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A Tale of Two Houses: The Human Dimension of Demand Response Enabling Technology from a Case Study of an Adaptive Wireless Thermostat

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ABSTRACT

Demand response—the management of customer electricity demand in response to supply—has emerged as a promising means of increasing grid reliability by reducing peak demand. One potential technology to enable residential Demand Response (DR) is a Programmable Communicating Thermostat (PCT) that receives price signals from the electrical utility. However, several issues preclude the widespread adoption of this technology and policy. One is the poor adoption and energy-conserving performance of a similar technology and policy—the programmable setback thermostat. Another is lukewarm customer response to residential DR air conditioning cycling programs. Finally, financial incentive alone may not suffice to persistently reduce peak electricity consumption.

A team at UC Berkeley developed an alternative model for a residential demand response enabling technology, called the Demand Response Electrical Appliance Manager (DREAM). The DREAM system acts as both an intelligent thermostat and in-home energy display. DREAM consists of a wireless network of data sensors, appliance actuators and a central controller that can communicate variable price signals. We tested the DREAM in two houses in the summer of 2007 for six weeks. The DREAM controlled the HVAC system, monitored electricity from appliances, sensed temperature and occupancy, and displayed temperature and energy consumption. This paper discusses potential issues for DR policy and technology, and describes potential solutions in improving user adoption.

Background

Over the past 30 years, technology and policy have enjoyed a push-pull role in achieving California's energy efficiency goals. With appliance standards, policy drove technological design towards better efficiency. With household HVAC control, the technology preceded the policy: clock setback thermostats developed in 1960 became a requirement of California's first energy code in 1978. Policy drove further development: digital Programmable Thermostats essentially replaced clock setback thermostats in the mid 1980s. With the proposed policy to require Progammable Communicating Thermostats (PCTs)[1], which add communication ability, the policy will drive the design and the technology will in fact enable the policy.

Lessons Learned from the Programmable Thermostat (PT)

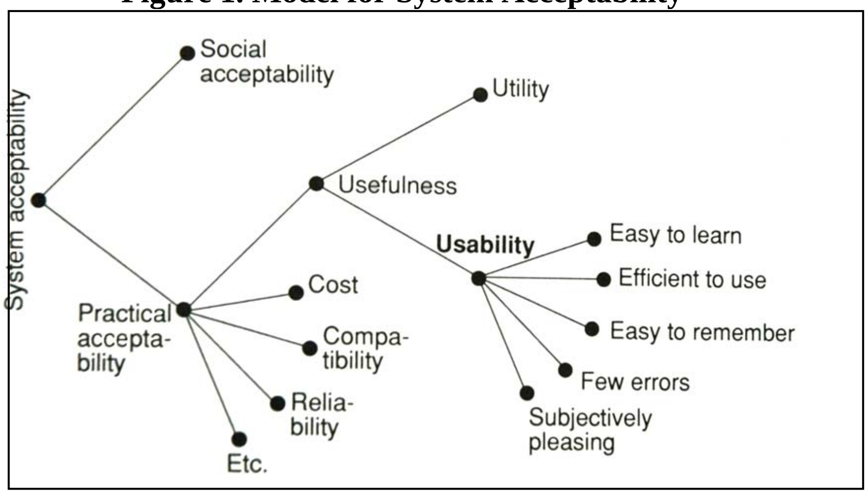
One role of energy efficiency policy is to speed the adoption of cost-effective technology through incentives or other measures. However, while the setback and now Programmable Thermostat (PT) has been available for over 30 years, it has not been widely adopted beyond the

[1] While in January 2008, the proposed inclusion of PCTs in California's 2008 Title 24 residential energy code was removed, the California Energy Commission continues to strongly support demand response and PCT technology.

code requirement (CEC 2004; US Census 2000), programming features are used by perhaps only half to two-thirds of the users (Archacki 2003, CEC 2004), and the thermostat doesn't necessarily save energy (Shiller 2006). The 2003 Residence Appliance Saturation Survey (RASS) found that about half (54%) of all California dwellings have programmable setback thermostats (CEC 2004). This suggests that only about a third of pre-1978 housing units (which represents two-thirds of the housing stock) have programmable thermostats, and a proportion of these would have been required as part of renovations. A study by Carrier indicated that about 35% of the thermostats in houses in the jurisdiction of two California utilities were in "hold" mode. This overrides the programming features and turns the thermostat into a manual thermostat (Archacki 2003). Several studies have suggested a programmable thermostat does not save energy, but behavior is a better indicator of energy savings (Haiad et al. 2004; Shiller 2006).

