Assessment of Utilizing Mobile App in Delivering Eco-Feedback Information for Building Energy Conservation

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Abstract –

Researchers have developed various eco-feedback systems that aim at reshaping energy consumption behaviors of building occupants for energy conservation. Different technologies have been used to build eco-feedback systems through which occupants receive and respond to eco-feedback information. One emerging technology that has been envisioned for this purpose but rarely tested in practice is mobile app. This paper aims to examine the possibility of utilizing mobile app in eco-feedback system, and assess its effectiveness, benchmarked against web technology, a technology that has been proven effective in prior research for delivering eco-feedback information. Two eco-feedback systems were developed in this study and implemented in three student dormitories on a university campus. These systems used web technology and mobile app, respectively, to deliver the same eco-feedback information, and they differed significantly in their level of accessibility. Participants of a 15-week experiment were divided into two groups, each provided with access to one of the two systems. Experiment results showed that mobile app-based eco-feedback system led to relatively more intensive engagement of the participants with the system, and was significantly more effective in promoting building energy conservation.

Keywords –

Mobile app; Website; Behavior; Eco-feedback technology; Energy consumption

1 Introduction

Energy consumed in buildings has been considered a prime target for energy conservation, as buildings are responsible for 39.78% of whole energy consumption in the U.S. in 2015. Eco-feedback, which provides occupants with their energy consumption information, is a promising approach to gradually reshaping building occupants' energy consumption behavior and hence save energy [1]. The effectiveness of eco-feedback systems in energy conservation varies from 5% to 55% [2,3]. There is a number of factors impacting the effectiveness of eco-feedback systems that have been examined in prior study. Examples of such factors include culture [1,4], information representation [5] and interface design [6]. Technology used for developing eco-feedback systems, in particular, has been proven an important factor. Eco-feedback technologies can take on various forms such as utility bills, messages, emails, home-displays and websites. Website is one of the most effective and widely researched technology in prior studies [6,7]. Prior research also discussed the potential of utilizing mobile app in delivering eco-feedback information, as mobile phones provide a powerful and ubiquitous computing platform [8]. However, the effectiveness of app-based eco-feedback system is rarely experimentally examined, and its relative performance compared to more widely used eco-feedback technologies is unknown. To fill this gap, this paper aims to assess the effectiveness of app-based eco-feedback system, benchmarked with web-based eco-feedback system, and discuss possible causes of the discrepancies between them if any. The remainder of this paper is organized as follows: section 2 presents a brief overview of related research, followed by section 3 that introduces the settings of two eco-feedback systems developed in this study. Section 4 describes the design and implementation of an eco-feedback experiment. Section 5 then presents findings of this study. Section 6 concludes the paper.

2 Related Research

Various forms of eco-feedback systems developed with different technologies have been reported in prior research and used for reshaping occupants' energy consumption behavior in buildings [9]. Traditionally, energy consumption information was delivered by bills and posters. However, the frequency of updating information in these traditional methods is too low to provide real-time eco-feedback information, and is therefore a barrier in improving the awareness of habitual energy consumption behavior. Messages, emails, websites and in-home displays are then introduced, thanks to fast development of information and computing technologies in the last decades. A comparative study that involved website, in-home displays and improved electricity bill reported that occupants utilizing website-based eco-feedback system saved more energy than those utilizing the other two [7]. More recently, the possibility of utilizing mobile app to eco-feedback information has drawn considerable attention, due to the ubiquitous computing capabilities mobile app provides [10].

Eco-feedback system is a type of information system, whose accessibility can vary when different technologies are used to deliver information. Accessibility is an important dimension of system quality, and it is a major challenge in eco-feedback systems [8]. Accessibility refers to “the degree to which the system and the information it contains can be accessed with relatively low effort” [11]. According to information system success model [12], accessibility influences system success through impacting user satisfaction, attitude and user engagement with a system. For eco-feedback system, in particular, its effectiveness is influenced by attitude [13] and engagement [14] on which accessibility can be impactful [15]. Thus, the different effectiveness of eco-feedback systems built with different technologies can be possibly explained from the accessibility point of view.

