A Demonstration of an Energy Feedback Research Platform in a Field Study of Real-Time Social Comparisons

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ABSTRACT

This paper presents the design and demonstration of an energy feedback research platform using an Internet of Things approach with free and open-source software. Implemented in a rental multi-unit residential building (MURB) in Toronto, Canada, the feedback platform was a central component of an energy conservation program and field study examining the efficacy of near-real-time feedback and social comparisons. A preliminary analysis of the results showed a significant effect of the conservation program with a relative year-over-year, weather-normalized savings of approximately 11%. Additionally, a 3.5% improvement in savings was observed with the provision of real-time social comparison data. While this improvement was not statistically significant, it may still be worth pursuing in a utility-scale implementation as there would be relatively low incremental implementation cost.

INTRODUCTION

Research in energy conservation behaviours for building inhabitants burgeoned during the 1970's energy crisis to reduce dependence on foreign oil. As climate change has emerged on the political agenda in recent years, energy conservation has also regained traction; and is now acknowledged as perhaps the most cost-effective way of reducing greenhouse gas emissions (IEA, 2010).

In the field of residential energy conservation, providing tenants with feedback on their energy use has been demonstrated as an effective intervention with savings ranging from 4-12% (Ehrhardt-Martinez, Donnelly, & Laitner, 2010). When considering that Canadian residential sector consumes 410 TWh of energy per year (Government of Canada, 2012), a 4-12% savings amounts to approximately 16-49 TWh. In Toronto, Canada, the current flat-rate, marginal price for delivered electricity is approximately 0.14 $/kWh. This means with feedback, there is a potential to collectively save residential consumers $2.3B to $7.0B.

In addition to the political and social influences on energy conservation research, technological advances have also enabled new ways to promote conservation, with feedback as a key strategy. In the past several years, on the strength of the smart grid technology and advanced metering infrastructure, industry has produced many feedback instruments on the market. These have ranged from smart bills, in-home displays, to web-based portals. Figure 1 shows an example in each of these categories.

Figure 1. Examples of different feedback approaches
From left to right: OPOWER paper bill shows neighborhood comparisons. Aztech In-Home Display shows aggregate home energy consumption. LucidDesign Building Dashboard is a web-based portal offering interactive views of energy use.

However, despite the many commercial implementations of feedback and a plethora of studies on the efficacy of feedback approaches, researchers (Ehrhardt-Martinez et al., 2010; Fischer, 2008; Flemming, Hilliard, & Jamieson, 2008) have pointed to three key challenges that have limited our understanding of how best to design feedback. First, methodological problems have hindered consolidation of the literature. In her review of 26 original feedback projects Fischer (2008, p. 87) writes:

> *"[Feedback projects] differ markedly with respect to study design, sample, and method of data gathering, differences occurring both in substance and in scientific elaborateness. What is more, results are not always reported quantitatively or in sufficient detail to make a comparison. And if they are reported, studies use very diverse reporting schemes. They vary in baseline, in time and duration of measurement, and in the unit for which savings are reported."*

Second, there is no consensus on how best to visually design feedback. Feedback designs range from traditional quantitative representations (e.g., charts and graphs) to artistic, data-driven renderings of energy. Furthermore, design decisions on graph choice, measurement units, or wording may also impact user satisfaction, and overall adoption of the feedback. Unfortunately, very few studies have focussed on evaluating such design decisions.

A third challenge, identified by Ehrhardt-Martinez (2012), reflects the lack of details known about behaviours induced by feedback. As will be detailed later, a popular dichotomization of behaviours distinguishes between efficiency and curtailment behaviours. However, this dichotomy does not describe the variety of ways in which technology can be used, maintained, or interchanged (ibid). Without a clear understanding of how feedback can be designed to shape behaviour, it is likely difficult to make optimal design choices. As utilized in Ehrhardt-Martinez's study, surveys are an effective method to understand these nuanced behaviour changes.

Interestingly, a common theme in all three challenges is the fundamental methodological limitations of past feedback research. What appears problematic is that these limitations have also made it difficult for feedback researchers to advance the state of the art and science on feedback design and on maximizing the potential of feedback strategies. While there is no straightforward solution to any of these challenges, it is clear that if there was a common platform on which feedback research was conducted, could help advance the field more rapidly and with coherence. The goal of such a feedback research platform would be to afford a systematic approach to evaluating feedback designs given the wide variety of contexts possible. To this end a feedback research platform was designed and demonstrated.

