Pilot Study of a Plug Load Management System: Preparing for Sustainability Base

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***Abstract*—NASA Ames Research Center's Sustainability Base is a new 50,000 sq. ft. high-performance office building targeting a LEED Platinum rating. Plug loads are expected to account for a significant portion of overall energy consumption because building design choices resulted in greatly reduced energy demand from Heating, Ventilation, and Air Conditioning (HVAC) and lighting systems, which are typically major contributors to energy consumption in traditional buildings. This paper reports on a pilot study where data from a variety of plug loads were collected in a reference office building to understand usage patterns, to make a preliminary assessment as to the effectiveness of controlling (i.e., turning off and on) selected loads, and to evaluate the utility of the plug load management system chosen for the study. Findings indicate that choosing energy efficient equipment, ensuring that power saving functionality is operating effectively, promoting beneficial occupant energy behavior, and employing plug load controls to turn off equipment when not in use can lead to significant energy savings. These recommendations will be applied to Sustainability Base and further studies of plug load management systems and techniques to reduce plug energy consumption will be pursued.**

I. INTRODUCTION

In the past several years there has been tremendous interest in green technologies and sustainable practices within the building industry. In the United States there were approximately 130 million residential housing units in 2009 [1] and nearly 5 million commercial buildings as of 2003 [2]. In 2007, residential and commercial building construction and renovation was estimated to cost 1.2 trillion dollars, over 8% of the U.S. gross domestic product. Residential and commercial buildings accounted for 40% of total U.S. primary energy consumption and 72% of electricity consumption [3] and were responsible for 40% of carbon dioxide emissions in 2009 [4].

Several government initiatives have focused attention on sustainability, energy efficiency, and the environment. One such initiative is NASA's Renovation by Replacement (RbR), which aims to replace outdated and inefficient buildings at NASA centers with new, energy-efficient buildings. NASA Ames Research Center won a RbR competition and worked with partners to design and build Sustainability Base (depicted in Figure 1 and named to associate with Tranquility Base, the site of the first human moon landing), a 50,000 sq. ft. high-performance office building targeting a LEED Platinum rating. In addition to using commercially available technologies, Sustainability Base will employ innovations and technologies originally developed for aerospace missions to monitor and control building systems while reducing energy and water consumption.


Fig. 1: NASA's Sustainability Base Building

A goal of Sustainability Base is to provide a research testbed where different sustainable technologies and concepts can be implemented, tested, and demonstrated. One example, and the focus of this paper, is measuring and controlling electrical plug loads. Whereas in traditional, minimally code-compliant office buildings plug loads may account for 25% or less of total energy consumption, in high efficiency buildings plug loads may account for more than 50% of the total energy consumption [5]. Since Sustainability Base was not occupied at the time of this investigation, the pilot study of a plug load management system was conducted in a traditional building with similar electrical loads. Lessons learned in this pilot study and in other studies [5]–[7] will be put to use in Sustainability Base.

II. PILOT STUDY

In preparation for deploying a plug load management system in Sustainability Base, a pilot study was conducted on the NASA Ames campus during the spring and summer 2011. The goals of the pilot study were to passively collect data from a variety of plug loads, to make a preliminary assessment as to the effectiveness of controlling (i.e., turning off and on) selected loads, and to evaluate the utility of the plug load management system chosen for the study.

The study was performed using a plug load management

(a) Power Port (b) Bridge

Fig. 2: Plug Load Management Equipment

system from Enmetric Systems, Inc.[1] that allows for the metering and control of individual electrical plug loads. The system includes Power Ports and Bridges, shown in Figures 2a and 2b, respectively. The Power Port is a power strip with four channels (receptacles) that are individually metered and controlled. The Power Ports transmitted power draw data once per second to the Bridges. Data were stored in a cloud-based data service once per minute with the minimum, mean, and maximum power draw over each one minute interval recorded.

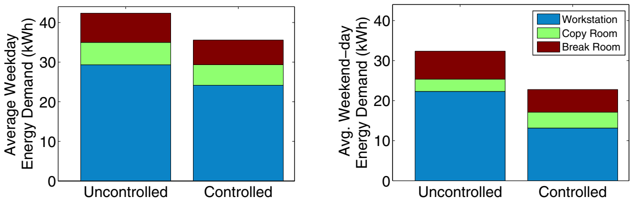
Fifteen Power Ports and three Bridges were used for the pilot study. Power strips were deployed to locations that included a variety of plug load devices anticipated in Sustainability Base. Workstations of administrative, financial, project management, and technical personnel were chosen as well as a break room and shared printer/copy room. Table I shows a breakdown of the plug load device types included in the study.

