Building the Case For Automated Building Energy Management

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Abstract

Energy consumption in buildings comprises a significant fraction of total worldwide energy consumption and is strongly influenced by occupant behavior. To explore the quantitative effect of particular occupant actions on building energy consumption, we have evaluated eight energy-saving behaviors, as well as the use of an in-home display (IHD), in 10 homes over the course of ten weeks. The results showed maximum savings ranging from 0%-20% attributed to the IHD, indicating that real-time feedback combined with actionable suggestions can motivate substantial conservation. By examining the data along with pre and post-experiment surveys, we conclude that automation is necessary to ease the more tedious tasks such as "unplug when not in use" and "unplug the TV," where fewer than half of the highly capable and motivated participants performed the actions.

Categories and Subject Descriptors

J.4 [**Social and Behavioral Sciences**]: Miscellaneous

1 Introduction

The U.S. Department of Energy (DOE) reports that buildings accounted for 39% of the total energy consumption in the U.S. in 2009 [17]. Because energy consumption is closely tied to occupant behavior, numerous building energy monitoring systems have been recently developed [1, 6, 7] that provide homeowners with real-time electrical consumption data to enable more informed energy use choices. However, it is clear that monitoring alone does not always result in savings. For example, one recent study observed an initial 31.9% reduction in energy consumption immediately after installing a monitoring system, but after a month the reduction fell to only 3.7% [8]. This suggests that while significant savings are possible, relying on occupants to change their long-term behavior may be difficult.

An automated building management system (BMS) may be used to reduce the energy impact of occupant behaviors so that operating a building in the most energy-efficient manner is convenient for the occupants. Integrated BMS systems are commonly found in commercial buildings but these systems are still an emerging technology in residential settings. The expected energy savings for a residential automated BMS has been estimated at $5 \sim 10\%$ [2, 3, 10]. However, these estimates are based on the assumption that all systems in the home are automated, a daunting task considering the many and varied end-uses in a typical residence. We believe that to achieve significant and *persistent* energy savings, an automated BMS combined with a judicious choice of control strategies is required.

In this paper we present findings from a ten-week field investigation of the efficacies of various energy-saving control strategies. Our goal is to explore a simple method for quantitatively evaluating potential control strategies in real homes to identify cost-effective automation algorithms. We monitored whole-house energy consumption while occupants manually implemented each energy-saving strategy. Although our sample size and duration were limited, our results indicate that a much larger study of this type is both feasible and likely to result in very useful findings.

2 Energy Saving Behaviors

There are numerous opportunities to save energy in residential buildings. Common strategies include increasing insulation, replacing old windows, and buying energy-efficient appliances. These approaches are effective (if costly), but do not consider simple changes that occupants can make in their energy-use behaviors, which can significantly impact consumption without making physical changes to the building. To explore how changing behaviors can reduce energy consumption we consulted the recommendations made by the Natural Resources Defense Council (NRDC) to reduce household energy consumption [9]. To assess the quantitative impact on energy consumption of adopting some or all of these recommendations, we slightly modified the NRDC

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Table 1. Suggestions for saving energy (adapted from NRDC recommendations [9])