There are two key socio-technical developments that have helped enable this objective: The Internet of Things (IoT), and free and open source software (FOSS). The IoT refers to the interconnection of electronic devices (e.g., energy or air quality sensors) on the Internet. The movement towards an IoT has increased access to sensors and wireless communication technologies enabling the cost-effective collection of real time and disaggregated energy data amongst other applications. In conjunction with web-enabled mobile devices (i.e., smart phones, tablets), energy feedback can be as easily delivered as a consumer phone app is to download.

FOSS (e.g., Linux, GIMP) is software that is made freely available for the public to use, copy, study, and modify. This is in contrast to proprietary software (e.g., Windows, Photoshop), which is restricted under copyright and has source code hidden from users. FOSS communities have developed with the belief that their approach fosters learning, collaboration, community, and innovation. As the feedback research platform leveraged several FOSS projects with an IoT focus, it is in the same spirit, that its design will be shared back to the FOSS community and to the energy feedback research community.

This paper describes how the platform was configured as part of a year-long conservation program and field study to test the effectiveness of near real-time social comparisons – something that, to the author's knowledge, has not been evaluated in conjunction with feedback. Results of the field study and future work are discussed.

FIELD STUDY

Conservation Program Background

Approximately 30% of Canadian households reside in MURBs (Government of Canada, 2012). With an overall aging of the stock of MURBs there has been a growing effort on the part of industry and government to develop measures to improve their efficiency. The City of Toronto's Tower Renewal project (City of Toronto, 2015) is an example of one such initiative. However, while there are many conventional approaches to improving MURB energy, water and indoor environmental performance, most are directed at improving the building itself. It can be argued that reducing energy consumption in buildings and enhancing their performance is equally a social problem and technical one. Proponents of this vantage point argue that "buildings don't use energy: people do" (Janda, 2011).

Rental MURB dwellers tend to be of a lower or working class relative to their peers in single family homes. This likely results in energy use per tenant to be lower and it can be argued that there is less savings to promote. Neilsen (1993, from Fischer, 2008) found that savings were harder to tease out. However, it can be argued that low income households have most to gain since they spend about twice the percentage of their income on energy as compared to middle- or upper-class homes (Tweed, 2013). This sentiment appears to corroborate the view that feedback is not as effective for affluent homes where the cost of energy is low relative to income (Froehlich, 2009).

Given a pre-existing and longstanding relationship with Ryerson University, this research was set at a mid-rise rental MURB in Toronto's Parkdale community. The MURB is an affordable housing project, and home to those new to Canada, who have been living in shelters or sub-standard housing, or who lack resources to find decent shelter elsewhere. The tower itself contains 136 suites; 134 of which are nearly identical bachelors each with approximately 20.5m^2

of space. Figure 2 shows a typical floor plan in the 11 storey tower. The near-identical units are intended for single occupancy and also contain the same standard fridges, stoves, range hoods, and light fixtures. Additionally, the electrical wiring in each suite was isolated from others allowing for energy sub-metering as is currently being conducted by the property manager. Given the similarities and electrical isolation of each suite, the building was very amenable to field study work, as many typical infrastructure confounds are immaterial.