Many hypotheses exist as to why the PT has not been adopted nor used in the manner it was designed. A useful model for studying the acceptance of technology (Figure 1) was developed by Nielsen to evaluate website design, and will frame the following discussion.

Figure 1. Model for System Acceptability



(Nielsen 1993)

One issue often quoted by installers is *usability*. Some programmable thermostats come with 100+ page manuals, and are not easy to learn or remember how to program. In addition, PTs may not be subjectively pleasing to use; the typical colorless digital LCD in a white plastic box is not very attractive. In a recent study of a similar device, an in-home energy display, one participant considered the device "an eyesore" (Parker, Hoak, and Cummings 2008).

Utility relates to functionality—does it do what its users need? One potential *utility* issue is the fixed schedule provided by the PT. The typical PT does not allow much flexibility in scheduling: only two time periods and two temperature choices per day. Many studies describe patterns of thermostat use. Lutz et al (Lutzenhiser 1993) reported that half of those people who control their heating system manually produce load shapes that are so regular that they are indistinguishable from those produced by automatic operation. Weihl & Gladhart (as reported in Lutzenhiser 1993) proposed six distinct patterns of thermostat control: night setback, flat, erratic, morning setup, day setback, dual setback, and found that once a pattern is set, it remains remarkably stable. However, another study, Bernard et al (in Lutzenhiser 1993), describes three types of household energy use: consumption when the building is unoccupied, habitual consumption from routine behavior, and daily variation consumption from events like holidays, a sick child or visitor. The non-routine events showed a significant impact on consumption. These studies indicate that a fixed schedule may work for some, but certainly not all people.

Another issue of *utility* is seasonal thermal comfort: static temperature settings provided by a PT may not provide comfort year-round. All PTs with the EnergyStar[2] label have static default temperature settings for heating (70F (21.1C) and 62F (16.7C) for away and night setback) and cooling (78F (25.6C) and 85F (29.4C) for away setup, 82F (27.8C) for night setup) (EPA). Yet in two studies, one with manual thermostat control and the other with a programmable thermostat, people changed the thermostat settings seasonally (Kempton and Krabacher 1987; Woods 2006). One study revealed that even among a similar population, a wide range of temperatures was considered comfortable (Hackett and McBride 2001). From commercial sector studies, people in naturally ventilated offices can withstand a wider temperature range than air conditioned offices (de Dear and Brager 1998). Since houses are by law naturally ventilated,[3] the Adaptive Comfort Standard (ACS), described in ASHRAE Standard 55-2004 (ASHRAE 2004) for naturally ventilated buildings, may be most appropriate for defining comfort in residential buildings (Ubbelohde, Loisos, and McBride 2003; Lovins 1992). This standard allows the indoor temperature to change seasonally, allowing warmer temperatures in summer and cooler ones in winter. However, people who are used to air conditioned homes historically and have air conditioning at work may prefer the more narrow temperature range found in offices (Cooper 1998; Ubbelohde, Loisos, and McBride 2003). These studies suggest that PTs may work for some people, yet for others, the current PTs are not flexible enough to emulate their behavior.

A related issue of *utility* is daily thermal comfort and expected energy savings. The default temperature setpoints mentioned previously do not necessarily reflect how people actually set their thermostat. A study in California found that these setpoints overestimate the cooling setpoint and underestimate the heating setpoint (Woods 2006). Similarly, the nighttime setup/setback default does not reflect comfortable temperatures found in lab studies (Tsuzuki et al. 2005; Muzer, Libert, and Candas 1984; Schmidt-Kessen and Kendel 1973). Yet these default temperatures found in programmable thermostats are used to determine energy savings in Title-24 compliance software programs (Woods 2006). One reason PTs do not necessarily save energy might be because the default "energy-saving" settings do not provide comfortable temperatures.