TABLE I: Plug Load Device Breakdown

Location	Device	Number
Workstations (7)	Desktop Computers	6
	Laptop Computers	3
	Monitors	7
	Printers	5
	Phones	2
	Shredders	2
	Speakers	3
	Scanners	3
	Other	10
Copy Room (1)	Printers	2
	Copier	1
	Shredder	1
Break Room (1)	Refrigerator	1
	Vending Machines	2
	Microwave	1
	Coffee Maker	1

III. RESULTS

The uncontrolled portion of the testing spanned five weeks and established a baseline energy consumption. The controlled portion of the testing employed schedule-based rules for turning off selected loads during non-business hours; it also modified the energy saver policies for certain devices. The default schedule was to turn off devices at 10 pm and turn them on at 6 am. Different timings were implemented for a couple workstations/workspaces to better fit the occupants' work schedule; however, in general the rules were not optimized to the work schedules of the occupants. In all cases, the same timing was used for weekdays and weekends. This was a very conservative approach to accommodate anticipated occasional work during the weekends. Note that we did not adjust energy consumption calculations for vacation or travel, which occurred during both the uncontrolled and controlled portions of the test period.



(a) Weekdays (b) Weekends

Fig. 3: Uncontrolled and Controlled Average Daily Energy Consumption

After initial tests of schedule-based rules over the course of several weeks, a 'final' set of rules was deployed and controlled energy consumption data were gathered for approximately nine weeks. Figure 3a shows the uncontrolled and controlled average daily energy consumption for weekdays; Figure 3b shows weekends. For both plots, the left stacked bar shows the uncontrolled average daily energy consumption while the right bar shows the controlled. Adjustments have not been made for changes in use patterns (for example, the average number of print jobs per day being different) between the controlled and uncontrolled periods. The controlled energy consumption includes the contribution from the plug load management system. The energy consumption of the plug load management system was measured and distributed in proportion to the number of power strips per location. The energy savings for employing schedule-based controls and energy policy changes is 6.8 kWh/day (16%) for weekdays and 9.6 kWh/day (30%) for weekends and holidays. The larger power draw of the copy room during the controlled portion of the testing is primarily due to a malfunctioning copier, which did not enter the power saving mode consistently.

Figure 4 shows the daily energy consumption over the 106 day study period. The uncontrolled and controlled days are to the left and right of the dotted line (day 39), respectively.