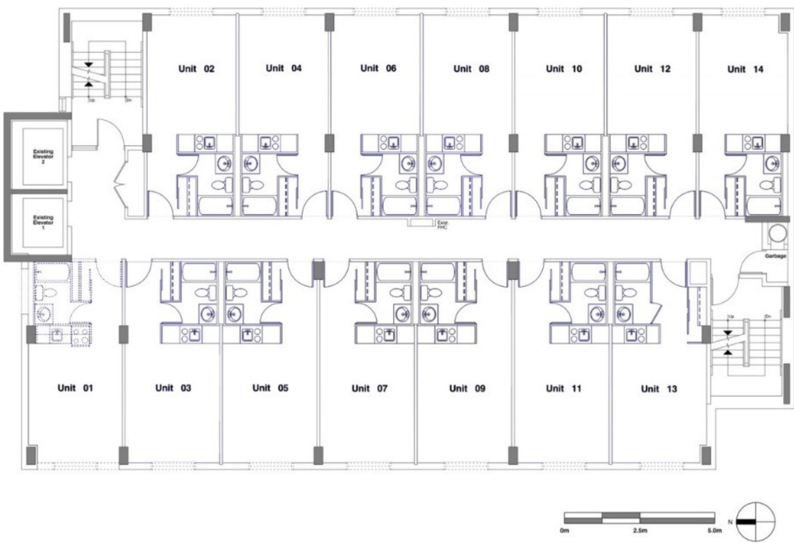

Figure 2. Typical floor plan at the study MURB

Hypotheses

The primary research question for the field study was: Can combining real-time feedback with real-time social comparisons help communities of users reach individual and collective energy conservation goals? In the context of an energy conservation program, this led to the following two hypotheses for the study:

Hypothesis 1: The conservation program comprised of an information campaign, participant commitment, and real-time feedback promotes energy conservation.

Hypothesis 2: Real-time feedback with social comparisons promotes more energy conservation than with just real-time feedback alone for total home energy use.

Participants

Of the 134 tenants in the MURB, 24 participants fulfilled the screening criteria of having lived there for at least one year prior, being 18 or older, and having working knowledge of the English language. 106 of the remaining tenants in the building were considered the control group; with permission, their energy usage data from the building's long-standing sub-metering system was used as part of the statistical analyses.

Apparatus – Feedback Research Platform (FBRP)

The system architecture implemented for this study was a modification from the general FBRP architecture described in the primary author's master's thesis. For the purpose of demonstrating the broader platform functionality, each suite was fitted with the following components from designs specially configured hardware based on designs from the open-source OpenEnergyMonitor project (http://www.openenergymonitor.org/):

1. A battery-powered emonTXv3 node installed inside the FCU to measure its fan power draw and output temperature measured at the top diffusing grate of the unit. Data were sampled every 10 seconds.
2. A battery-powered emonTH node measuring ambient temperature and humidity, installed in the "neck" of the apartment where the corridor opens up to the main living space.
3. A Raspberry Pi gateway to relay the sensor data collected for the suite to the content management system on-line.

In addition to the hardware installed in suites, there were components installed in the main hallway corridors and in electrical cabinets. emonTHs were installed in the hallway corridor of each floor. Inside the electrical cabinets, emonTXv3s were installed to measure up to two suites' total energy use (i.e., with each suite requiring two 120V lines). Raspberry Pi gateways were installed in the same electrical cabinets to relay all data collected from sensors in these spaces.

Android Tablets (ASUS MemoPad 7 HD with Jellybean 4.2) were given to each participant to allow them to view their own energy feedback dashboards using an app that was developed specifically for the study. The app also allowed participants to complete in-situ thermal comfort surveys on a weekly basis. Figure 3 offers a rich-picture illustration of these devices in the context of an empty suite.

Figure 3: Rich-picture diagram of feedback hardware
From bottom-left counterclockwise: emonTXv3 installed inside the fan coil unit, emonTH to sense ambient room temperature and humidity, a Raspberry Pi gateway/hub, emonCMS cloud service, Android tablet with dashboard app

The emonCMS cloud service was hosted on a private server on the internet. Data from all sensors in the study were stored on the same account and database to afford centralized data management. As part of the FBRP, weather data was pulled in from the Weather Underground service (www.wunderground.com) to the same database. Furthermore, while not analysed in this paper, in-situ surveys on thermal comfort were developed with Open Data Kit project (http://opendatakit.org/) and integrated into the dashboard app for participants. Dashboard usage analytics were tracked with Piwik (http://piwik.org/).

A building-wide, shared internet connection was provided to allow all sensor data to be forwarded to the cloud service and for data to be downloaded to tablets. Participants were also allowed to use it for general browsing on the provided tablets. To enable this building-wide internet connection, a mesh of 15 wired and wireless Wi-Fi repeaters from OpenMesh (http://www.open-mesh.com/) were utilized.