Nielsen's diagram links *utility* with *usability* to describe *usefulness*. While some technologies such as cell phones also have an initial learning curve, apparently for many the benefits of the PT do not outweigh the time and energy to learn how to use it.

Existing Residential Demand Response (DR) Programs

Utilities have been implementing residential Demand Response (DR) programs across the U.S. for the past 20 years. The programs are mostly voluntary and have not grown substantially over time. A review of residential demand response programs in late 2006 revealed that 80% employ direct load control for air conditioning cycling[4] (Rosenstock 2005). One reason that these programs haven't seen wider acceptance relates to control, arguably a *social acceptability*[5] issue.

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[2] The EPA is considering withdrawing EnergyStar labels from PTs since they have not proven to save energy.
[3] Uniform Building Code 1203.3 requires all habitable rooms have operable windows equal to 5% floor area.
[4] The utility has a device on the customer's air conditioner compressor to turn it off during peak demand periods.
[5] *Social acceptance* in Nielsen's model includes both personal (psychological) and social (sociological) issues.

Residents tend to prefer voluntary to restrictive programs (Blanc 2006; Haiad 2006). Even when the customer volunteers for the program, they often opt out or override the system. "Every time an event occurs, we get 10,000 calls from 150,000 customers wanting to get out of the program" (Haiad 2006). Several studies suggest that personal control highly influences thermal comfort and satisfaction. A study conducted by Wyon et al as reported in (Markus and Morris 1980) showed that subjects that were free to adjust temperature swings accepted much greater swings than that acceptable by ASHRAE Standard 55. In an office study, people with a higher degree of control (proximity to window) were comfortable at warmer temperatures than people with less control (Brager, Paliaga, and de Dear 2004).

Incentives and Motivation Beyond Price

Incentives encourage both *social* and *practical acceptability* of a technology and policy. With the PCT, a high electricity price is the primary motivator to reduce peak consumption—the California Statewide Pricing Pilot (SPP) showed positive results using price to reduce peak electrical demand. Yet price may not be the most effective motivator nor be persistent over time: one variable rate pilot showed that sometimes even high energy prices were readily accepted by consumers (Lutzenhiser 1993). Price elasticity has its limits; the SPP showed no significant difference in energy use curtailment between a $0.68 and a $0.50 critical peak price (Herter 2006). However, incentives to increase participation in demand response programs have been effective. After the first year of the SPP, when asked if they would continue with the program, 77% of the participants responded that they would, but when the initial incentive was removed, only 50% actually continued (Herter 2006). A GoodWatts program survey showed similar results: 20% would definitely continue if they had to pay $5 per month, but 52% would continue if the program were free (Boice 2005).