3 Eco-Feedback Systems

Two eco-feedback systems, which differ in the way eco-feedback information is delivered, are developed in this study, as shown in Figure 1. One is a widely researched web-based eco-feedback system built with web technology. The other one is an app-based eco-feedback system built with emerging mobile computing technology. These two systems share the same data capture and processing component, including electric meters for each residential unit, data concentrators for each building, cables and a server where information is stored, processed, and prepared for delivery. The server updates daily energy consumption data for each unit and prepares it for user request. Web-based eco-feedback system delivers eco-feedback information through website interface. Information provided includes personal daily energy consumption data, historical personal data from the last seven days and last thirty days, and normative comparison with the user’s peers. App-based eco-feedback system provides the same information as web-based eco-feedback system, but through mobile app. Furthermore, mobile app provides a gadget in the notification panel of mobile phones, where energy consumption overview of the previous day and the last seven days is displayed to the user. The two systems also share an email portal, which is responsible for sending emails to users to remind them of using eco-feedback systems to access eco-feedback information. For web-based eco-feedback system, the email portal sends reminders every Monday morning. For app-based eco-feedback system, the email portal sends reminders whenever a user remains inactive for over 24 hours, which is considered an alert that the mobile app has been killed or malfunctioning for some reason.

A fundamental difference of the two systems is their level of accessibility. The accessibility of online systems can be assessed in three dimensions, including physical accessibility, interface accessibility and information accessibility [16]. Physical accessibility assesses users’ access to terminal and access to online system [16]. Interface accessibility assesses users’ use of command language in online system [17]. Information accessibility assesses the extent to which users can employ a system to reach information [17]. The app-based eco-feedback technology has higher accessibility than the web-based eco-feedback technology due to the following reasons: 1) mobile app users do not need to remember or type in account information as website users have to do, leading to better access to online system and hence high physical accessibility; 2) the app-based system includes a gadget that provides an additional pathway to the full interface, which improves the interface accessibility of the system; and 3) the use of gadget improves the information accessibility of the system, by providing users with a quick overview of key eco-feedback information in the notification bar without having to access the full interface.

4 Eco-Feedback Experiment

4.1 Test-bed Buildings and Participants

An experiment was designed and carried out in this study, to empirically compare the effectiveness of eco-feedback systems with different levels of accessibility in changing the energy consumption behaviors of occupants. Test-bed buildings used in this study were three six-story student dormitories on the campus of Tongji University. Each residential unit in these test-bed buildings had a bathroom, a bedroom and a balcony, and could accommodate one or two occupants depending on its area that varied between 8m^2 and 13.77m^2. Given that each unit had a designated electric meter and hence the energy consumption was measured at the unit level, only single units were included in the experiment so that the eco-feedback information could be processed and provided at the individual occupant level. Typical appliances in these units included lights, air conditioners, phone chargers and computers, according to site visits and informal interviews. Students living in single units in the test-bed buildings were face-to-face interviewed, during which they were explained the purpose of the experiment, and informed that they would be provided with an individual login account to the website or mobile app for accessing their respective electricity usage data and the averaged data of their peers. They were also informed that they would receive emails reminding them of checking the energy consumption information. A total of 33 single-unit occupants in the test-bed buildings signed up to participate in the experiment.