Apparatus – Feedback Designs

The feedback design in this study arose from three design iterations. The first iteration was based on feedback design best practices established by Trinh and Jamieson (2014).The second iterations was the result of a team-wide review. The third and final iteration (shown in Figures 4 and 5) leveraged findings from an informal usability study with two tenants from the study population.

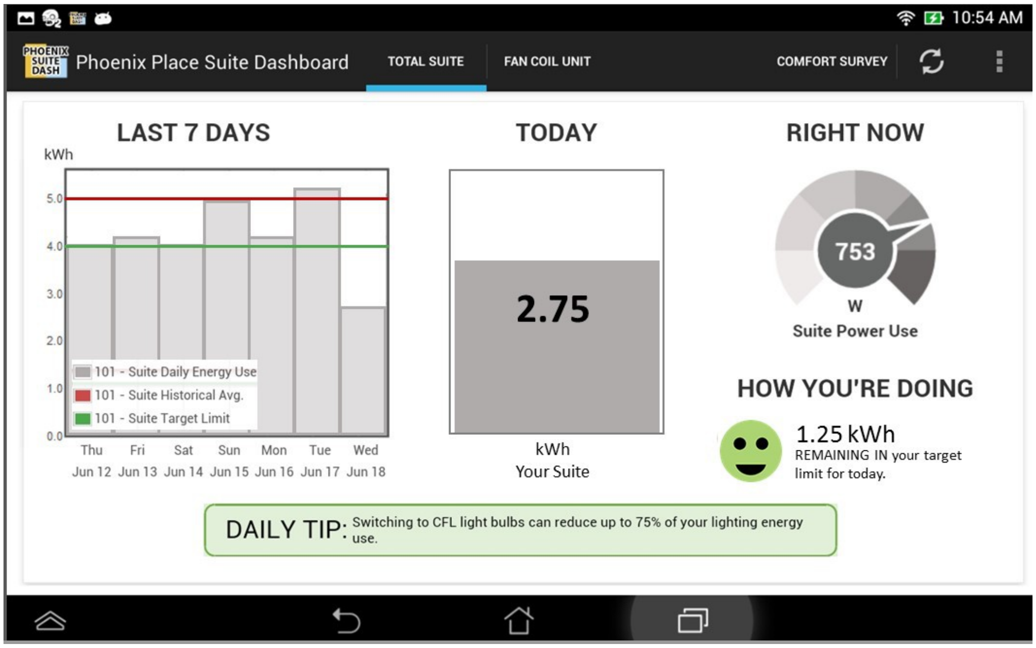

Figure 4: Basic feedback display

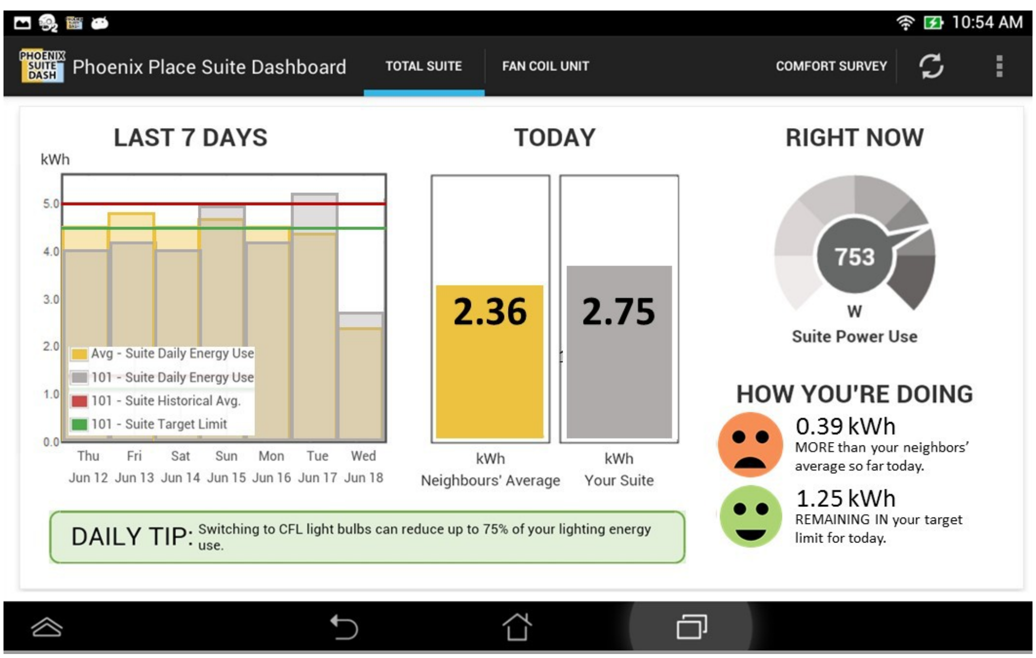

Figure 5: Basic feedback display with social comparisons

This final design can be explained through the following 5 heuristics:

