star, California Energy Commission Title 24 code officials, and other stakeholders identify services that save more energy than others?

This research explored the ways that algorithms can be used to save energy and the information required to drive those algorithms. Algorithms that manage the thermostat have the opportunity to reduce natural gas use in a number of specific ways, all but one of which involves lowering the indoor temperature. The sources of information include occupancy sensors, security systems, outside temperatures, and mobile telephone geolocational services. Service providers use different sources of information to inform the algorithms, depending on business model and technological sophistication.

Researchers identified (and in one case created) several approaches to assess the effectiveness of algorithms, that is, a metric. The "Gold standard" is observed metered savings. The observed savings are especially credible but the requirement of long monitoring periods (and collection of ancillary data) make the approach more suitable for periodic program-wide verifications but unrealistic as a metric. Simulations of energy use in prototype homes driven by data provided by thermostats offer standardized results. This approach is attractive in terms of standardizing energy savings but the results are not connected to actual savings in real homes. Furnace run-time is an excellent first-order estimate of energy use and the difference in run-time is an excellent indicator of savings. Unfortunately, it is difficult to translate changes in run-time into actual energy savings and to compare results across homes. Furthermore, the increasing popularity of multi-speed systems undermines the definition of run-time.

Savings-Degree Hours captures the reductions in indoor temperature achieved by more careful management of the thermostat. It is attractive because it provides a simple number. It also uses a fixed reference setpoint from which to measure savings, so no measurement prior to installation of the service is required. This dramatically shortens the monitoring period. The SDH suffers from drawbacks too, in the same way that heating degree-days has limitations. The

SDH probably does not change in a predictable way with the choice of reference temperature. It does not take humidity or sunlight into account.

3.1 Recommendations for Future Work

Future work should focus on testing different metrics on real data collected by actual networked thermostats. The goal is to test metrics on thousands of different homes. In this way, weaknesses of the metrics can be identified, especially if ancillary data is made available. The ancillary data would include location, home size, age, heating system type, and so on. Ideally, the thermostat data would be supplemented with metered data from the utilities or obtained via furnace submetering.

Some of the research questions are:

- What is the ideal reference temperature?
- Does the metric perform differently in especially mild climates or efficient homes?
- When does the heating season begin?
- How should results from one climate to be compared with another?
- How should impact of behavioral feedback be treated?

Obtaining data is extremely difficult owing to restrictions imposed by the thermostat service providers who are understandably concerned about potentially divulging aspects of their proprietary algorithms. There are also privacy concerns.

The providers of networked thermostats have generally supported attempts by Energy Star and other entities to develop evaluation procedures for their products. The challenge, however, is to create a metric that is technically fair and economically feasible to apply. If successful, there is a strong likelihood that the metric will be quickly adopted.

GLOSSARY

Term	**Definition**
AC	Air conditioning
ACEEE	American Council for an Energy-Efficient Economy
EPRI	Electric Power Research Institute
EPA	Environmental Protection Agency
HVAC	Heating, ventilation and air conditioning
MBtu	Thousand British Thermal Units
RCT	Randomized Control Trial
SaaS	Software as a Service
SDH	Savings degree-hours
TBtu	Trillion British Thermal Units

REFERENCES

Bouchelle, Matthew P., Danny S. Parker, and Michael T. Anello. 2000. "Factors Influencing Space Heat and Heat Pump Efficiency from a Large-Scale Residential Monitoring Study." In *Proceedings of the 2000 ACEEE Summer Study on Energy Efficiency in Buildings*. Pacific Grove (Calif.): American Council for An Energy-Efficient Economy.

Cross, D., and D. Judd. 1997. "Automatic Setback Thermostats: Measure Persistence and Customer Behavior." *In Proceedings of the International Energy Program Evaluation Conference*. Chicago: IEPEC.

Department of Energy. 2011. *Technical Support Document: Energy Efficiency Program for Consumer Products: Residential Central Air Conditioners, Heat Pumps, and Furnaces.* 2011-06-06. Washington: U.S. Department of Energy. http://www.regulations.gov/#!documentDetail;D=EERE-2011-BT-STD-0011-0012.

Haiad, Carlos, John Peterson, Paul Reeves, and John Hirsch. 2004. *Programmable Thermostats Installed into Residential Buildings: Predicting Energy Savings Using Occupant Behavior & Simulation.* 954. Rosemead: Southern California Edison.

Kema, Inc. 2010. 2009 *California Residential Appliance Saturation Study*. CEC- 200-2010-004-ES. Sacramento: California Energy Commission.

Meier, Alan, Cecilia Aragon, Therese Peffer, Daniel Perry, and Marco Pritoni. 2011. "Usability of Residential Thermostats: Preliminary Investigations." *Building and Environment* 46 (10): 1891–98. doi:10.1016/j.buildenv.2011.03.009.

Nevius, MJ, and S Pigg. 2000. "Programmable Thermostats That Go Berserk: Taking a Social Perspective on Space Heating in Wisconsin." In *Proceedings of the 2000 ACEEE Summer Study on Energy Efficiency in Buildings,* 8.233–38.244. Pacific Grove (Calif.). http://72.36.212.11/prod/berserk.pdf.

Peffer, Therese, Marco Pritoni, Alan Meier, Cecilia Aragon, and Daniel Perry. 2011. "How People Use Thermostats in Homes: A Review." *Building and Environment* 46 (12): 2529–41. doi:16/j.buildenv.2011.06.002.

Shipworth, Michelle, Steven K. Firth, Michael I. Gentry, Andrew J. Wright, David T. Shipworth, and Kevin J. Lomas. 2010. "Central Heating Thermostat Settings and Timing: Building Demographics." *Building Research & Information* 38 (1): 50–69.

Urban, Bryan, and Kurth W. Roth. 2014. *A Data-Driven Framework For Comparing Residential Thermostat Energy Performance.* Cambridge (MA): Fraunhofer Center for Sustainable Energy Systems.