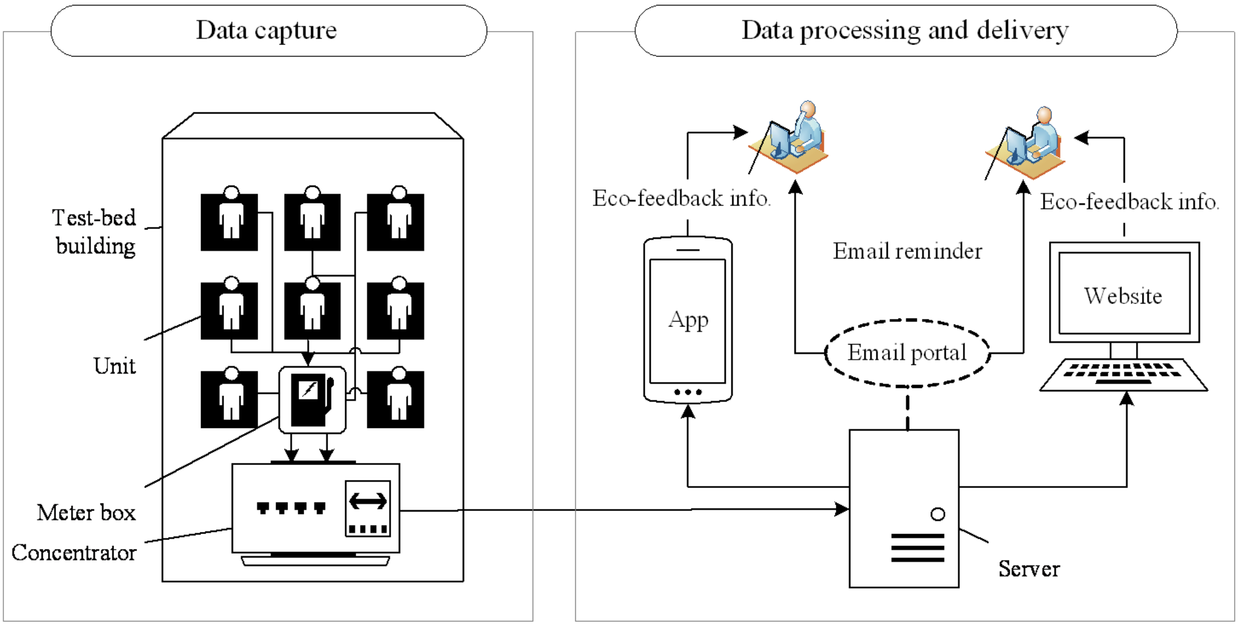

Figure 1: Architecture of two eco-feedback systems

4.2 Experiment Design

The experiment lasted for 15 weeks, from October 17, 2015 to January 29, 2016. It included a pre-study phase and a study phase. The pre-study period (phase 0) lasted for 6 weeks from October 17 to November 27, 2015. Daily energy consumption data were collected during this period and used for offsetting the effect of inherent difference between two SGs. Participants received no eco-feedback information or behavior intervention of any kind during this period. Then, participants received an email containing their individual account information of the eco-feedback system, and a link to the login page of the website or download page of the app on November 28. The study period (phase 1) lasted for 9 weeks from November 28, 2015 to January 29, 2016. During phase 1, participants using the web-based system received emails every Monday morning reminding them of logging into the website to check their eco-feedback information, and participants using the app-based system received emails once their app remained inactive for over 24 hours. Daily energy consumption data in all single units were collected during phases 0 and 1 for comparing the effectiveness of two eco-feedback systems in reshaping the participants' energy consumption behaviors. All single-unit occupants in the test-bed buildings were divided into the following three groups:

- Study Group A (SG A) – Experiment participants provided with web-based access to eco-feedback information.
- Study Group B (SG B) – Experiment participants provided with app-based access to eco-feedback information.
- Control Group (CG) – Occupants not participating individually in the experiment and not provided with access to any eco-feedback information.

There were 14 and 19 participants in SG A and SG B, respectively, and 257 occupants in CG. They were all PhD students between 21 and 30 years old. Among participants in SGs, 54.55% were male and 45.45% were female. A total of 54.55% participants indicated in a questionnaire that normally they would check emails immediately when they were alerted by mobile app of incoming new emails, and 96.97% of them would check emails at least once per day. A total of 76.76%

participants indicated they would keep their mobile phones connected to Internet at least 8 hours a day, and 39.39% of them would keep their mobile phones online all the time.

5 Findings and Discussions

After missing or corrupted data points were cleaned, a total of 25,858 valid data points of daily energy usages in single occupancy units were collected during the entire experiment. These included 22,617 data points for CG, 1,375 data points for SG A, and 1,866 data points for SG B. The statistical percentage difference in energy consumption resulting from the use of the eco-feedback system (Δ_b (%)), a measure of behavior change of occupants, was calculated as follows ([5]):

$$\delta_{pre-study\_b}(\%) = \frac{\sum_{i=1}^{n}((P-C)/C)}{n} \quad (1)$$

$$\delta_{study\_b}(\%) = (P-C)/C \quad (2)$$

$$\Delta_b(\%) = \delta_{study\_b} - \delta_{pre-study\_b} \quad (3)$$

where P denotes the energy consumption of a given room on a given day, C denotes the average daily consumption per unit in CG, Δ_b denotes the energy consumption behavior changes, measured in percentage, of a SG in energy consumption, relative to the corresponding CG, between the pre-study period and the study period, $\delta_{pre-study\_b}$ denotes the average percentage difference between P and C for a given day of the week in the pre-study period, δ_{study_b} denotes the percentage difference between P and C for a given day of the week in the study period, and n denotes the number of the days of the pre-study period.