1. **Consider the audience; be specific and personalized.** A lot of legwork to tailoring this display took place before even this first design was conceived. The feedback information provided on both displays are by definition personalized to the user.
2. **Benchmark in a fair and meaningful way.** The focus of this feedback is to provide not only real-time data for users to learn from, but also to provide clear and motivational points of references. The goal of the conservation program was to encourage 10% savings building-wide; a goal that is designed to cascade down to individual tenants. In the Total Suite display, the suite baseline curves (red lines) were determined based on the average monthly data from over three years' worth of data from the sub-metering system. The Suite Goal curve (green lines) reflect a 90% value from that goal.
3. **Average feedback over meaningful intervals**. When real-time feedback is first introduced it was anticipated that the "Right Now" power use dial would be most useful. However, as users begin understanding the energy impact from immediate behaviours and specific appliances, it was anticipated they would likely want to see this data averaged over a longer period to more effectively track savings. In anticipation of this trend, a bar chart for the "Past 24 Hours" was also provided. Similarly this was the rationale for the "Last 7 Days" graphs. It could be argued that weekly or monthly levels of aggregation would be useful as well; however, they were not included for a couple reasons. First, they would have required more display real-estate or more interactivity, possibly overcomplicating the dashboard given the nature of the study demographic. Second, having such displays might condone less frequent checks into the dashboard, providing less reason to check in at least weekly.
4. **Make the feedback information task relevant.** The overall task for the user is to keep their total suite energy use within their target upper limit of 90% of their baseline energy use (i.e., achieving a 10% overall reduction in their energy use). We also wanted to see how social norming may motivate them to conserve. As mentioned, specific comparisons were made to summarize these in the form of the happy or sad faces under the "How You're Doing" heading. As reflected in the list of tips, there were multiple target behaviours.
5. **Frame feedback data using concrete, tangible equivalents.** Currently, energy and power use are communicated in kWh and kW. Using better units of measure is an area that could be useful to help users understand the data. However, it was not clear what equivalent would resonate best with participants. An easy solution would be to show the equivalents in terms of its cost in dollars. However, the effects of time-of-use pricing can be difficult to grasp and the estimation of which introduces sources of inaccuracy. However, for the purposes of historical and social comparisons and goal setting, the unit of measure is of less importance. This is especially the case with visual comparisons of data as was relied upon in these dashboards. In summary, this heuristic was not as critical to meet.

Experiment Design

This field study used a univariate design with feedback type as a between-subjects variable. There were three levels of feedback: no feedback (control), basic feedback (which contained real-time feedback with historical comparisons), and basic feedback + social comparisons. The recruited participants were randomly assigned to receive one of the two feedback conditions. The final counts had 12 participants in each feedback condition, and 106 in the control condition.

Procedure

This field study was part of a larger energy conservation program lasting an entire year from September 2014 through August 2015. With permission of the board and the building's property management, tenants were first recruited in July-August 2014 timeframe to take part in an information session to kick-start the program. In this session they were provided with energy saving tips, and introduced to the program goal of saving 10% of energy use throughout the building and were also asked to commit, in writing, to personally saving 10% of their own energy use. Additionally, participants completed the New Environmental Paradigm (NEP) questionnaire (Dunlap, Liere, D, Mertig, & Jones, 2000) and demographics survey.

Following the information session, hardware installations were scheduled with participants in the following two weeks. Alongside the hardware installation, a basic energy audit of electrical appliances was conducted to help participants further understand their energy use and potential areas for savings within the suites. In total, the hardware and installation and energy audit took on average 30 minutes to complete.