Short name	Description
Unplug When Not In Use	Unplug seldom-used appliances, like an extra refrigerator in the basement or garage that contains just a few items. Unplug your chargers when you're not charging. Every house is full of little plastic power supplies to charge cell phones, PDA's, digital cameras, cordless tools and other personal gadgets. Keep them unplugged until you need them.
Unplug the TV	Use power strips to switch off televisions, home theater equipment, and stereos when you're not using them. Even when you think these products are off, together, their "standby" consumption can be equivalent to that of a 75 or 100 watt light bulb running continuously.
Set Computers to Sleep and Hibernate	Enable the "sleep mode" feature on your computer, allowing it to use less power during periods of inactivity Configure your computer to "hibernate" automatically after 30 minutes or so of inactivity.
Take Control of Temperature	Set your thermostat in winter to 68 degrees or less during the daytime, and 55 degrees before going to sleep (or when you're away for the day). During the summer, set your thermostat to 78 degrees or more. Set the thermostat on your water heater between 120 and 130 degrees.
Use Sunlight	Use sunlight wisely. During the heating season, leave shades and blinds open on sunny days, but close them at night to reduce the amount of heat lost through windows. Close shades and blinds during the summer or when the air conditioner is in use or will be in use later in the day.
Tweak your Refrigerator	Set your refrigerator temperature at 38 to 42 degrees Fahrenheit; your freezer should be set between 0 and 5 degrees Fahrenheit. Use the "power-save" switch if your fridge has one, and make sure the door seals tightly.
Use Appliances Efficiently	Don't preheat or "peek" inside the oven more than necessary. Check the seal on the oven door, and use a microwave oven for cooking or reheating small items. Wash only full loads in your dishwasher, using short cycles for all but the dirtiest dishes. This saves water and the energy used to pump and heat it. Air-drying, if you have the time, can also reduce energy use. In your clothes washer, set the appropriate water level for the size of the load; wash in cold water when practical, and always rinse in cold. Clean the lint filter in the dryer after each use. Dry heavy and light fabrics separately and don't add wet items to a load that's already partly dry. If available, use the moisture sensor setting. (A clothesline is the most energy-efficient clothes dryer of all!)
Turn Down the Lights	Don't forget to flick the switch when you leave a room. Use fewer lights. Just turn on the lights nearby instead of having all the lights on in a room. Use sunlight whenever possible.

suggestions to separate each recommendation into distinct actions, which are listed in Table 1. We used published data to estimate the effect of each behavior on whole-house energy use, then implemented each of these behaviors in 10 homes over 10 weeks while monitoring whole-house energy consumption. By statistically comparing energy consumption from week to week we estimate the energy savings due to each behavior.

2.1 Estimated Savings

Using data from the residential end-use consumption reported by the 2011 Buildings Energy Databook [11] as a guide (see Table 2), we first estimated the effect that each of the actions listed in Table 1 would have on whole-house energy use:

Unplug When Not In Use

This behavior aims to reduce waste primarily in the electronics end-use (4.7%). Because electronic devices vary widely in standby vs. active energy consumption the achievable savings would depend strongly on the particular suite of

Table 2. Residential site energy consumption [11]

End-use	Fraction of total
Space Heating	44.7%
Water Heating	16.4%
Space Cooling	9.2%
Lighting	5.9%
Electronics	4.7%
Refrigeration	3.9%
Cooking	3.7%
Wet Cleaning	3.3%
Computers	1.5%
Other[a]	3.2%
Adjust to SEDS[b]	3.6%

[a]Includes small electric devices, heating elements, motors, swimming pool heaters, hot tub heaters, outdoor grills, and natural gas outdoor lighting.

[b]Energy adjustment that U.S. Energy Information Administration (EIA) uses to relieve discrepancies between data sources. Refers to energy attributable to the residential buildings sector, but not directly to specific end-uses. SEDS is State Energy Data System.

electronics used in each home. At first glance it may be easy to dismiss this category, but consider that a hypothetical charger that consumes 10 W in active mode and 1 W in standby might be used 4 hours per day and left plugged in at all times. On a daily basis it would consume 40 Wh in active mode and 20 Wh in standby. The rational for this behavior now becomes more obvious as this conservative case yields a potential 33% savings. Devices with high standby power use or a low ratio of active to standby mode will have higher savings potentials. To account for the many devices that do not have distinct on/standby modes and must stay plugged in (such as alarm clocks) we multiply by a factor of 0.5. A rough savings estimate is thus $0.5 \times 33\% \times 4.7\% = 0.8\%$.

