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Real-time, appliance-level electricity use feedback system: How to engage users?

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ABSTRACT

Engage is a rapidly deployable, retrofit energy monitoring system developed for direct support of a novel energy use behavior investigation and a large-scale deployment in campus apartments. We describe the end-to-end system and report results related to web dashboard engagement during a year-long experiment. The objective was to determine user engagement with real-time and easily accessible information about personal energy consumption. Leveraging low-cost components, this system was designed to measure separately appliance plug load, heating and cooling, and lighting electrical load in dense-occupancy building environments. We developed and used an open source technology for measurement of plug load and developed signal processing algorithms to significantly improve measurement accuracy. We also developed proxy sensors to measure heating and cooling and lighting. Our results indicate that 90% of the dashboard activity was undertaken by 50% of the participants and that website engagement was more likely in mid-day and more effective in combination with email reminders. Energy conservation was achieved when combining the dashboard with public information about energy consumption.

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1. Introduction

Electricity generation accounts for over 40% of the carbon dioxide emitted by the United States with residential and commercial buildings collectively accounting for over two-thirds of total U.S. energy consumption [1,2]. This is not surprising considering that residents of the United States spend more than 90% of their lives in buildings [3]. Recent studies estimate that behavioral changes can reduce residential energy consumption significantly [4,5]. Delmas et al. reviewed 156 studies and found an average 7.4% reduction in energy consumption, with the largest reductions resulting from individualized feedback [6]. However, many of the studies in the literature suffer from methodological limitations including small sample sizes [7,8], short time periods [9], or low-granularity feedback (i.e. providing only total usage for the building versus per-appliance usage) [10–12].

While scholars argue that high-granularity information can facilitate energy reduction [13], technological challenges make it unlikely to achieve large-scale deployment in the near future. The main constraint to obtain higher-granularity energy usage information in existing buildings is the infrastructure, which does not allow for direct measurement of distinct loads such as lighting or heating, ventilation and air conditioning (HVAC) for separate rooms. Current building-level meters do not provide high-resolution, high-granularity, real-time information at the room level, even with newer smart meters. This is because circuits in electrical panels in large buildings are not likely to be dedicated to room-specific, individual appliances. While plug-level and appliance-level approaches can provide energy use for specific appliances, they do not provide comprehensive monitoring. Plug-level devices, such as the Kill A Watt [14] and ACme [15], cannot measure energy consumption from built-in appliances like recessed lighting. Appliance-level sensors measure indirect energy emissions (including light, sound, vibration, or electromagnetic fields) to determine appliance state but face scalability challenges [16,17]. Appliance load disaggregation methods which aim to provide appliance-level information from aggregate energy measurements are promising but their overall effectiveness is not proven, especially in large-building infrastructures [18].

In this project, to achieve high-granularity, appliance-level feedback at the room level, we developed an end-to-end system architecture that included low-cost, wired appliance-level sensors and wireless plug-level meters, a remote gateway for

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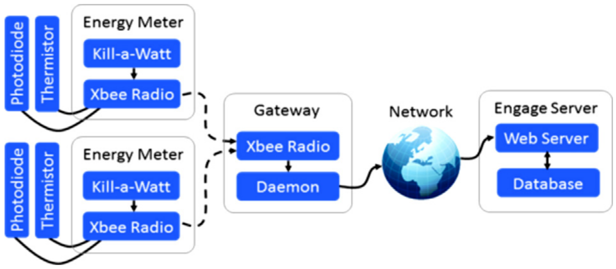

Fig. 1. Engage end-to-end system architecture.

local processing and data upload, and a backend for data storage, data processing, and web services. We monitored residents' energy usage over a 7-month period, providing high-resolution and high-granularity individualized information. We also observed dashboard engagement using website analytics. While several studies have assessed the effectiveness of various design components of feedback information [19–21], but to our knowledge none have used website analytics data to identify dashboard access patterns. Our study is therefore the first to test the effectiveness of and end-to-end feedback system on consumer engagement and energy consumption.