Prior to the distribution of tablets, a week of data had been collected, to ensure proper installation and to provide data for the first contact with the feedback. Participants were given a one-on-one walkthrough and a printed visual guide to explain how to read the dashboards and ensure a basic understanding of kW and kWh terms. As part of the walkthrough, their fan coil units and a readily available appliance (e.g., floor lamp, or oven) were power cycled to show the impact of its power use on the display. This was followed by a basic hands-on quiz intended to ensure they understood the information being displayed and how to navigate through the app. Participants were reminded of the overall 10% savings goal for the program and how the feedback dashboards showed how much kWh per month that goal meant for them given their n historical energy use from the year prior to the study.

Participants in the feedback + social comparisons condition had the additional comparative information explained. However, to avoid adding external motivation, these participants were told that such information and comparisons were for their knowledge only, and that being better than average was not a program objective.

All participants were informed their usage of the app would be tracked by the research team from the study period of September 2014 through August 2015. It was also recommended to them that they check their dashboards daily, and that their participation required them to check at least weekly. At the end of the study, participants were asked to complete an exit survey to comment on their overall impression of the study, provide feedback on the dashboards, and share their savings strategies.

Measures

The primary dependent measure of interest is the total suite percentage energy use difference between the study period and the year prior. To ensure consistency between historical and study measures, the building's sub-metering system, which was Measurement Canada certified, was used for this purpose. To form a stronger basis for determining energy use savings or increases, all energy use data was weather-normalized using climate data obtained for Toronto since 1978 from the Government of Canada (http://climate.weather.gc.ca). For statistical analyses, savings would be measured at the individual level. However, for overall program performance, aggregate savings would be calculated for each experimental condition and from the entire study population.

RESULTS & DISCUSSION

As mentioned earlier, one objective of the conservation program was to achieve an overall 10% in energy savings year-over-year. Naturally, this program-wide objective cascaded to individual tenants, who were asked to save 10% of their own year-over-year energy use. Figure 6 shows percentage savings of actual group-aggregated kWh use and normalized a group-aggregated kWh use across the three groups of participants. The average actual savings percentage between the two feedback groups was 10.6% compared to an increased use of 2.3% for those outside the study. This leads to a net delta of 12.9% in relative savings. Similarly for normalized savings percentage, the average for those with feedback was 8.4% compared to an increase of 2.8% for those outside the study for a net delta of 11.2% in relative savings. It appears that the program was successful in surpassing the 10% savings target.

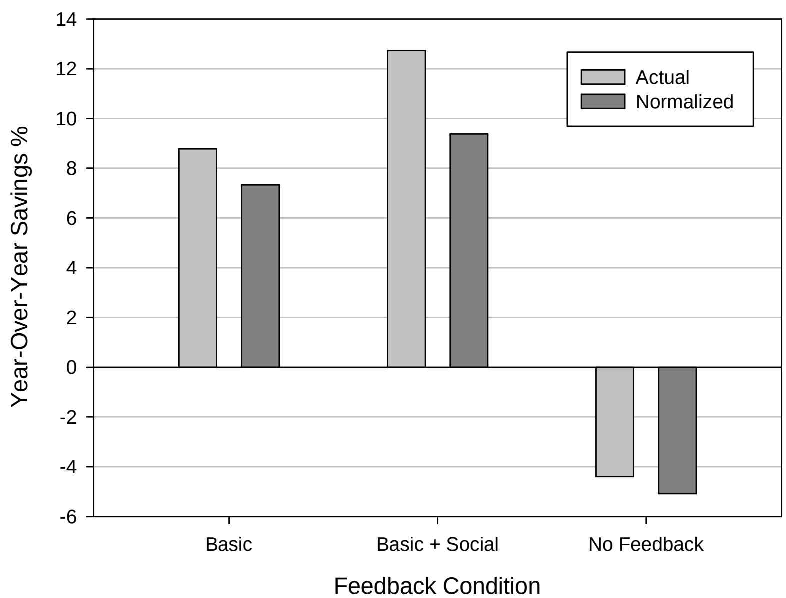

Figure 6. Aggregated year-over-year savings %

In addition to the conservation program objectives, this research also sought to test whether the savings would be statistically significant and thus reliable; and whether providing the real-time social comparisons would achieve improved savings in a similarly reliable fashion. The results shown in Figure 6 would suggest that there was a small improvement between the feedback conditions of approximately 6.2% and 5.8% in favor of having real-time social comparisons.