Unplug the TV

This behavior is a special case of "Unplug When Not In Use." We address this action separately because this end-use has been well studied (e.g., [12]) and thus energy savings may be more reliably estimated. A "typical" TV uses 97 W and 4 W in active and standby modes, respectively. (To qualify for Energy Star televisions must consume less than 1 W in standby mode but the above numbers reflect weighted means of all types and screen sizes currently found in U.S. households.) Annual usage for a television is 1860 hours in active mode and 6900 hours in off mode. Combining these values, we get an annual on-mode consumption of $97\ \text{W} \times 1860\ \text{h/yr} = 180\ \text{kWh}$ and an annual standby consumption of $4\ \text{W} \times 6900\ \text{h/yr} = 28\ \text{kWh}$. The standby use is roughly 13% of the energy used by each television, In theory all of this can be eliminated by unplugging each TV that is not in use. The mean number of TV's per household is 2.86. This yields a savings potential of 79 kWh per year per household, equivalent to 0.3% of site energy consumption.

Set Computers to Sleep and Hibernate A recent study identified computer power management as the highest potential energy saving opportunity for electronics in Minnesota homes [4]. This study found an average of 0.84 desktop computers and 0.56 laptop computers per home. Desktop computers were subdivided into four usage patterns. By applying the same power management strategy suggested by the NRDC (30 minute inactivity triggering sleep or hibernate), the highest savings potential was 67% for always on computers and the lowest savings potential was 15% for infrequently used computers. The weighted mean yearly estimated savings was 167.2 kWh. Accounting for the 0.84 desktop computers per home, the total expected whole-house savings is nearly 0.5%.

Take Control of Temperature
Rough estimates using the programmable thermostat savings calculator spreadsheet on the Energy Star website [19], implementing a heating set-back and cooling set-up can save approximately 20 $\sim$ 25% in space conditioning energy use. This adds up to $(20 \sim 25\%) \times [44.7\%(heating) + 9.2\%(cooling)] = 11 \sim 13\%$ savings in site energy use.

Use Sunlight
The effect of sunlight is difficult to estimate because solar heat gain depends strongly on the climate, orientation, and type of windows. We found no study that directly addresses the average effectiveness of sunlight on residential energy consumption. In some cases this could be a significant factor but we found previous analysis to base our estimate.

Tweak your Refrigerator
According to the U.S. Department of Agriculture fact sheet on food safety ([16]), refrigerator settings can go as high as 40°F and freezer settings can go as high as 5°F. A refrigerator-freezer consumes an average of 660 kWh annually. By raising the refrigerator setpoint from 30°F to 40°F and the freezer setpoint from 0°F to 5°F, energy use can be lowered by 20 $\sim$ 25%, or 0.8 $\sim$ 1% of total site energy consumption.

Use Appliances Efficiently
This behavior could affect multiple end-uses but the most relevant ones are cooking and wet cleaning; together they account for 7% of total energy consumption. We found no quantitative analysis of these behaviors but do not expect this behavior to achieve significant savings ($< 1\%$).

Turn Down the Lights
The entire lighting category is a sizable amount (5.9%) of total residential energy consumption. We could not find any quantitative analysis of the energy wasted from leaving lights on unnecessarily or from using more lights than needed. However, because lighting is the largest single end-use after space conditioning and water heating, we expect significant savings. To achieve 1% total energy savings a 10% reduction in lighting consumption is necessary while to reach 3% savings a 33% reduction is needed. From personal experience, a reduction in lighting by 10% - 33% seems conceivable, so we estimate the savings to be in the range 1%-3%. One caveat is that the growing use of high-efficacy lighting, such as compact fluorescent (CFL) bulbs, will substantially decrease the available energy savings in this category.

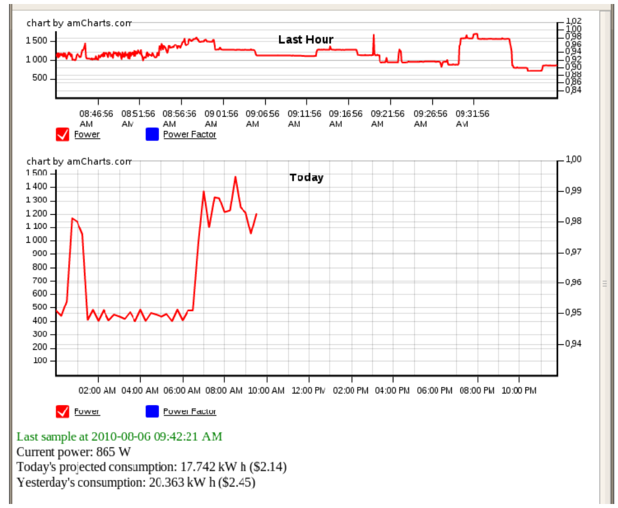

Figure 1. Screenshot of the in-home display (IHD). The "Last Hour" graph and textual information (last sample time, current power, and projected consumption) is updated every 5 seconds. The "Today" graph is updated every 15 minutes.