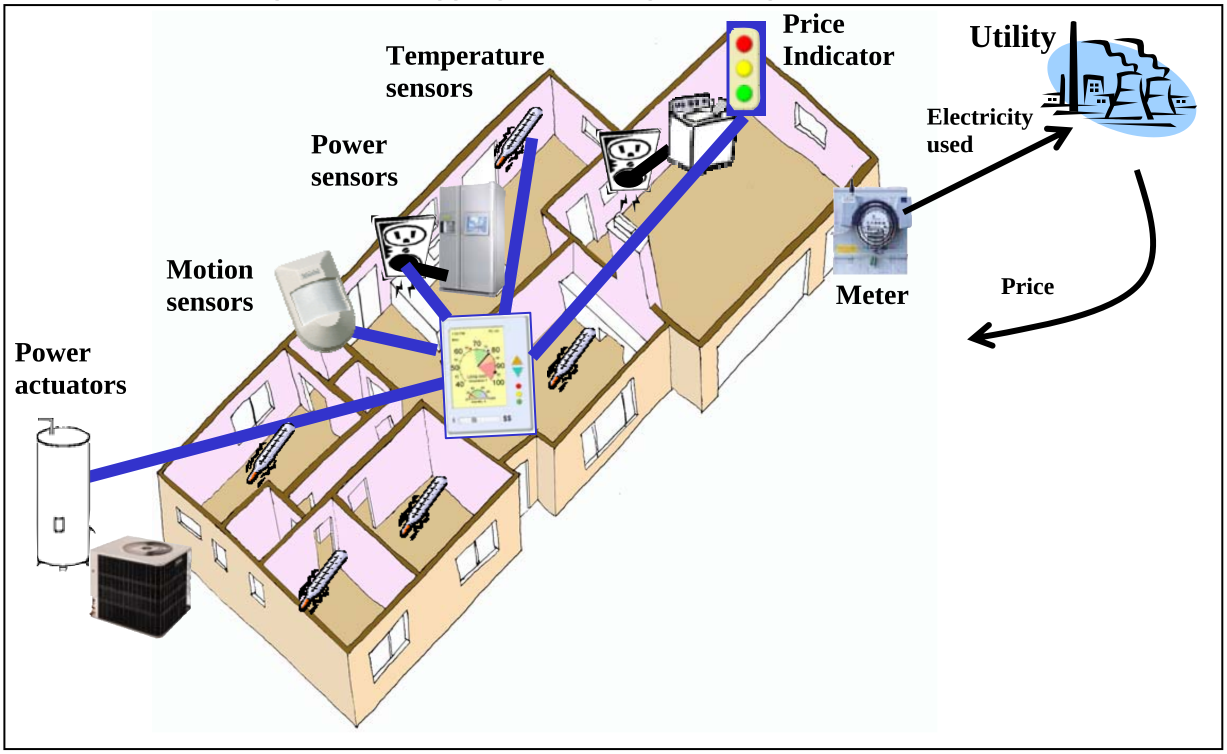
Other means of motivation, such as education, feedback, and social norms, may prove to be more effective than financial incentives alone. With the PT, education has been shown to increase energy savings (Jennings et al. 1995) and shows promise for the PCT as well (Momentum Market Intelligence 2003). A comprehensive review of in-home energy displays found that customers reduce energy consumption 4-15% in response to direct energy feedback (Stein 2004). A recent study, however, showed that some people increased their energy consumption with these displays, suggesting that feedback alone may not suffice (Parker, Hoak, and Cummings 2008). A study with California residents demonstrated that seeing the comparison of one's energy consumption with one's neighbors was effective in reducing consumption (Schultz et al. 2007). One study showed that the effect of peers is more effective than incentives such as saving money, conserving resources, or being socially conscious (Nolan et al. under review).

Research Design

The goal of our research in developing a demand responsive thermostat was to address the limitations of programmable thermostats, let people retain control, and to explore motivation in reducing peak electrical demand. In this process, we explored the application of learning tools.

Over the past five years, a team from UC Berkeley developed and tested the Demand Response Electrical Appliance Manager (DREAM). This system employs a network of wireless communicating sensors and actuators with a central controller that can receive price signals from the utility. See Figure 2 below. The distributed sensors allow an information-rich system for a smart controller to optimize thermal comfort and cost. This controller can also adapt to a specific house and its HVAC equipment (see Chen et al. 2008). Another algorithm adjusts the temperature setpoints seasonally and over the course of a day in response to outdoor temperature. DREAM provides price and real-time energy consumption information to people to allow them to make informed choices regarding energy consumption, especially during peak periods.

Figure 2. Disaggregated Energy Manager--The DREAM



A hypothesis underlying the design is that if a thermostat can work well right out of the box, then it is more likely to be adopted or accepted. We explored the feasibility of intelligence: through motion sensors and simple input from people, the system could "learn" their schedule and temperature preferences, which might relieve programming issues. Similarly, DREAM could "learn" the house and HVAC system, and optimize the controller for energy-saving performance.

Another research question was, can a thermostat provide thermal comfort and save energy during peak periods? The proposed default for the PCT is to increase the temperature setpoint 4F (2.2C) in response to a price signal from the utility. Simulation results from using adaptive temperature setpoints indicated energy savings potential. We explored optimization of cost/comfort using adaptive setpoints and learning the house/HVAC system.