Test of Hypothesis 1 – The effect of the conservation program

A 2-level (participation type: feedback, no feedback) between subjects ANCOVA was run on the weather-normalized, annual savings percentage dependent variable to test the effect of the conservation program. Individual participant’s energy use (in kWh) for the year prior to the study was entered as a covariate.

There was a significant effect for the Baseline energy use covariate (F(1,128)=5.085, p=.026*). This indicated that the higher the baseline energy use, the more savings potential there was. There was also a significant finding for the main effect of participation (F(1,128)=3.938, p=.049*) as seen in Figure 7. Note that the group averages in these charts differ slightly from the group aggregated figures shown in Figure 6 due to differences in how the savings percentages are calculated in each analysis.

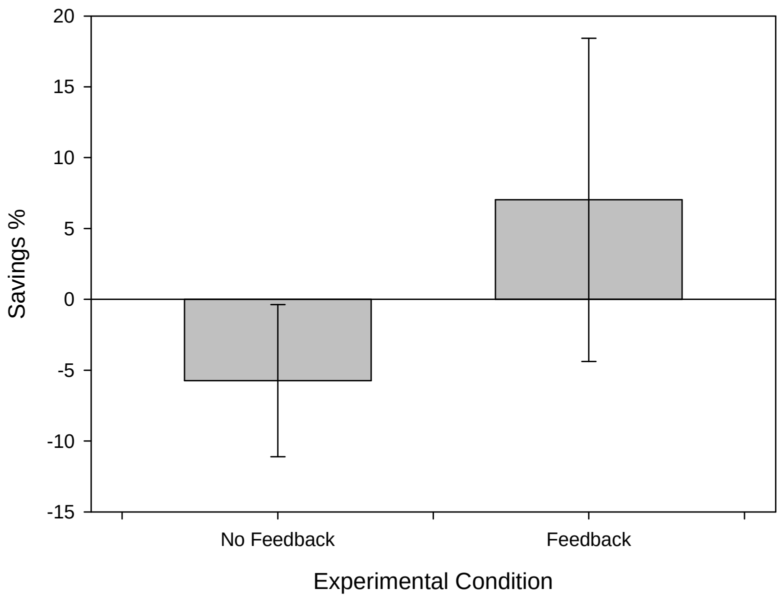

Figure 7. Error bar graph of experimental condition on savings %
Note error bar graphs represent 95% confidence intervals

It may be tempting to attribute the significant differences shown in Figure 7 to the availability of feedback; the provision of feedback was certainly a large component of the intervention. However, the experimental condition also comprised of an information campaign, a personal commitment to save 10%, and an energy audit. Furthermore, self-selection may have factored. Thus, it is still difficult to conclude to what extent feedback may have attributed to the savings. However, when enlarging the perspective of the field study, this is a very encouraging result for a couple reasons. First, the participants were not financially motivated to save. Second, many of the participants could be considered low power users with a baseline from which there was very little excess to trim.

Test of Hypothesis 2 – The effect of real-time social comparisons

A 2-level (feedback type: basic, basic + social comparisons) between subjects ANCOVA was run for the weather-normalized annual savings percentage dependent variable to test the effect of having additional information on social comparisons. Individual participant's NEP scores, page views, and pre-study energy use were entered as covariates.

There were no significant findings on normalized savings percentage for NEP scores (F(1,19)=.485, p=.50, n.s.) , page views (F(1,19)=.568, p=.46, n.s.), pre-study energy use (F(1,19)=.094, p=.76, n.s.) or feedback (F(1,21)=.114, p=.74, n.s.). Thus, hypothesis 2 was rejected. Figure 8 illustrates this non-significant effect.