2.2 Experimental Setup

Using randomly selected participants from the *removed for review* , our goal was to quantify the effect of each of these suggestions on energy consumption. Each household was assigned a different behavior from Table 1 for each week of the study including a "control" week where no special behavior was assigned and one week where an IHD was used to provide real-time feedback on energy consumption. Figure 1 shows a screenshot of the web-based IHD application that displayed the home's measured energy consumption on a standard laptop computer.

The behaviors were assigned in a different order for each household, so that for each week only one household was following any particular behavior. The participants were informed that the purpose of the experiment was to evaluate the energy savings potential of each behavior. They were given instructions based on the NRDC recommendations and asked to strictly follow the behavior as described. Because the participants were selected from *xxxx*, we expect them to be highly capable and willing to implement the behaviors.

At the start of the each week the participants were given their new behavior and reminded to stop performing the behavior from the previous week. We also asked participants to keep diaries of significant events that may impact the study such as vacations, having guests, etc. so that data from these days could be excluded from the analysis.

The experiment was conducted over 10 weeks, and during that period we monitored whole-house electrical energy consumption with 5 second resolution. The monitoring equipment is shown in Figure 2. Two current transformers (CT's) and a single Continental Control Systems WattNode were placed inside the electrical service panel at each home to monitor electric consumption (all participants had the U.S.

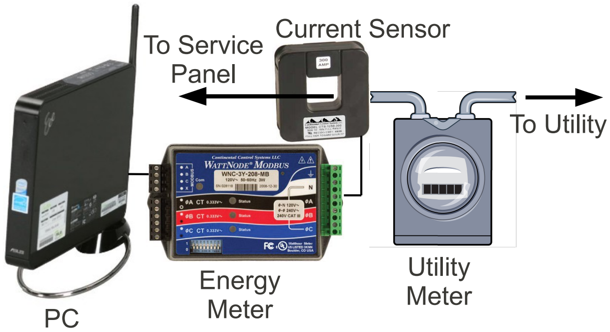

Figure 2. Monitoring equipment.

Table 3. Pre-Experiment survey average results.

Number of adults per home	2.20
Number of children per home	0.63
Number of refrigerators/freezers per home	1.78
Approximate hours occupied per day	16.7
CFL lighting use	53%
EnergyStar appliances	38%
Number of households with a central air conditioner	5
Number of households with an evaporative cooler	4
Number of households with a home business or energy-intensive hobby	1
Number of households with hot tubs	1

residential standard split-phase 240VAC service). A small form-factor PC queried the WattNode for power and energy information every 5 seconds. This data was first stored in a local database and then uploaded to a back-end server for analysis and permanent storage.

We also collected hourly average temperatures from the National Weather Service for the length of the study. This data enables us to compensate for weather-related changes in energy consumption using a PRISM-like analysis [5]. PRISM is a commonly used statistical procedure designed to separate the energy consumption due to heating and cooling from other uses, and is often used to evaluate the effect of energy-efficiency improvements.

2.3 Pre-Experiment Survey

Each participant was asked to complete a short pre-experiment survey designed to collect general information about the participant's home and several factors that may affect energy usage. Table 3 and Figure 3 summarize the results of this survey. (Some participants did not answer all of the questions.)