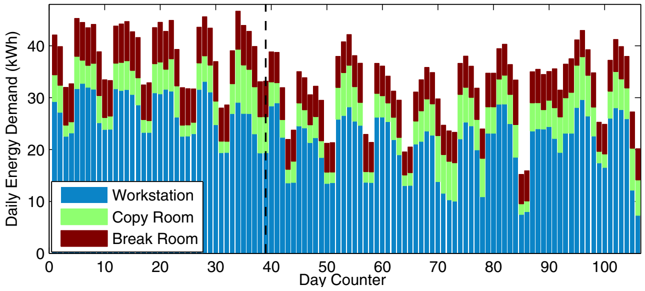


Fig. 4: Daily Total Energy Consumption

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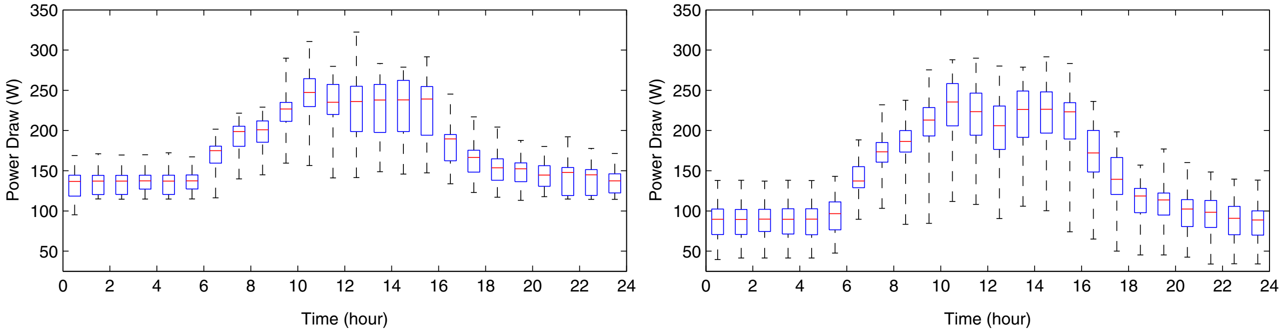
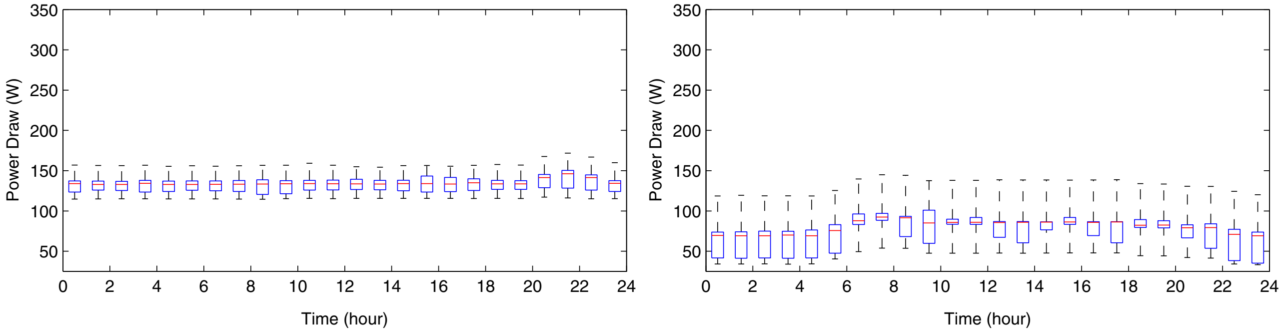
[1] http://www.enmetric.com/



(a) Weekday-Uncontrolled

(b) Weekday-Controlled



(c) Weekend-Uncontrolled

(d) Weekend-Controlled

Fig. 5: Distribution of Average Workstation Hourly Power Draw

Note that 39 of the 50 channels had schedule-based rules. Six channels had no rules because the connected computers could not be de-energized without possibility of damage or data loss; one channel was connected to a refrigerator containing food; two channels were found to consume more energy with rules in place; one channel had a plug load management system bridge connected which could not be de-energized; one channel did not return to a ready-to-use state once re-energized. These points and the energy consumption of workstation, copy room, and break room loads are described in more detail in the following subsections.

A. *Workstation Loads*

Workstation loads constitute a large portion of the metered energy consumption in the study. This is primarily because 41 of 50 monitored channels were classified as workstation loads, whereas there were only 4 in copy room and 5 in break room classifications. This corresponds to loads in 7 workstation locations, 1 copy room location and 1 break room location. This is similar to the pattern in Sustainability Base, which has 210 workstations, 4 copy rooms and 6 break rooms. Each workstation has a laptop or desktop computer, a phone, and a monitor. Some workstations also include other electrical loads such as speakers, printers, external hard drives, paper shredders and additional monitors or computers.

Most of the electrical loads at workstations have use-dependent energy demands. This results in a characteristic swell in the power draw distribution during workday business hours as seen in Figure 5a. As expected, the uncontrolled weekend power draw distribution shown in Figure 5c is relatively flat. To generate the plots, data for each day were segregated by hour of the day and an average workstation power draw was calculated for each hour. This was repeated for each day within the specified days. The box plot presents the distribution of the mean hourly workstation power draw calculated in this manner. For each hour of the day, the median of the average workstation power draw is marked with a red line. The bottom and top of the box are the 25^{th} and 75^{th} percentiles, respectively. The whiskers (bottom and top dashes) extend to the minimum and maximum data points. Each workstation consumed on average 27 kWh of energy every week with no controls in place.

Weekly energy consumption for the average workstation was 21 kWh with scheduled control and policy changes. Figures 5b and 5d show the controlled hourly energy demand for the average workstation during weekdays and weekends, respectively. There is a noticeable decrease in average hourly power draw when controlled. This energy savings is especially prevalent during non-business hours. However, note that the energy reduction cannot be attributed solely to scheduled control as changes in computer energy saver policies overlapped with the implementation of the schedule-based rules. This is discussed in more detail in the following sections. There is an obvious power demand decrease during non-business hours when rules are in effect. The reduction in power during the