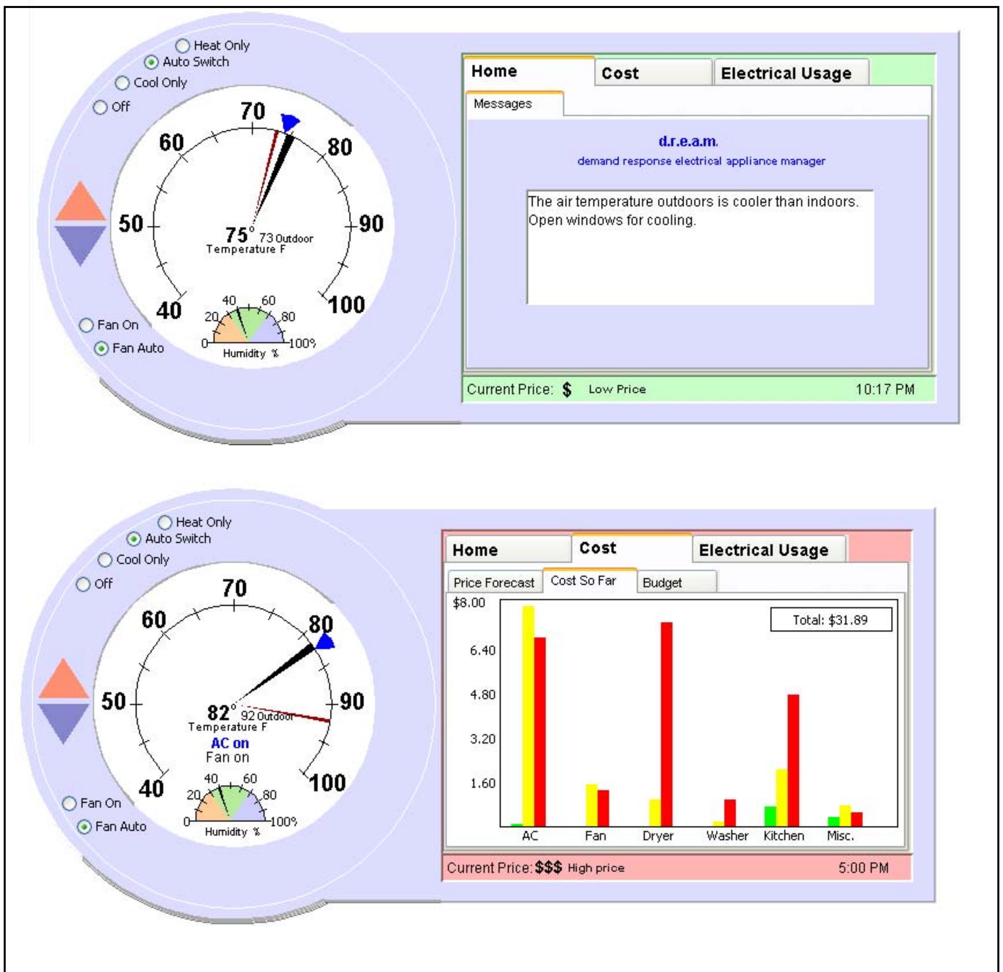
Regarding the issue of *social acceptability*, the DREAM was designed to both empower the resident with information and to use feedback as an intrinsic motivator. The energy usage feedback in DREAM allows people choices (i.e., turn down the air conditioner or use the clothes dryer at a different time). They can directly see the effects of their decisions. Another choice is the cost/comfort index, where people can select their level of comfort during high price periods.

User Interface

The basic user interface design (Figure 3 top) was developed, prototyped, and tested in a UC Berkeley course in the School of Information Management & Systems in Spring 2005 (Peffer et al. 2005). The design was then implemented in Java and further developed. The left of the interface was modeled after the Honeywell Round thermostat; this aesthetic design is over 50 years old and fairly intuitive. Temperature, relative humidity, temperature setpoint, and status of the air conditioner and fan are displayed. The indoor and outdoor temperatures are displayed in an analog format for quick and easy readability, and to discourage a fixation on an exact number. Studies on residential thermal comfort indicate that comfortable temperatures span a wide range over the day and the season, and are not well represented by a static number. In initial tests, users were able to easily read this screen and perform simple functions without instruction.

The right side of the interface is designed as a touch-screen "file folder" display, where users can see messages, cost information, electrical usage, and program their schedule and preferred temperature settings. Under Messages, one might see an alert message sent by the utility or a helpful hint. Under Cost, one finds information such as the current and forecasted price of electricity, the total cost by appliance, and the current cost compared to the budget (Figure 3 bottom). Finally, under Electrical Usage are current instantaneous power consumption, energy used today, and energy used so far this billing period. The electrical usage is broken down by major appliance, such as air conditioning, dryer, washer, and kitchen appliances.