For comparison, in 2007 the U.S. Census Bureau reported an average household size of 2.61 (adults plus children) [13], slightly smaller than our study average household size of 2.83. The median year of construction for our sample is 1965, somewhat older than the national average of 1973 [15], which may explain, in part, the slightly smaller median square footage (2,184 for study sample versus 2,438 U.S. new construction average [14].) The U.S. Energy Information Administration reports that 17% of homes have two or more refrigerators [18]; in stark contrast nearly 50% of the participants in our study had two or more refrigerators.

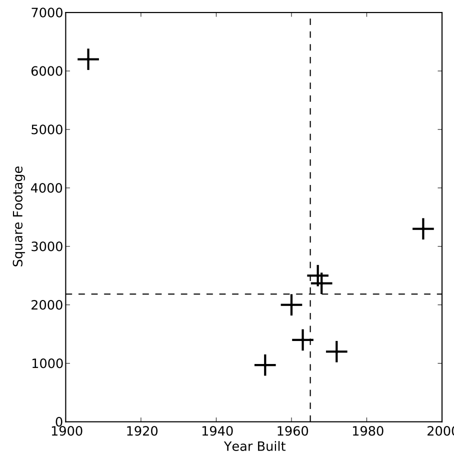

Figure 3. Construction year and square footage of participants' homes. Dotted lines indicate median values.

2.4 Results

The raw data are presented in Figure 4. Solid lines indicate mean weekday electricity used by each household. Weekend data are excluded for simplicity, as occupancy patterns are more likely differ dramatically between weekdays and weekends than between different weekdays. The vertical bars correspond to the mean daily energy usage for each behavior across the study sample. The dotted line at 28.84 kWh is the study-wide mean daily energy consumption. As expected, there is wide diversity and variation in energy use patterns. For example, House7 shows very little change in consumption, while House3 shows large variability from week to week. Behaviors where no marker is present indicates the homeowner was not able to complete the behavior (e.g., on vacation or other unusual circumstances).

To determine the effect of each behavior on energy consumption, we construct a linear model for mean daily energy consumption and solve for each coefficient with an analysis of covariance. The model is shown in Equation 1, where Y_{ijk} is the energy consumption in house j with behavior i on day of the week k, α is the intercept, β_i is the effect of behavior i, γ_j is the effect of house j, δ_k is the effect of day of the week k, $\rho_j * t_{ijk}$ is the effect of ambient temperature relevant to house j, behavior i, and day of the week k, and η_{ijk} are random errors assumed to be independent and normally distributed with constant variance.

$$Y_{ijk} = \alpha + \beta_i + \gamma_j + \delta_k + \rho_j * t_{ijk} + \eta_{ijk} \quad (1)$$

We found that replacing the mean daily outdoor temperature with the cooling degree-hours computed assuming a fixed set point (as is customary in PRISM analysis [5]) had no significant effect on the results, so we use the simpler mean daily temperatures.

Figure 5 shows the computed coefficients for effect of the day of week relative to Friday. The confidence intervals are at 90%. Clearly the day of week is not significant in this study, even with 90% confidence. However, given a larger sample size, it may be possible to identify variations due to the day of week.

