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Promoting Energy Efficient Behaviors in the Home through Feedback: The Role of Human-Computer Interaction

Jon Froehlich
DUB Institute
Department of Computer Science and Engineering
University of Washington, Seattle, WA 98195 USA
jfroehli@cs.washington.edu

Abstract

The consumption of energy is unlike most consumable goods. It is abstract, invisible, and untouchable. Without a tangible manifestation, home energy usage often goes unnoticed. Advances in resource monitoring systems will soon provide real-time data on electricity, gas, and water usage in the home. This will produce a tremendous amount of data that can be analyzed and fed back to the user—creating a rich space of opportunities for HCI research. This paper outlines common misconceptions of energy usage in the home, establishes the potential of feedback to change energy consumption behavior, and introduces ten design dimensions of feedback technology with which to build and evaluate future systems.

Keyword

Feedback

Introduction

The United States consumes one quarter of the world's energy resources, despite accounting for less than five percent of the world's population (US Department of Energy, 2002). The residential sector accounts for 21% of the nation's energy use and the average American household spends nearly $2,000 on energy bills per year (US Department of Energy, 2006). Home energy and personal transport are the top two contributors of the average American's CO_2 emissions into the environment (Weber and Matthews, 2007), accounting for over 50% of their total carbon footprint. To date, the primary methods applied to improving energy efficiency and/or reducing energy usage been technological and economic (Armel, 2008). For example, the production of hybrid or hydrogen vehicles has been emphasized as a major solution to CO_2 reduction and oil dependence. However, there is growing evidence that a human-centered, *behavioral* approach should also be pursued to educate, inform, and motivate energy efficient human behaviors.

In a study evaluating the energy consumption of 10 identical Habitat for Humanity all-electric homes outfitted with the same appliances and equipment, homes were found to exhibit a large range in energy consumption, with the most energy intensive home consuming *2.6 times* more energy than the least (Parker et al., 2008). Indeed, it has been consistently found that energy use can differ by two to three times in identical homes, occupied by people with similar demographics (Socolow, 1978; Winett et al., 1979). Such findings reveal how differences in human behavior can significantly affect energy consumption and suggest that intervention strategies to promote sustainable behaviors could result in significant energy savings.

Yet, curtailing energy usage in the home is a difficult task. The consumption of energy—be it heating fuel or electricity—is unlike most consumable goods. It is abstract, invisible, and untouchable (Fischer, 2008). Without a tangible manifestation, home energy usage often goes unnoticed—unlike, for example, the decreasing amount of milk in the fridge, the increasing dullness of a razor blade, or a gas gauge nearing empty. Most people have no

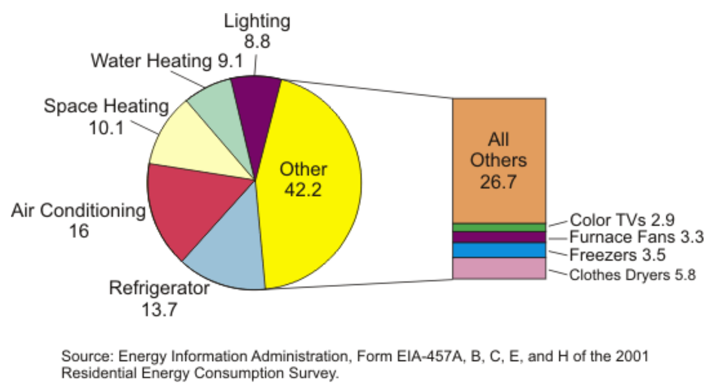

Figure 1. Percentage breakdown of energy usage in the home

means of judging their household energy usage other than a monthly (or bi-monthly) energy bill (Winett, 1978), much less its environmental impact. Kempton and Layne (1994) draw the analogy that this would be like shopping at a grocery store where the goods are not marked with individual prices and the only feedback received about purchasing is through a monthly bill which provides one, aggregate total cost. In addition, energy consumption is rarely a goal within itself but rather a by-product of a wide variety of diverse actions such as doing laundry, driving to work, staying warm, or watching television. Moreover, some of the largest consumers of energy in the home are always-on appliances such as the water heater or refrigerator (see Figure 1), things that we may not feel in control of. Finally, much information about energy use is presented in dull, uninteresting formats (Stern and Aronson, 1984) so although valuable information may be present, it is unlikely to be read (or remembered).