Figure 3. Java Implementation of DREAM Interface



Testing

Before the field test, we tested the DREAM controller and interface with an energy simulation tool. We also tested the controller and wireless network in the lab as well as a test house. Then we tested the DREAM system in two occupied houses during summer 2007 for six weeks. The purpose was to test the functions of the system, to verify simulation results, and to obtain feedback from participants. Our two volunteer single-family detached houses were located about 10 miles apart in a climate similar to Sacramento, but the house, HVAC system and residents' schedules were different. The participants were interviewed before and after the tests.

Fourteen "motes"—small microprocessors with radio transmitters—were installed in each house (Figure 4 left). Attached sensors measured temperature, motion, relative humidity, and current from the air conditioner, fan, clothes washer and dryer, and dishwasher. We used an ultra mobile PC—the Samsung Q1—to host both the controller and the interface (Figure 4 right).

Figure 4. Left: Example of Generic Mote Installation
Right: The DREAM Controller and Interface

House 1

One house is a 1700 square foot two-story stucco house built in 1991. Three ceiling fans are controlled manually in the living room, kitchen and master bedroom. The HVAC system is a Carrier split-system air conditioner/furnace, with supply grilles in the floor throughout the house. The owner replaced the original setback thermostat with a programmable thermostat.

Two people occupied the house: one male that works from home and leaves for business irregularly during the day and one teenage female who is there some of the time. A dog is inside most of the time. The participant reported that he normally keeps the thermostat set to 74F (23.3C) during day and night. When he leaves and remembers to offset the temperature, he sets the thermostat to 79F (26.1C). Participant opens up the windows (upstairs) at night and closes them during the day. The main electrical appliances are the clothes washer and dryer.

House 2

The other house is a 1500 square foot one-story house built in 1984. One ceiling fan continuously runs in the family room. The HVAC system is a General Electric split-system air conditioner/furnace, with supply grilles in the ceiling. The thermostat is the original manual setback thermostat. The house has two skylights in the roof and an attic fan.

Two people occupied the house, one male and one female who are normally away from the house during weekdays, but during a portion of the test were at home taking care of newborn puppies. The participant looked at weather forecast in deciding whether or not to use the air conditioning. Usually the setpoint during the day is 70F (21.1C) and turned off at night. If the weather is going to be hot, the setpoint is 68F (20C) and 70F (21.1C) at night. The participant opens up the house at night; two windows are open during the day as well.

Tests

We used several setpoints to determine HVAC cycle rate and thermal decay in the house, and tested the viability of precooling. We looked at the feasibility of learning algorithms for the occupant and the house. Other tests “tuned” the internal house model in the controller. We tested the optimization of cost and comfort using an economic index to allow the participant to choose sensitivity to price by a temperature offset. We transferred data to a server via the internet.

Results and Discussion

Replacing a household thermostat is no trivial matter, and we encountered a few problems throughout the test. Most problems involved minor issues with hardware, data transfer, and changing the controller through a remote link, and were resolved. In general the DREAM system successfully controlled the house’s HVAC system, allowed input by the occupants, and displayed energy consumption data in both houses throughout the six week test.

The weather cooperated as well: we captured the behavior of the house and HVAC system for warm days and very hot days. The outdoor daily high temperature ranged from 27 to 41C (80.6 to 105.8F). House 1 performed reasonably well under hot conditions, and responded well to precooling scenarios. House 2 however appeared to have an undersized HVAC unit, which could barely keep up on hot days, and was completely underpowered for very hot days. Precooling was not an option for this house.

Learning Schedules

We discovered it is easier to “learn” about a house than its occupants. The distributed temperature sensors allowed us to see the balance of the system in the house. With outdoor temperature and solar radiation data, we could distinguish patterns due to solar radiation and orientation versus the HVAC system.