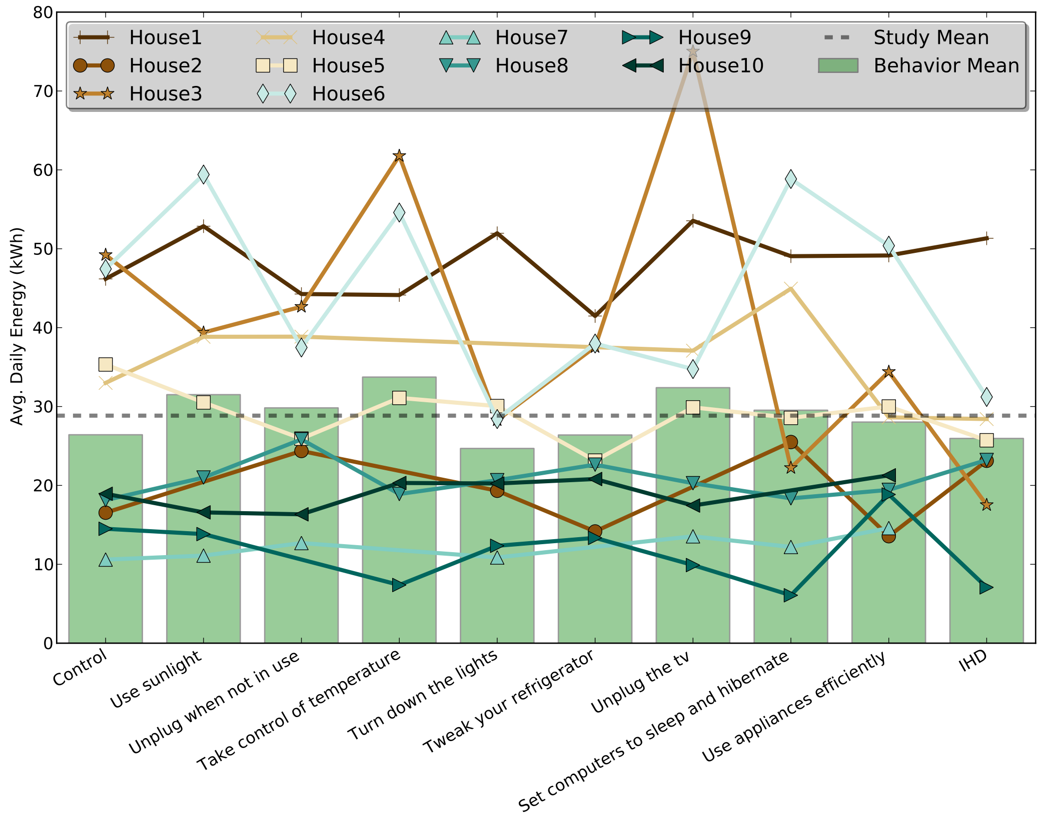

Figure 4. Summary of collected data separated by house and behavior.

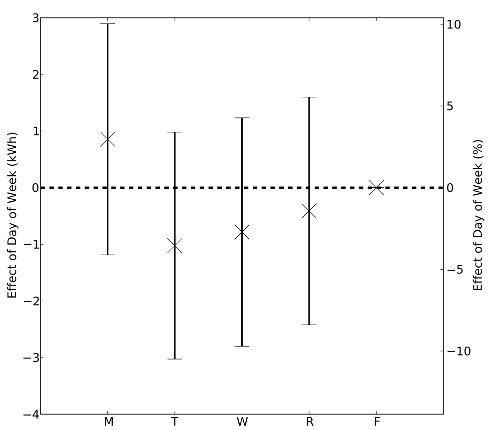

Figure 5. Change in energy usage by day of week relative to Friday (90% confidence intervals shown).

Figure 6 shows the computed effect of each behavior (the β_i terms from Equation 1). Due to the small sample size, no results were significant with 95% confidence, so we relaxed the confidence to 90% for discussion. The in-home display (IHD) was significantly better at reducing energy consumption than any single behavior for our study group. This is not surprising, because during the IHD week participants were able to use the provided feedback to reduce their energy consumption by targeting any number of end-uses. Over one week, this resulted in a $0 \sim 20\%$ energy savings. This correlates very well with the $0 \sim 18\%$ reported by the Electric Power Research Institute (EPRI) [10] based on several independent IHD studies.

Due to the small sample size and short duration of our study, no other results showed significant energy savings. However, there is some indication that "turn down the lights" may yield energy savings consistent with our 1% estimate for this behavior. This avenue for savings could diminish over time because our pre-study survey indicated only 53% of lighting was using CFL or other energy efficient technologies. If this percentage is increased, the potential savings will diminish.

The behaviors "Tweak your refrigerator," "Unplug when not in use," "Use appliances efficiently," and "Set computers to sleep and hibernate" were not found to be effective. This result is unsurprising because none of these behaviors were expected contribute more than 1% savings and 1% is not significant due to the normal variations in energy consumption. These results help to confirm our initial savings estimates. However, it is also possible that the participants were already performing these behaviors or the occupants may have only partially performed the behavior (if at all). To explore this possibility we conducted a post-experiment survey, described in Section 2.5.