This paper outlines the potential role for human-computer interaction research in the space of home energy and feedback systems. Advances in resource monitoring systems will soon provide real-time data on electricity, gas, and water usage in the home (Kim, 2008; Patel, 2008; Fogarty, 2006). This will produce a tremendous amount of data that can be analyzed and fed back to the user—creating a rich space of opportunities for HCI research. Some open research questions:

- What are the most effective strategies in motivating energy efficient behavior through feedback technology?
- How can we successfully incorporate theories of human behavior from environmental psychology, behavioral economics, decision-theory, goal-setting theory, etc. into our designs?
- Why do people want to reduce consumption? Why would they use these feedback systems? How can we design for the *least* motivated individuals?
- What presentation medium should the feedback use? How is it accessed? How often should it update?
- How can energy feedback technologies be valuable without being disruptive?
- How do we generate adoption of feedback technologies and motivate their long-term use?
- What are some practical lower-bounds on consumption/reduction can be expected? How might these change over time? In particular, when (if ever) can we expect a threshold to be reached where feedback/education no longer affects consumption?
- How can intelligent user interfaces be used to open up new opportunities for feedback? Can we automatically link higher level human activities to energy usage, thereby presenting information not just in terms of energy consumption but also in terms of the activities that occurred to cause the consumption?
- Can machine learning help determine the best time and format to feed information back to the user?

This work builds upon other home energy feedback papers in the human-computer interaction (HCI) community (e.g., Holmes, 2007; Pierce, 2008; He and Greenberg, 2008) by: (1) Providing a review of studies that explore the common perceptions and misconceptions of energy usage in the home and establishing the effectiveness of feedback technologies to change behavior by summarizing prior work in environmental and behavioral psychology;

and (2) Presenting ten design dimensions for feedback systems in the home, which are motivated and supported by (1).

Perceptions of Energy

The manner with which consumers perceive and understand energy has implications for designing effective feedback systems (e.g., in determining what should be sensed and how it should be presented). The two most common units used to measure energy consumption are the energy unit itself (e.g., kWh, mpg) and cost. Unlike mpg for vehicles, standard measurement home energy units such as Kilowatts/hour (kWh) for electricity and Cubic Centimeters (CCM) for water are not well understood. It's unsurprising, then, that Kempton and Montgomery (1982) found that consumers usually perceive home energy consumption in dollars. Although cost is a useful indicator and can be an important motivator for reducing consumption (Fischer, 2008), it is an indirect measure and thus can be misleading. In the Kempton and Montgomery study, consumers that focused on cost underestimated the effectiveness of their conservation measures because of fluctuating energy prices.

Prior work has also looked at consumer understanding of the amount of energy appliances, lights, devices, and heating/cooling systems use in the home. Mettler-Meibom and Wichmann (1982) interviewed 52 households in Munich, West Germany and asked them to estimate the proportional energy cost of specific end uses. These responses were then compared to actual usage. Consumers vastly underestimated the energy used for heating (estimated 79% vs. 49% actual) and overestimated the energy used for appliances, lighting, and cooking. Similar findings were found by Costanzo et al. (1986) and Kemptom and Montgomery (1982). Kemptom and Mongomery also found that consumers often estimate an appliance's energy use by its perceptual salience (e.g., television and lighting are often overestimated) and also overestimate energy used by machines that replace manual labor tasks (e.g., dishwasher, clothes washer). Understanding aggregate energy usage does not fair better. In multiple studies spanning a total of 700 persons, Winett et al. (see Geller et al., 1982) found that only a small percentage (1-2%) knew how many KWh they used per month or per day—most did not even know where their electricity meter was located.