People—both their schedule and behavior—are less predictable. We knew the people in House 1 had an irregular schedule since the participant ran a business from his home. He used the setback feature of the thermostat when he remembered as he left. But the people in House 2 who both had regular jobs showed a fairly irregular schedule as well, which precludes effective learning. They indicated that a setback feature would be useful, but didn’t know their thermostat already had a setback mechanism. They set their thermostat manually, according to the weather forecast. Since their air conditioner was undersized, if they didn’t start the air conditioner early in the day on very hot days, the house would not reach a comfortably cool temperature.

For variable schedules, occupancy sensors or timers might be effectively used to control the thermostat. Also, remote-control thermostats are now available and may appeal to the technically-savvy. We used a participant-actuated occupancy sensor to change the setpoint when the house was unoccupied; this worked well only when the occupant remembered to use it. For future tests, occupancy sensors other than motion sensors, such as carbon dioxide sensors, might improve performance. Other studies (Kempton, Feuermann, and McGarity 1992) have suggested having an on-timer, so people can turn on the air conditioner for a specified length of time. An off-timer might be helpful as well, to turn off the air conditioner when one runs an errand.

Thermal Comfort

One household set the thermostat to 74F (23.3C) and the other to 70F (21.1C), hoping to keep the house under 80F (26.7C). This indicates that setpoint offset may not be the best solution without information about the house. An air conditioning system may be over or undersized for the house, the house could have a lot of thermal mass and/or be well insulated and tightly sealed or not.

While offset in discomfort may be a more equitable measure, there is surprisingly little evidence on how to define thermal comfort in a home. Our tests and other field research indicate a large disparity in temperatures that are considered comfortable. The participant who worked at home and had grown up in a closed-house environment preferred a tight temperature range (71.6 to 78.8F (22 to 26C). The other household was tolerant of much higher temperatures (69.8 to 82.4F (21 to 28C); they have lived with an undersized air conditioner for 18 years.

Control and Motivation

One participant welcomed smart technology and recently volunteered for a utility-controlled load cycling DR program using a PCT; the other seemed more wary of technology and suggested he would go offgrid to avoid “offensive” electricity rates. The personal choice offered by the cost-comfort index requires further user testing; however, it successfully provided appropriate thermal comfort per price in these tests.

The participants were able to use the interface to control their system and appreciated having information about their electrical consumption. One participant suggested using a pie chart display and preferred cost information to energy consumption data. The other participant found the number of graphs a bit overwhelming. Other means of motivation besides energy consumption feedback and cost information are currently undergoing testing. The user interface can display carbon emissions diverted and allow the user to set energy conservation goals.

Diagnostics

While not part of our tests, we discovered that the system can also be used for diagnostics. Before the tests, the supply air temperature in house 1 was in the 60sF (15+C). After the refrigerant was charged, the temperature dropped to the 50sF (10+C). This information could be used to notify the occupant when the air conditioning system requires maintenance, and would save energy if fixed.

Conclusion

The field tests conducted in two houses provided a successful proof-of-concept for the DREAM system—a wireless thermostat plus in-home energy display system—to enable residential demand response. We endeavored to improve upon existing programmable thermostats and DR programs. DREAM includes a user-friendly interface that is information-rich to help people make decisions about their energy consumption. A person-defined cost-comfort index shows promise in providing control over one's cost and comfort. We also designed an intelligent controller that can optimize cost and comfort by learning about the house and HVAC system.

This study suggests that human behavior regarding programmable thermostats and demand response is multi-dimensional. Usability is not the only issue in the adoption of a demand-response enabled technology. Aesthetics, thermal comfort, schedule flexibility, personal choice and control, and motivation beyond price also play a role. We suggest a multi-dimensional solution incorporating several levels is in order. While some people may want to "set it and forget it", we expect that others may appreciate a broad preference indicator, and still others will prefer more specific input and feedback, or to adjust the setpoint directly. Much more research is needed in the following three areas. First, what do people want from their thermostats (i.e., functionality such as occupancy sensors, timers)? Secondly, what is the potential cost-comfort/convenience tradeoff of demand response for different people (i.e., need to explore residential thermal comfort)? Finally, what are other means of motivation to reduce household electricity usage (especially peak) besides price and feedback? Understanding the wide range of skills, knowledge, and values of people is vital in encouraging energy conservation at home.

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