The behaviors "Use sunlight" and "Take control of temperature" showed possible increases in energy consumption, with the latter being significant. These results are most likely

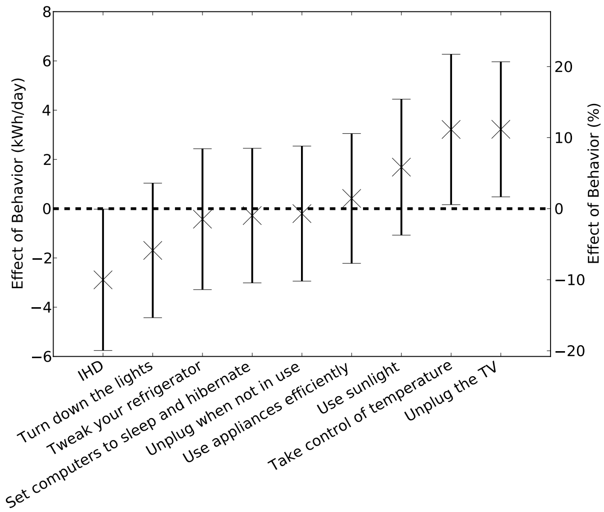

Figure 6. Change in energy usage by behavior relative to baseline (control) behavior (90% confidence intervals shown).

a result of miscommunication or performing the behavior incorrectly. For example, "Take control of temperature" suggested summer/winter HVAC set points. If the participant did not normally use their air conditioner, but turned it on to comply with the behavior, we would expect increased consumption, although this was not the intent. This does, however, illustrate the dangers of generalizing when specifying energy saving behaviors, as "one-size-fits-all" approaches may lead to undesirable consequences.

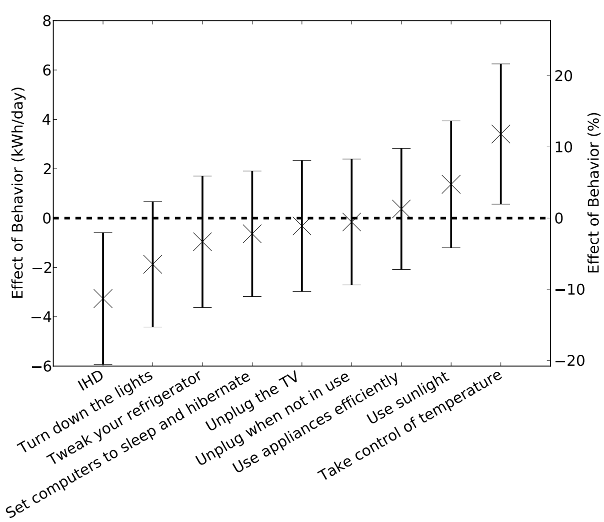

Figure 7. Change in energy usage by behavior relative to baseline (control) behavior with House3 excluded from behavior "Unplug the TV" (90% confidence intervals shown).

The significant increase for "Unplug the TV" was most likely caused by some other factor not accounted for in our model. Examining the raw data in Figure 4, we see that House3's energy consumption is nearly double while performing this behavior. It is possible that some unusual event occurred in this house during this week of the study to cause significantly higher energy consumption (e.g., hosted a party or had guests). To further explore this possibility, we excluded House3's results for this behavior and recomputed the results (See Figure 7). This results in a significant change for "Unplug the TV" as well as slight changes for the other behaviors as well. The results show "Unplug the TV" to be similar in effect to "Tweak your refrigerator," "Unplug when not in use," "Use appliances efficiently," and "Set computers to sleep and hibernate." This intuitively makes more sense as we expect the effect of "Unplug the TV" to be similar to the other behaviors.

The overall conclusions that we can draw from these results are mixed. Our IHD results are consistent with previous, more extensive studies, and demonstrate that significant energy savings are possible in residential homes. However, no single behavior that we tested was responsible for statistically significant whole-house energy savings. The most significant effect was the increased consumption observed with "Take control of temperature." This reinforces the fact that residential energy consumption is significantly impacted by space heating and cooling. Although our strategy resulted in increased energy consumption, we believe that opportunities exist for more intelligent control strategies.