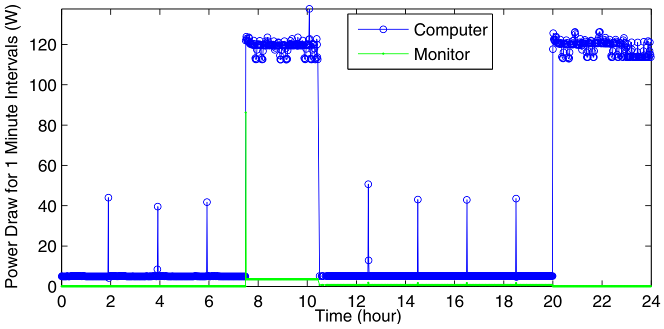


Fig. 6: Computer and Monitor Coupling

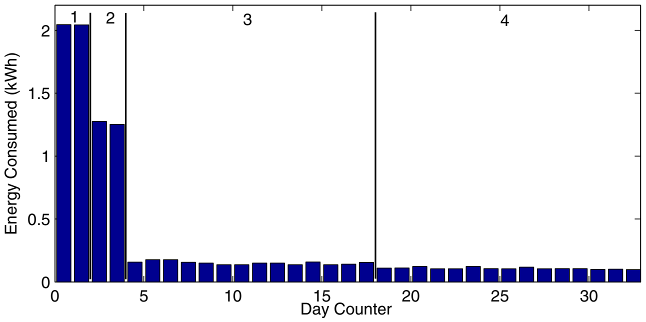


Fig. 7: 30” Display Energy Consumption

midday hours reflects the changes to workstation energy saver policies.

1) Computers: Computers constitute 82% of the energy demand in the average workstation. During the workday desktop computers consume on average 2.7 kWh while laptop computers consume only 0.36 kWh. By replacing desktops with laptops of similar specifications estimated yearly energy savings reach 770 kWh per computer switched.

When functioning properly, the most effective energy saving method was enabling built-in power management policies. During the uncontrolled portion of the testing, most desktop computers had power management policies specified such that the computer never entered a low power state. The setting was changed to enter a low power state after 3 hours of idle time while enabling wake for network activity, which still leaves substantial room for improvement. Changing energy saver policies can lead to large energy savings. However, several computers did not enter a low power state either at all or consistently because of perceived computer or network activity. Third party solutions were not explored to force the computer into a low power state for these systems. Days 85 and 86 in Figure 4 give an indication of the amount of energy that can be saved with proper functioning of low power modes. During this weekend all but one of the workstation computers was in a low power state, whereas other days typically had fewer computers in a low power state.

2) Monitors: Monitors constitute 15% of the average office’s energy consumption. A computer and its monitor form a closely related system. For some computers in energy saver mode, de-energizing the monitor wakes the computer, causing the computer and monitor to use more energy collectively than the amount that is saved by turning off the monitor. Figure 6 illustrates this phenomenon. The monitor was turned on at 7:30 am and off at 8 pm. Each of these control actions caused the connected computer to wake. In such cases applying schedule-based control to monitors is counter productive.

As with computers, the most effective way to save energy is by employing built-in power management policies. For example, some workstations used screen savers that displayed pictures, which led to a high power draw 24/7. Changing monitor screen saver policies to a blank screen results in large energy savings as seen with a 30 inch monitor in Figure 7. This monitor was uncontrolled in zone 1 (days 1 & 2). In zone 2 (days 3 & 4), scheduled-based rules turned the monitor off at 10 pm and back on at 6 am. For zone 3 (days 5-18) the monitor was uncontrolled, but more energy efficient screen saver policies were used. Changing the screen saver policies was shown to have more than twice the savings of enacting scheduled-based rules alone. Zone 4 (days 19-33) was both controlled and with new screen saver policies.

3) Other Workstation Electrical Loads: Workstation printers used on average 2.7 kWh of energy every week. Turning them off during non-business hours saved 0.82 kWh per week. Typical workstation speakers consume 0.67 kWh of energy every week. Turning them off during non-business hours saved on average 0.11 kWh per week.

B. Copy Room

The copy room pilot study loads consist of two shared printers (black-and-white and color), a copy machine and one shredder. These devices are shared by everyone on a floor and are used throughout the workday. Scheduled control of loads yielded mixed results depending on the equipment.

The shared printers and copier constitute 40% and 59% of the copy room energy demand, respectively. The black-and-white shared printer used more energy when controlled because of its startup power draw profile in relation to its standby power draw. Even with the reduction of the time-to-standby setting from 4 hours to 1 hour, the black-and-white printer consumed more energy turning it off for 8 hours and then turning it on compared to leaving the printer in standby mode; consequently, the schedule-based rules were removed for this device.