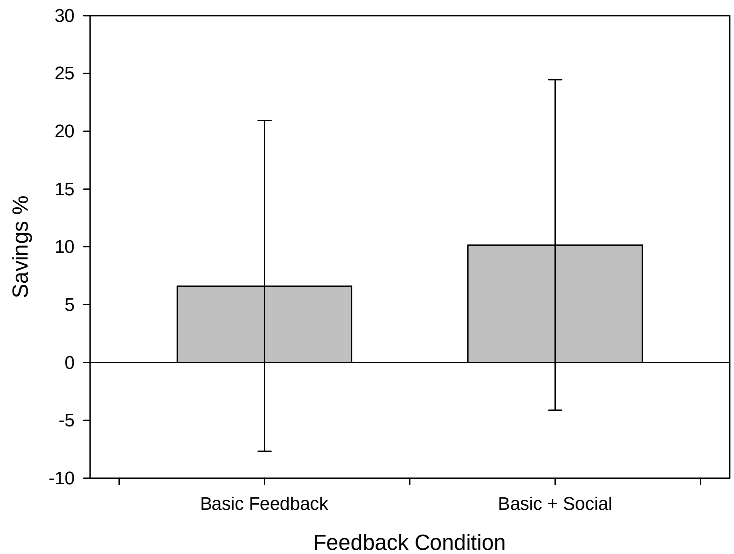

Figure 8. Error bar graph of feedback condition on savings %
Note: Non-significant effect. Error bars represent 95% confidence intervals.

This non-significant effect is not unexpected given the wide variability of energy savings observed year-over-year, the relatively small difference in savings between the two feedback conditions of 3.5% (i.e., 6.6% vs 10.1%) and the relatively small sample size for each feedback condition. Given the effect size between the two conditions is $r_{contrast}$ = .072, a power analysis (using an alpha = .05, beta = .8) suggests that a study sample size of 1,516 participants would have been required to obtain significant results.

While the benefit of real-time social comparisons is unclear, it would be prudent to still address the question: Would such a feedback strategy be worth the cost? Using a superficial inspection, the costs may not be too large for utilities who already have existing smart meter infrastructure in place. The main component missing is software comparison algorithms. Ensuring a fair social comparison would be perhaps the most difficult, but far from impossible, challenge. While atypical, the benefit of conducting the present study at Phoenix Place was that such complexities were circumvented by virtue of the homogenous nature of the suites and tenant population.

CONCLUSIONS

The purpose of this study was to develop and demonstrate a feedback research platform (FBRP) that affords a systematic approach to evaluating feedback designs. The implementation of this platform leveraged heavily on the advancement of Internet of Things (IoT) and free and open source software (FOSS). The FOSS-IoT-based platform was tailored as part of a larger energy conservation program to demonstrate three key features: disaggregated feedback, real-time social comparisons, and in-situ surveys to help understand user behaviours. Evaluating the efficacy of real-time social comparisons was the analytical focus of this paper. The preliminary results showed that the FBRP is useful and can generate data in a meaningful and coherent way for further research.

Feedback interventions should not and do not exist in a vacuum. For this reason, the energy conservation program presented in this thesis employed several interventions in addition to feedback, including an information campaign, suite energy audits, and participant pledges to save 10% towards a collective 10% savings for the program. The results showed a statistical significant effect of the conservation program with a significant, relative year-over-year, weather-normalized savings of approximately 11%. While there was a 3.5% difference in savings favoring an enhanced feedback with social comparisons (vs basic feedback) and warrants further investigation, this was not statistically significant.

Platform Potential Growth: Future Work

There are several key features worth pursuing in future versions of the platform. For example, one useful feature to include would be push notifications to alert or inform tenants when key thresholds have been crossed. Notifications may also be used to prompt users to perform specific tasks like opening windows with the weather is mild. Another feature would be to incorporate time of use (TOU) pricing for users who pay their own energy bills. This can be an important because lower energy use does not necessarily equate to lower energy costs. Furthermore, it is well known that managing peak demands by shifting energy use to lower peak times can save utilities and the general public billions of dollars in infrastructure costs.

Finally, in the context of managing micro-generation from solar and wind power generation, the platform may also be configured to ensure that a home operates on net-zero energy. Such a system could enable a lofty goal of sustainable off-grid homes. Many other technologies would obviously be required to turn this vision into a reality. For example, large batteries and passive housing designs come to mind. Perhaps with small steps such a vision can be realized. In combination with demonstrations like the one presented in this paper the authors hope to have shown that a sustainable future is closer than we might have imagined.

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