2.5 Post-Experiment Survey

Behavior	Used Much Less	Used Less	No change	Used More	Used Much More
IHD	1	3	2	1	0
Unplug when not in use	0	2	2	5	0
Unplug the TV	0	3	4	2	0
Set computers to sleep and hibernate	0	2	4	2	1
Take control of temperature	2	0	2	1	3
Use sunlight	0	2	4	1	1
Tweak your refrigerator	0	1	4	3	0
Use appliances efficiently	2	0	3	2	1
Turn down the lights	0	3	2	3	1

Table 4. Survey results to: "What do you expect the effect of this behavior to be on your daily energy consumption?"

At the conclusion of the experiment, we asked participants to complete a second short survey. The survey was sent to all participants before they received any results from the study. Nine of the ten participants completed the survey.

Question one asks "'What do you expect the effect of this behavior to be on your daily energy consumption?" Table 4 shows the results. These results were surprising because for each behavior, at least one participant expected it to increase daily energy consumption. The largest expected increase was for "Take control of temperature," which matches the observed result. This supports our speculation that the participants turned on their air conditioners specifically to comply with the behavior.

At the other extreme, more people expected the IHD to provide energy savings than any other behavior. Perhaps the most surprising survey result was that some people expected the behaviors: "Unplug when not in use," "Use appliances efficiently," and "Set computers to sleep and hibernate" to increase energy consumption.

Behavior	Not at all	Less than half of the time	About half of the time	More than half of the time	All of the time
IHD	2	0	4	1	0
Unplug when not in use	1	0	4	4	0
Unplug the TV	4	1	0	0	4
Set computers to sleep and hibernate	0	0	3	2	4
Take control of temperature	0	0	1	3	4
Use sunlight	0	0	2	3	3
Tweak your refrigerator	4	2	0	0	2
Use appliances efficiently	0	0	2	3	3
Turn down the lights	0	1	2	3	3

Table 5. Survey results to: " How well did you (and your family) follow each behavior?"

The final question was "How well did you (and your family) follow each behavior?" The results are shown in Table 5. These results can be used to estimate what energy saving behaviors people are willing to implement manually. Because our participants were all employees of *xxxx*, we expect this group to have higher compliance than if we selected from the entire population. "Take control of temperature" had the highest reported compliance. This makes sense because it involves setting the thermostat one time. The behaviors with lowest reported compliance were "Unplug the TV" and "Tweak your refrigerator." Unplugging the TV requires an extra step each time the TV is turned on/off, so it is not surprising that people did not perform this behavior consistently. We suspect that the low compliance for "Tweak your refrigerator" was due to the need to find and use a refrigerator thermometer and wait a long time between making adjustments. The low levels of compliance suggest that these behaviors could benefit from automation.

3 Conclusions

In our quest to reduce residential energy consumption, we have conducted an experimental study to quantify potential savings from eight different behaviors as well as real-time monitoring via an IHD. The results of this study indicates that none of suggested behaviors were as effective at reducing energy consumption as the IHD. This is not surprising; given appropriate information savvy homeowners can significantly reduce their energy consumption on their own. However, not all homeowners are equally interested in saving energy. This is confirmed by the post-experiment survey where less than half of the participants reported unplugging devices as instructed. Although we estimate a total savings potential of 1.5% from unplugging miscellaneous electrical loads, computers, and televisions, we observed little to no effect from these behaviors. Because highly motivated and capable homeowners were unsuccessful at saving energy using these behaviors, we conclude that automated BMSs are likely necessary to curtail residential energy waste from electronic devices. The significant impact of space heating and cooling was also evident, although our simple control strategy was ultimately unsuccessful. Because a significant portion of residential energy is consumed by space heating and cooling and the effect of occupant behaviors is evident, we believe that more intelligent and adaptive approaches are necessary to improve efficiency.

4 Acknowledgments

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