The copier was also found to have undesirable behavior while controlled. When power was returned to the device it did not automatically power on. The first users in the mornings had to manually power up the copier, which had a long startup time. Because of this behavior rules were turned off for the copier. Another undesirable characteristic of the copier was a high standby power draw of approximately 60 W. Furthermore, about halfway through the study period the copier ceased to transition to the standby mode consistently, leading to greatly increased energy consumption. The power draw in the idle state averaged over 250 W. Figure 8 shows power data from

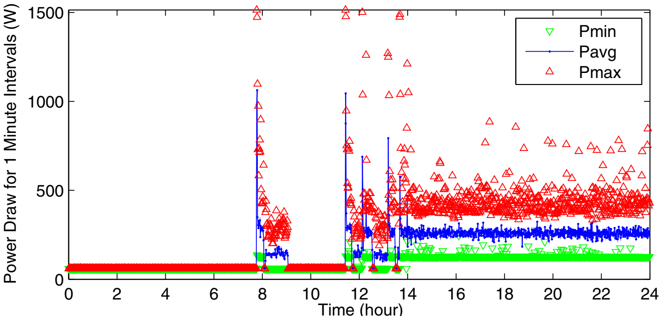


Fig. 8: Copier Power Draw

the copier on a day when the power saving functionality was initially working correctly but after 3 pm the device remained in the idle state rather than transitioning to the standby mode. The copy room used more energy in the controlled period because of the previously discussed copier issues as well as increased color printer use.

C. Break Room

The break room loads consist of two vending machines, a coffee machine, refrigerator, and microwave. Of these, the largest sources of power draw are the vending machines. The pilot study vending machine loads constitute 84% of the monitored break room loads. Schedule-based control was used for all electrical loads except for the refrigerator; the refrigerator was excluded to avoid food spoilage. Enacting these rules saved a total of 9.0 kWh of energy every week.

There were two vending machines included in the study: one dispenses snacks and the other drinks. The snack machine has a light which is always on when plugged in. The drink vending machine has a much higher energy demand due to its refrigeration cycles. Rules were enacted for both of these vending machines to turn them off during non-business hours (10 pm to 6 am). On startup, the drink vending machine requires a large amount of energy to cool down to its operating temperature. Even with the large startup energy, enacting rules saved a total of 5.1 kWh per week. Additional savings can be achieved by replacing the vending machines with energy efficient models.

The same rules were enacted for the break room microwave. Unlike the vending machines, the microwave's power draw is almost entirely use-dependent. When it is not in use it has a power draw between 1.2 and 1.4 W. Because of this low power draw during off hours enacting schedule-based control only saves 0.08 kWh weekly. The coffee machine is another use-dependent electrical load. The single-cup coffee machine draws approximately 5 W in standby mode then reaches a peak of 1300 W as it warms up. By enacting the same time-based control as applied to the microwave and vending machines energy demand was decreased by 0.31kWh weekly. This is more than the microwave but is very small in comparison to the vending machines.

IV. DISCUSSION AND RECOMMENDATIONS

The objectives of this pilot study were to obtain experience deploying a plug load management system, gain insight into the energy consumption of typical office building electrical loads, and make a preliminary assessment of energy saving strategies which maintain employee productivity. The recommendations made here will be applied to Sustainability Base.

Our testing confirmed previous observations about plug loads [5]–[7] and also highlighted some considerations which have not received as much attention in the literature. We found that the greatest energy savings can be obtained by choosing energy efficient equipment with consistent operations of low energy modes. Ensuring that built-in device low power functionality is utilized effectively is key to reducing energy consumption. Occupant participation in energy conservation is important and can prove very effective in reducing energy consumption. Finally, employing plug load control strategies to put devices into a low or no energy state when not used can also save energy, especially for devices which do not have efficient low energy modes. However, an important observation is that some electrical loads consume more energy or do not return to a ready-to-use state when they are power cycled. A few recommendations are provided in the following subsections.