More recently, in 2007, a UK marketing firm surveyed 10,048 Europeans across 10 countries about consumer energy awareness and consumption practices (Logica, 2007). Although 80% of the respondents claimed that they were concerned about climate change and 75% felt that their personal actions had an impact, 45% reported that they were unaware of how much energy they used at any one moment (over 60% in France and Spain). Finally, over half (~55%) felt that they did enough already to limit their energy consumption However, there appears to be an attitude-behaviour gap, as an objective measure of energy efficient behavior showed that respondents engaged in an average of only 1.4 out of 6 key efficiency behaviors. These results point to the need for more accurate and specific information about how actions in the home affect energy consumption. The numbers are encouraging as they show that people believe that climate change is an important issue and are willing to consider changing their behavior. The high percentage of those who feel they are doing enough to limit consumption may point to a social desirability bias (i.e., respondents over reported the socially favorable behavior). Another reason may be that the respondents were unaware that they do not have a good understanding of their energy use, or they simply believed inaccurate information. For example, Costanzo et al. (1986) found staggering differences between the respondent's claimed understanding and an actual understanding of home energy conservation programs.

Inaccurate understanding of the ways energy is used in the home is directly tied to the steps consumers believe they can take to conserve energy. Winett et al. (1981) found that many people (incorrectly) thought that setting a thermostat back on a winter's evening would result in more energy use because the house would have to "reheat" in the morning. Others have shown dramatic misunderstandings of the benefits of weatherization, retrofits, and tax breaks (Geller et al., 1982). The role of smart feedback systems, then, is not only to provide pertinent information about energy usage but also to educate consumers at opportune times and tailored to their specific situation.

The Promise of Feedback Technologies

In feedback intervention theory, behavior is regulated by comparisons of feedback to goals, standards or norms (Avraham and DeNisi, 1996). Feedback provides a basic mechanism with which to monitor and compare behavior and allows an individual to better evaluate their performance. Feedback technologies have been shown to be one of the most effective strategies in reducing energy consumption in the home (Geller et al., 1982). Corinna Fischer (2008) reviewed approximately twenty studies and five compilation publications from 1987 onward exploring the effects of feedback on electricity consumption and on consumer reactions, attitudes, and wishes concerning such feedback. She found that typical energy savings were between 5 and 12% (though the absolute range was between 0 – 20%). In a similar review of thirty-eight feedback studies carried out over a period of 25 years, Sarah Darby (2000), found typical energy savings of 10-15%. Both Fischer and Darby point out the difficulty in synthesizing, comparing, and categorizing these studies as they range in sample size (from 3 to 2,000), housing type, and feedback method (*e.g.,* frequency of update, historical duration, visual design). Also, in some studies, other interventions such as financial incentives were used in addition to feedback. Despite such disclaimers, as Fischer argues, the sheer number of studies that reported savings is a good indicator for the general effectiveness of using feedback to change consumption behaviors. A brief summary of their findings follows.

In those cases where no savings were found: the feedback occurred too infrequently (e.g., in the form of a semi-annual bill update), was too unobtrusive, or the homes themselves were already low consumers. Designs that performed best provided computerized feedback (rather than say augmented paper bills) with multiple feedback options (e.g., consumption over various time periods, comparisons, additional information like environmental impact or energy saving tips), were updated frequently (daily or more), were interactive (e.g., the device provided configuration options or user could “drill-down” into data), and/or were capable of providing detailed, appliance specific breakdown of energy usage. Interestingly, providing direct financial incentives for consumers to drive energy reduction had little lasting effect: consumption reverted to its previous levels once the incentive was removed. This phenomenon highlights one of the major deficiencies in the current literature—few have studied the underlying cause of behavior change influenced by feedback technology nor its longitudinal impact.