The statistical absolute difference in energy consumption resulting from the eco-feedback information (Δ_{con} (kWh)), a measure of energy consumption savings of occupants, was calculated based on the following equations ([5]):

$$\delta_{pre-study\_con}(kWh) = \frac{\sum_{i=1}^{n}(P-C)}{n} \quad (4)$$

$$\delta_{study\_con}(kWh) = P - C \quad (5)$$

$$\Delta_{con}(kWh) = \delta_{study\_con} - \delta_{pre-study\_con} \quad (6)$$

where Δ_{con} denotes the absolute energy savings, measured in kWh, of a SG in energy consumption, relative to the corresponding CG, between the pre-study period and the study period, $\delta_{pre-study\_con}$ denotes the average absolute difference between P and C for a given day of the week in the pre-study period, δ_{study_con} denotes the absolute difference between P and C for a given day of the week in the study period, n denotes the number of days of the pre-study period. It needs to be noted that Δ_b and Δ_{con} differ mainly in the way they factor in variable C , which varies depending on external factors such as temperature. It needs to be noted that it is mathematically possible, and was actually observed in the experiment, that trend of energy consumption savings (Δ_{con}), i.e. increase or decrease, may not always agree with the trend of energy consumption behavior change (Δ_b).

Cumulative energy savings (Δ_{cum} (kWh)), a measure of cumulative energy savings of a SG since the beginning of phase 1, was calculated based on the following equation:

$$\Delta_{cum}(kWh) = \sum_{i=1}^{d} \Delta_{con} \quad (7)$$

where Δ_{cum} denotes the cumulative energy savings in kWh for a SG in energy consumption, relative to the corresponding CG, and d denotes any given day in the study phases.

Both energy consumption behavior changes and energy savings of the participants in SG A and SG B, were analyzed based on data collected in the experiment. Table 1 shows the mean Δ_b and Δ_{con} of SG A and SG B in phase 1. Negative values in the table indicate positive behavior changes or energy savings, and vice versa.

Table 2: Behavior change of SG A and SG B

	Δ_b (%)	Δ_{con} (kWh)
SG A	-0.26	0.37
SG B	-24.27	-0.78
Sig.	0.000	0.000

To compare the results between two groups and between two phases, independent-samples T test was conducted using SPSS 20. The results showed that, at a confidence level of 95%, participants using web-based eco-feedback system barely changed their energy consumption behavior, with negligible positive behavior change by 0.26% (p-value=0.968>0.05). Meanwhile, they significantly increased their energy consumption by 0.37 kWh per participant per day on average (p-value=0.004<0.05). Similar observation where eco-feedback led to more energy consumption was also reported in prior studies. For instance, Jain et al. [5] found that unsuitable information representation in eco-feedback system could cause increase of energy consumption. Another possible reason for this observation is that some participants, by receiving eco-feedback information, may realize that they overestimated their daily energy consumption before and they were actually using less energy. Consequently, they may become less concerned about energy conservation and start increasing their energy consumption. While this hypothesis requires further validation, it suggests the possibility that eco-feedback may be counterproductive for users who are already over concerned about energy conservation. In addition, the participants came from different regions in China with different cultural and social background. Culture [1,4] and social norm [18] are influential factors on the effectiveness of eco-feedback. They could be another reason why the participants reacted differently to eco-feedback, with some of them showing significant negative behavior changes.

To the contrary, participants using app-based eco-feedback system showed significant positive behavior change of 24.27% (p-value=0.000<0.05), and significant energy savings of 0.78 kWh per participant per day on average (p-value=0.000<0.05). At a 95% confidence level, both Δ_b and Δ_{con} were statistically different between the two SGs in phase 1 (p-value=0.000<0.05 for both variables). In other words, the difference in eco-feedback technology resulted in different behavior-changing and energy-saving effects in the experiments. For behavior change (Δ_b), participants utilizing app-based eco-feedback system saved 23.01% more than participants utilizing web-based system on average, which indicated that app-based eco-feedback system was more effective than web-based eco-feedback system in reshaping occupants' energy consumption behavior. For energy consumption change (Δ_{con}) , participants utilizing app-based eco-feedback system saved 1.15 kWh more electricity per participant per day on average than participants utilizing web-based eco-feedback system, which indicated that app-based eco-feedback system saved more energy than web-based system.