A. Choose Energy Efficient Equipment

Choosing energy efficient equipment can greatly reduce building energy demand. Device type is also a consideration in energy efficiency. Replacing desktop computers with laptop computers can reduce computer energy consumption by as much as 85%, as projected from the pilot study observations. Second, it is recommended that equipment have automatic startup behavior when energized to avoid user inconvenience. This is especially important for equipment with long startup times or that accept jobs remotely such as shared printers. Third, reducing the number of electrical loads by providing shared assets can reduce energy consumption. Removing personal printers in favor of a small number of large shared printers saves energy at the expense of convenience. Finally, keeping devices well maintained and replacing older electrical loads can lead to decreased energy demand. Removing older personal mini-refrigerators and providing a shared full-sized Energy Star refrigerator in a break room is one example for the last two points.

B. Set Effective Energy Policies

It was surprising that the initial energy policies for many of the computers (primarily desktops) and monitors in the study kept the device in active mode, never entering a low power state. Changing the energy saver policies to transition to a low power state using already present applications was found to save more energy than schedule-based control where loads were completely de-energized during off-hours. These energy policy changes are especially effective on use-dependent load devices such as computers, monitors, copiers, and printers. Many electronics have three modes: standby/sleep, idle, and active. Standby mode uses considerably less energy than idle mode. By reducing the time-to-standby the equipment will spend more time in a lower power mode, resulting in lower energy consumption. A balance must be struck between energy savings and inconvenience to users who must wait for wake or warm-up times upon leaving a lower power mode. For computers and monitors, the wake time is typically insignificant; for printers and copiers, the warm-up times can range from a few seconds to minutes.

C. Promote Beneficial Occupant Behavior

One of the largest sources of potential energy savings is attributable to beneficial occupant behavior. Having a reminder to be energy conscious can cause the occupant to change their behavior in favor of energy conservation. This can be achieved by allowing the occupant to view their own workstation energy use via websites, smartphone apps, or desktop widgets. Showing estimates for real world impact such as cost or amount of CO2 emitted into the atmosphere can help occupants better understand their environmental impact. The easier it is made for occupants to view and understand their impact, the greater the effect will be. Only limited feedback was provided in this pilot study but it had a noticeable effect. In the monitor example discussed in previous sections, the workstation user was presented a graph of power draw over the course of a week which showed that the monitor used approximately 85 W continuously. The user was also shown a graph of the power draw of a monitor that routinely transitioned to a low power state. Upon seeing the comparison, the user was eager to change the screen saver policies to reduce energy consumption. In another example, an occupant was shown the plug load management system website which plotted real-time energy consumption when the space heater in the workstation area was turned on. The large increase in workstation and even total metered power draw was quite dramatic and led the user to acquire a heated mouse, which decreased the sensation of feeling cold and eliminated additional use of the space heater.

D. Employ Plug Load Controls

Since office buildings are typically unoccupied for a larger percentage of time than they are occupied, additional energy savings can be achieved by using plug load controls to de-energize devices during non-business hours. As previously discussed, only schedule-based control was investigated in this study. For best results, control rule times should be tailored to individual user's schedules. Occupants should be instructed on how to use manual overrides for occasional work outside the typical schedule. Plug load controls are most effective for electrical loads which have a high power draw such as the vending machines. For devices with near constant power draw, the energy savings will be directly proportional to the amount of time the device is 'unplugged'.

However, some devices cannot or should not be de-energized. Desktop computers cannot be powered off without a proper shutdown procedure. Laptops may be powered off if they are in a low power mode and there is sufficient battery charge. Large-capacity printers may use more energy when de-energized and re-energized because of the power profile during the warm-up period. Furthermore, powering off some monitors resulted in the connected computer being awoken from standby mode, resulting in increased energy consumption. This requires more investigation with other computer/monitor setups.

When planning the use of plug load control system, it is important to factor in the power draw of the management system itself. The power strips used in our study had a power draw of around 1.8 W with all channels in the on state and 0.8 W with all channels in the off state. The bridges had an additional power consumption of 1.1 W. In order to be an efficient placement for the strip, the total power saved for devices plugged in must be greater than approximately 0.3 kWh per week.

V. FUTURE WORK

This pilot study investigated only one active control strategy, schedule-based control, using one plug load management system. Future research will examine additional plug load control strategies such as load-sensing control, occupancy control, and manual control in Sustainability Base. Additionally, studies of different plug load management products will be conducted and their effectiveness in reducing plug load energy consumption will be evaluated.

An important area of research is examining the effect of personal energy dashboards on occupant behavior. As discussed in Section IV, a considerable amount of energy can be saved by promoting positive energy behavior. Giving occupants personal feedback and control of workstation plug load usage through web-based or smartphone applications is seen as key to reducing energy consumption.

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