Though feedback has great potential, simply revealing behavioral data, however, does not guarantee positive change or uniformly improve performance. As Latham and Locke (1991) state, “feedback is only information, that is, data and as such has no necessary consequences at all.” Other factors such as age, the cost of energy, home ownership, income level, and family size may affect feedback’s effectiveness. For example, feedback is not as effective for households where the cost of energy is proportionally low with respect to income (Geller et al., 1982).

The Feedback Design Space – Ten Design Dimensions

In this section, we map out ten design dimensions for feedback systems and use existing designs to help illustrate them. Note that the design dimensions are not purely orthogonal (indeed, many overlap); however, they are sufficiently different as to warrant separation. This list is intended to provide a framework with which to understand the features that researchers and designers may manipulate and evaluate in their designs.

1. Frequency: The frequency with which a feedback system updates appears to improve the link between action and effect and, therefore, increases an individual’s consciousness about their action’s consequences (Fischer, 2008). Several studies have demonstrated the benefit of frequently updated feedback to reduce consumption. Bittle et al. (1979) placed feedback cards that described the amount of kilowatts consumed the previous day into residential mailboxes. The feedback group used an average of 1-9% less electricity than the control group. In a more recent study, homes that used a computerized feedback display of real-time electricity usage reduced electricity consumption by 12.9% (Dobson and Griffin, 1992). The ideal frequency of feedback is unclear, but computerized feedback systems provide a level of flexibility in data presentation and access that was previously unavailable.

2. Measurement Unit: Feedback may be provided using any number of measurement units from electricity consumption (e.g., kWh), to cost, to environmental impacts (e.g., carbon emissions). As previously described, some units are more difficult to comprehend than others (e.g., often water flow is measured in esoteric units like CCM rather than gallons/hr). Often, computerized feedback systems can be configured to use the consumer's preferred units. The Energy Detective (Figure 2), for example, can display information in kilowatts, dollars per hour ($/hr), energy consumed so far today, current voltage and the current energy rate in dollars per kilowatt hour. Many displays also calculate a carbon footprint and translate that into equivalent but more comprehensible units (e.g., number of car trips, number of flights). Displaying a particular measurement dimension will inevitably frame the problem in different terms for the user, making certain characteristics of consumption more salient over others, and thus activate different motives and personal and social norms (Fischer, 2008).

3. Data Granularity: Data granularity describes the resolution and scope of the data that is fed back to the user. This may be in terms of time (e.g., data can be viewed at different temporal resolutions, amount of consumption per day, per month, per year), space (e.g., specific rooms, upstairs vs. downstairs), specific source (e.g., refrigerator, washing machine, upstairs shower), or source category (e.g., kitchen appliances, lights, bathrooms). Most energy usage studies have been constrained to looking at aggregate information provided by the utility company or through sensors attached to the home's main circuit breaker (Fischer, 2008; McCalley and Midden, 2002). Few studies have been conducted that explore the effectiveness of presenting appliance-specific data. Dennis (2002) speculates that linking energy consumption to source is essential, "part of the reason that feedback is not more effective appears to be that consumers do not know what each component of their electricity consumption costs."

4. Push/Pull: Should information always be available (e.g., via a LCD flat-panel display in the kitchen), only inform the user when excessive energy usage (or other anomalies) have been detected (e.g., via a text message or email) or only available through a portal or website that must be explicitly navigated? Often, this is a tradeoff between attentiveness, cognitive load, user motivation, information relevancy, and the cost of operating the feedback