We deployed our end-to-end system in 66 rooms in three high-rise residence halls on the UCLA campus over the course of one academic year. The population consisted of 102 undergraduate students living in single-, double-, and triple-occupancy rooms. These buildings were constructed in 2005 and 2006 as part of a single construction phase with only minor variations in design. This allowed us to isolate differences in energy consumption due to information feedback rather than infrastructure. Furthermore, because students do not pay for electricity, they are an ideal population to study behavior responses to various forms of information feedback. This allowed us to test the effectiveness of information in the absence of an inherent financial incentive to conserve electricity.

The remainder of the paper is organized as follows. We describe the system design and each of the components. We also describe in detail the signal processing for our energy meters as it significantly improves the capabilities of the reference design on which it is based. Finally, we describe the user web dashboard and provide results from the analytics data and energy consumption.

2. System design

Our objective was to test the effect of access to appliance level, real-time and historical energy use information on energy consumption. To achieve high granularity, we developed an end-to-end system architecture shown in Fig. 1 that included low-cost sensors, a remote gateway for local processing and data upload, and a backend for data storage, data post-processing, and web hosting. We identified three load categories that were controllable by residents, and were practical to measure: (1) the appliance plug load from the electrical outlets, (2) the overhead lighting, and (3) the heating, ventilation, and air conditioning (HVAC) system. This allowed participants to learn about the contribution of different types of appliances to overall energy consumption and adjust accordingly. For example, we found from survey results that residents consistently overestimated the share of energy from lighting use as being nearly equal to heating and cooling use whereas results from our system indicated that heating and cooling comprised 72% of energy versus 5% for lighting.

It was important to develop a solution that balanced many factors including cost, development time, reliability, accuracy, and deployment setting. The system also needed to be rapidly deployable, given the short time span allotted for installation by the administration between the end of summer occupancy and start of fall occupancy. Further, budget constraints required us to strive for a low cost solution in order to reach a deployment scale and population sample size that would yield statistically significant behavioral analysis. The total hardware cost per installation was under $200.

2.1. Hardware

The deployment hardware consisted of four components designed to collect information about electricity consumption and appliance state and transmit it to our database via the building's wired network: the energy meter, light and temperature proxy sensors, and gateway.

2.1.1. Energy meter

The energy meter was a modified Kill A Watt which allowed us to measure the electrical plug load, interface with proxy sensors, and transmit measurements to the gateway. The augmentation was inspired by a popular open source modification called Tweet A Watt [22], which integrates a wireless XBee radio [23] into the Kill A Watt to enable the device to "tweet" energy usage data to the online microblogging service Twitter, via an internet-connected computer acting as a gateway. The Tweet A Watt design leverages two of the six analog input channels on the XBee radio module to measure the current and voltage signals on the Kill A Watt. Our design made use of the additional analog input channels on the XBee radio to interface with the proxy sensors.

For each room, we installed two energy meters to capture the energy usage. This number was based on the room design such as the placement of electrical outlets, arrangement of appliances and convenience to the residents. We installed the meters on two selected electrical outlets and the power strips were plugged into the meters with other outlets covered over with tape to discourage use. All electrical devices were plugged into the energy meters via the powerstrips. This way, the energy meters measured the total energy consumed by all the electrical devices (i.e. computer, microfridge, phone charger, TV, game consoles, etc.). Energy measurements from the two meters were then added together and we refer to this as the plug load.

2.1.2. Proxy sensors

To allay cost and work with infrastructure constraints, we developed proxy sensors using photodiodes and linear active thermistors. The photodiodes were used to determine light state, which we then converted to light energy consumption. Similarly, the thermistors were used to determine HVAC state and energy consumption. The component materials cost only a few dollars and are less expensive than direct energy measurement using current transducers which would have also required infrastructure modification. We further reduced cost by designing the sensors as cable strands rather than as wireless sensor platforms. While wireless sensors would have helped expedite the installation, the hardware cost of a wireless platform using our limited budget would have been prohibitive to the deployment scale we required.

An example floor plan and sensor installation is shown in Fig. 2. To the extent possible, the cables were installed along the corners of the participants' rooms to be minimally conspicuous and reduce the potential for accidental tampering.

Each room contained either one or two overhead lights. We affixed light sensors to the light source so as to minimize the amount of ambient light. It was important to consider the variability in maximum ambient light levels across different housing units that result from a room's floor level and orientation relative to the path of the sun as well as external occlusions. However, testing across rooms revealed that photodiode output from the overhead lights was significantly higher than from ambient light. We were