Cumulative energy savings (Δ_{cum}) of two groups were also analyzed to assess the cumulative energy-saving effectiveness of the two systems over the entire experiment. The results are showed in Figure 2. As can be seen in the figure, when participants were not affected by eco-feedback during phase 0, their energy consumption behavior generally remained stable, and the two SGs were alike. Once participants started receiving eco-feedback information, the results showed that those in SG B who used app-based eco-feedback system changed their behaviors towards energy conservation, and their cumulative energy savings was positive and steadily increasing. Participants in SG A who used web-based eco-feedback system, however, reported negative cumulative energy savings of up to 62.31 kWh over the entire phase 1.

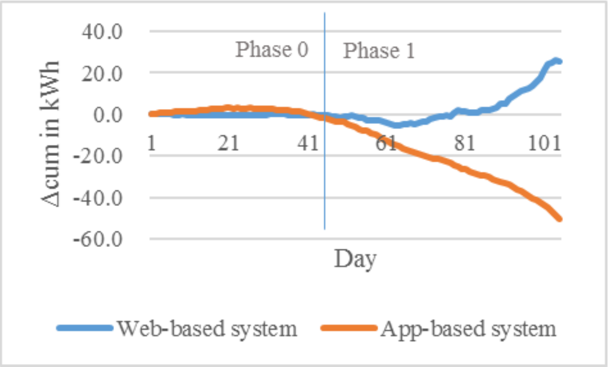

Figure 2: Cumulative energy savings among phases

To sum up, during phase 1, the app-based system resulted in positive energy consumption behavior change (Δ_b =-24.27%), whereas the web-based system did not yield any significant behavior changes. Such difference could probably be attributed to the different levels of accessibility between the two systems. As discussed in Section 3, the app-based system had higher accessibility than the web-based system. Drawing on the information system success model, success of information systems, in this case positive change of energy consumption behavior and positive energy savings achieved by eco-feedback systems, could be impacted by accessibility through participants' engagement [19]. Prior research has found that participants' engagement was correlated with the behavior-changing effect of eco-feedback systems [6]. The participants frequently engaging in eco-feedback were more liked to be affected by eco-feedback and would tend to save more energy. To test this hypothesis in this study, participants' engagement with eco-feedback systems recorded in the server was further analyzed, and the results are shown in Figure 3. The results showed that participants in SG A were much less active in engaging with the system to retrieve eco-feedback information than participants in SG B, with an average of 1.15 and 54.90 activities (logins plus data views) per week per participant, respectively. It is therefore hypothesized that accessibility might have positively affected occupants' engagement with eco-feedback systems which, in turn, positively affected the effectiveness of the eco-feedback systems in reshaping participants energy consumption behaviors.

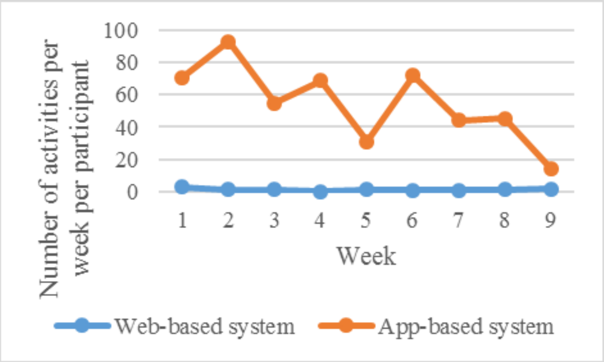

Figure 3: Engagement of participants with two eco-feedback systems

6 Conclusions

This study assesses the effectiveness of utilizing eco-feedback systems, built with two technologies including web technology and mobile app, in reshaping the energy consumption behavior of building occupants for building energy conservation. Two eco-feedback systems were developed in this study, using web and mobile app technologies, respectively, and deployed in three test-bed buildings, where an eco-feedback experiment was conducted over 15 weeks. By analyzing the behavior changes and energy consumption changes of the participants utilizing two eco-feedback systems, the results showed that the two eco-feedback systems exhibited noticeably different behavior-changing and energy-saving effectiveness. Overall speaking, mobile app-based system achieved significantly better performance, and a probable reason for such difference is the higher accessibility of app-based system. Practically speaking, mobile app provides more effective delivery of eco-feedback information and should be considered as an effective alternative technology in eco-feedback systems. It suggests that technologies and system designs that can improve system accessibility and increase user engagement should be encouraged in the development of eco-feedback systems in practice.

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