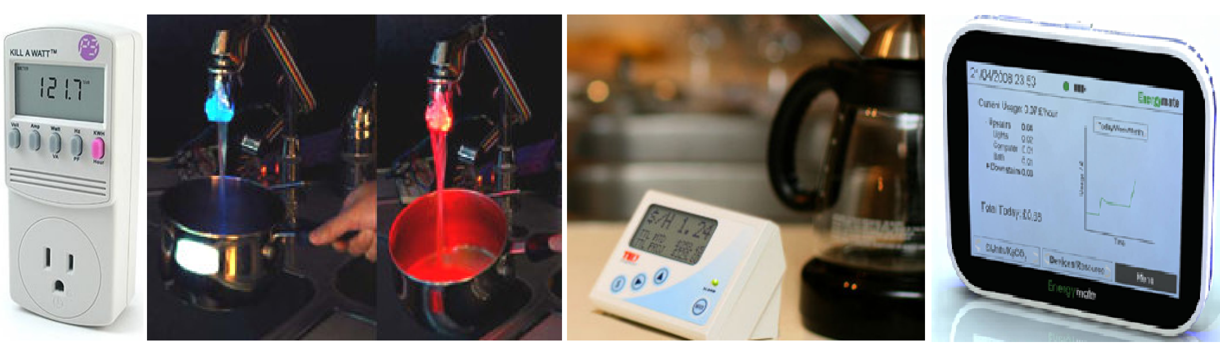

Figure 1. The first two examples illustrate highly localized feedback. The other two examples provide aggregate energy usage information and can be placed anywhere in the home. (from left-to-right). The Kill-A-Watt provides energy usage information for appliances plugged into the proxy outlet. The MIT HeatSink (Arroyo, 2005) illuminates water according to temperature directly at the point of consumption. The Energy Detective (TED) presents overall electricity consumption information numerically via a monochrome display. The EnergyMate, a conceptual design, is an LCD flat panel display meant to be positioned in a visible place in the home and offers real time feedback about energy usage.

system. Even lightweight "push" mechanisms seem to be effective. In an early version of an ambient-like display for the home, Becker and Seligman (1978) investigated the effectiveness of a light that went on "in a highly visible part of the home" whenever the air conditioner was on, but the outdoor temperature was 68° F. An average of 15% savings in energy consumption was found in homes that contained the signaling device. It's likely that an effective system would consist of both push and pull approaches.

5. Presentation Medium: Fischer (2008) distinguishes between two types of feedback media: paper and electronic displays. As a traditional medium, paper has the advantage of familiarity and low-cost; however, it is non-interactive and can only display static information. Positive Energy, a greentech startup company based in Arlington, VA., provides analysis tools and novel graphics to utility companies to improve the information and presentation on paper bills. For example, bills contain a bar graph that compares the current consumer's last month's energy usage with their neighbors (left image in Figure 2). It's unclear if what defines a "neighbor"—if it's used in the traditional sense (e.g., by spatial proximity) or calculated based on energy usage measures. In its first trial in Sacramento, CA, homes with Positive Energy's modified bills reduced energy consumption by 2% over homes that continued to receive regularly formatted bills (LaMonica, 2009).

Electronic displays may come in the form of meters on an appliance, personalized internet portals for the home, mobile phone widgets, or tangible ambient displays. Ambient displays such as the Energy Orb or Wattson (middle image in Figure 2) can provide low-bandwidth information (e.g., by glowing red when energy usage reaches a certain level and green otherwise). Ambient displays require much less attention in comparison to interactive displays such as internet web portals but provide much less information and do not provide mechanisms for consumers to drill down into their data. It's unclear, however, how much time a consumer would be willing to explore their energy usage data. It's likely that highly accessible information which is present (or nearly always present) would fair best in raising awareness. However, awareness alone does not always translate into behavior change (Latham and Locke, 1991).

6. Location: The location of the feedback may be highly localized (e.g., on the appliance itself) or completely independent (e.g., via an internet portal or paper bill). A single display may be positioned in a highly trafficked part of the home, for example, in the family room or kitchen. Feedback location is restricted by sensing capabilities and the cost of installation. Currently, localized displays tend to either be built into the appliance or part of the sensing assembly unit. Two recent studies show that linking energy consumption and source through localized displays is a promising direction. McCalley and Midden (2003) gave consumers immediate feedback about washing machine energy usage via an attached control panel and found a 21% reduction in energy use. Ueno et al. (2005) installed

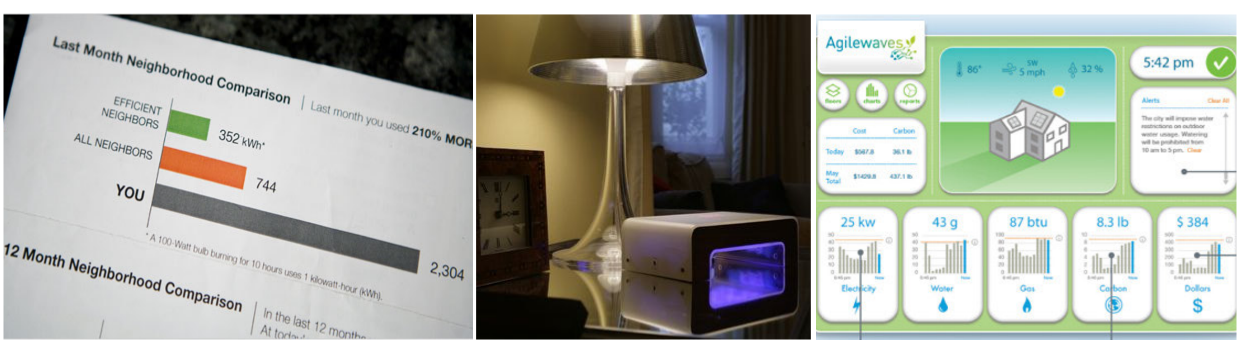

Figure 2. (from left-to-right) The Positive Energy paper bill with neighborhood comparisons. The Wattson ambient display which glows according to energy consumption level. The AgileWaves internet portal for the home displays energy usage information for gas, water, and electricity and allows the user to "drill-down" to finer levels of detail.

sensors for each home appliance and also monitored total electric power and gas consumption and found a 12% reduction in energy usage after system installation.

7. Visual Design: Very few studies have considered the role of graphic design or the format of presentation (Fischer, 2008). Figure 4 reveals a spectrum of visualization designs from numeric quantifications to artistic renderings (Holmes, 2007) of energy. A household's reaction to a particular visual design depends on its overall aesthetic, comprehensibility, graph choice, measurement units and wording choice. Pierce et al. (2008) distinguish between two general types of data visualization: pragmatic visualization (left and middle image of Figure 4) and artistic visualizations (right image in Figure 4). Pragmatic visualizations are more common and provide concrete quantitative information; however, they often require a ramp-up period to learn (i.e., visualizations are learned interfaces). Artistic visualizations are more abstract by nature and can use visual representations that the consumer may find evocative but often at a cost of explicitness. For example, in UbiGreen, Froehlich et al. found that although users appreciated artistic metaphors that represented their travel activity, they also sought more precise information that would allow them, for example, to better compare their current performance to previous performances. More research is necessary to know when, where, and how pragmatic and artistic visual designs should be used.

8. Recommending Action: Many conservation programs use high-level written or verbal messages (called prompts) to promote conservation (e.g., "Use Energy Wisely" or "A Short Shower Converses Water"). Investigations into general prompting strategies have shown it has limited influence on behavior but can be made more effective by improving specificity, timing, and placement (Geller et al., 1982). For example, Winett et al. (1978) showed how placing signs next to doorways with specific information about when and who should turn out the lights (e.g., the last person leaving the room) resulted in a 60% reduction in days when the lights were left on compared to signs that were placed above light switches and contained general messages about saving energy. Other research suggests that humans tend to assign disproportionate weight to information that is highly concrete and personalized (Borgida and Nisbett, 1977). Computerized feedback may be able to offer highly personalized recommendations tailored to the sensed energy usage in the home. For example, the system may be able to detect a malfunctioning water heater which is consuming excessive amounts of energy. In those cases, the system could, for example, provide links to more efficient water heaters that would be more economical in the long-term (with specific cost/benefit analyses).

9. Comparisons: Providing methods for consumers to compare their current performance to past performances is essential. These comparisons could be offered at various levels of temporal granularity (e.g., day, week, month)

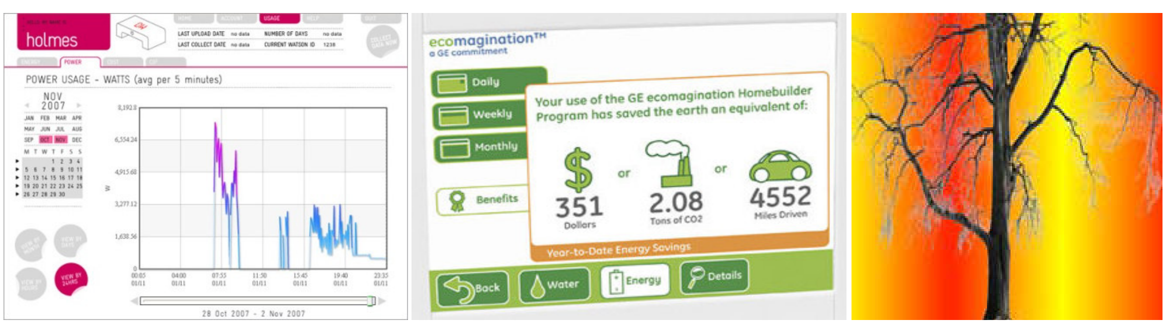

Figure 3. (from left-to-right) The Wattson visualizer presents time series graphs of different points in history and at different temporal resolutions. General Electric's ecomagination display uses cartoonish iconography to display energy consumption values in terms of dollars, tons of CO_2 and miles driven. Holmes (2007) "7000 Oaks and Counting" visualization uses a tree metaphor to communicate energy flows in a building.

and should be normalized based on weather. One complexity with comparison as a motivator, however, is that eventually a certain threshold of performance is reached—emphasizing improvement over historical performances may then result in frustration. In additional to self-comparisons, there is also social or normative comparisons. In Fischer's (2008) feedback review, none of the twelve studies that incorporated normative comparisons could demonstrate an effect. She offers that, "while [normative comparisons] stimulates high users to conserve, it suggests low users that things are going not so bad and they may upgrade a little. These effects probably tend to cancel out each other." Still, social norming can be a powerful motivator. For example, Goldstein et al. (2008) found that hotel guests who were exposed to descriptive norms about towel reuse activity were 33% more likely to reuse their towels than a comparison group who were not. More research is needed to understand how normative comparisons can be effectively integrated into feedback systems.

10. Social Sharing: The role of Facebook and other social sharing sites in supporting social issues (e.g., grassroots political campaigning, sustainability) is a relatively new topic of research (Mankoff et al., 2007). It is perhaps one of the most underexplored aspects of motivating behavior change. Of course, not all social sharing must be mediated by existing social networking sites; however, they do provide an attractive medium for certain segments of the population (e.g., young adult home owners) because of the amount of time spent interacting on them (e.g., many opportunities for feedback exposure). One role that social networking sites may play is in providing accountability and pressure to be energy efficient. Pallack et al. (1980) applied this principle in a field experiment involving households. Randomly assigned households were asked for permission to publicize their names and results of their performance in the conservation study before the study began. The group that agreed to publicize their results used 15% less natural gas and 20% less electricity. It's likely that users who share their energy usage online will similarly feel pressure to engage in energy efficient behavior.

Conclusion

Human behavior plays a critical role in consumption. A 10% reduction in all energy intensity implies that 8.5 quads of fossil fuels are not used, reducing CO_2 emissions by 8.5% which is equivalent to doubling the nuclear power output in America (Armel, 2008). In-home feedback technology has been shown to reduce energy use by 10-15% on average, with significant decreases linked to more frequent feedback and higher data granularity (e.g., specific energy usage data on appliances). As the cost of home energy sensing decreases, we will see a huge upsurge in the amount of data available to be visualized and fed back to the consumer about their energy usage. The ways in which to most effective build interfaces around this data to reduce consumption is an open research question and one that involves psychology and HCI.

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