Title
Integration of a Smart Outlet-Based Plug Load Management System with a Building Automation System

Authors
Chia, Keaton
LeBar, Amy
Agarwal, Vardhan
et al.

Publication Date
2023-04-13

DOI
10.1109/gridedge54130.2023.10102749

Integration of a Smart Outlet-Based Plug Load Management System with a Building Automation System

Keaton Chia
Mechanical and Aerospace Engineering
University of California, San Diego
San Diego, California
kwchia@eng.ucsd.edu

Amy LeBar*
National Renewable Energy Laboratory
Golden, Colorado
amy.lebar@nrel.gov

Vardhan Agarwal*
Computer Science and Engineering
University of California, San Diego
San Diego, California
v7agarwa@ucsd.edu

Mandy Lee*
Data Science
University of California, San Diego
San Diego, California
mal001@ucsd.edu

Joe Ikedo
Computer Science and Engineering
University of California, San Diego
San Diego, California
jikedo@ucsd.edu

Jesse Wolf
Computer Science and Engineering
University of California, San Diego
San Diego, California
jtwolf@ucsd.edu

Kim Trenbath
National Renewable Energy Laboratory
Golden, Colorado
kim.trenbath@nrel.gov

Jan Kleissl
Mechanical and Aerospace Engineering
University of California, San Diego
San Diego, California
jkleissl@eng.ucsd.edu

***Abstract*— The growth of and reliance on renewable energy necessitate a multi-pronged approach to achieve grid reliability and economics. As they represent a notable portion of U.S. energy consumption, commercial buildings must play an active role in this effort. Conserving energy and responding to grid conditions through demand flexibility can be achieved through the integration of major building systems. Integration of plug and process loads with lighting and heating, ventilation, and air conditioning systems maximizes the effectiveness of integrated building energy management. In this research, we demonstrate the integration of smart outlets into a building automation system. We cover the installation process as well as the architecture required for smart outlets to communicate data to the building automation system and to receive commands back. After recording power measurements for one week as a baseline, we configured the building automation system to turn the smart outlets "on" and "off" according to a set schedule. This resulted in energy savings of 66% during 1 week on 25 plug loads. This work demonstrates that grid-interactive efficient buildings are achievable through building system integration.**

***Index Terms*—building automation system, commercial building, demand response, grid-interactive efficient buildings, plug load control**

I. Introduction

Grid-interactive efficient buildings (GEBs) are buildings that have optimized controls to manage building loads, as well as respond to grid signals to accommodate grid needs, all while meeting occupants' comfort and productivity requirements [1]. They are a growing area of research, especially as more electricity is generated via renewable sources. Plug and process loads (PPLs) are plug-in and hardwired loads not associated with other major commercial building end uses, such as lighting; heating, ventilation and air conditioning (HVAC); and water heating. As of 2017, PPLs were responsible for 40% of commercial building energy consumption in the United States [2], and this percentage is expected to increase. As such, there has been growing interest in not only reducing PPL energy consumption to save energy and money, but also controlling the loads to achieve GEBs and demand flexibility. As PPLs are a substantial portion of building load, optimized and – more importantly – integrated PPL control is a key element of a GEB.

There are several case studies in which PPL controls have been integrated with lighting systems. The Northwest Energy Efficiency Alliance tested the ability of luminaire level lighting controls to control plug loads as well as the HVAC system [3]. Tinker Air Force Base and Minnesota Department of Transportation's Cedar Truck Facility conducted similar studies in which occupancy sensors from the building lighting systems were used to control the HVAC system and receptacles [4], [5]. Although PPL and lighting integration increases energy savings, it does not enable a building to respond to grid signals, a fundamental capability of a GEB. The integration of all building systems is required to achieve GEBs.

We acknowledge funding from the California Energy Commission under grant EPC-20-009.

*These authors contributed equally to this work.

To date, there have been no whole-building integration projects, nor have there been any in which plug load management (PLM) systems have been integrated with building automation systems (BAS). This is largely due to hardware interoperability and management scalability challenges. Energy management system hardware is developed by independent manufacturers and therefore lacks compatibility with PLM systems. Plug load control (PLC) also presents several unique management challenges. Whereas HVAC and lighting systems are physically static, PLC hardware, such as smart outlets that are plugged into wall receptacles, may be moved when an occupant switches offices. Even when smart outlets are physically static, the attached loads may change, such as from a printer to a water dispenser. Both of these changes may necessitate a different automation strategy.

This work aims to tackle these challenges en route to answering the following research question: How can we integrate a PLM system with a commercial BAS? In this paper, we describe the approach and implementation of the integration of a smart outlet-based PLM system with a commercial BAS in several buildings at the University of California, San Diego (UCSD) campus. We demonstrate the integration by showing how the smart outlets can be controlled using an HVAC schedule in the BAS. While this paper shows the proof-of-concept, more comprehensive and systematic results will be presented in future papers.

II. System Integration

We integrated a new PLM system into a campus with an existing BAS and network infrastructure. In this section, we explain the integration components and processes.

A. Location

Located in coastal La Jolla, California, the main UCSD campus covers 1,200 acres and has more than 760 buildings. Although most of the smaller buildings lack an HVAC system or are locally controlled, a central BAS manages the HVAC systems for 70 of the larger buildings that are connected to the campus district heating and cooling infrastructure. The central BAS enables UCSD Facilities Management (FM) to monitor the health of these systems from a single interface and to configure schedules, set points, and other preferences across the entire group of large buildings.

B. Metasys Building Automation System

Metasys is a BAS developed by Johnson Controls International. UCSD FM uses Metasys to monitor and control the HVAC systems of campus buildings. Each building has one or more field controllers called network automation engines (NAEs). These NAEs are the interface between Metasys and different hardware including air handlers, variable air volume boxes, pumps, valves, thermostats, and sensors. The Metasys Site Supervisor software provides operators with a graphical user interface.

C. BERT Smart Plugs

Best Energy Reduction Technologies (BERT) is a smart outlet manufacturer. The smart outlet is installed directly on top of existing wall receptacles and has a manual override button, power metering capability, relay control, and Wi-Fi connectivity. BERT offers integration with Metasys via a BACnet gateway. BACnet is the American national protocol standard for Building Automation and Control networks. We integrated the smart outlets with Metasys for control and management through the Metasys Site Supervisor.

D. Smart Outlet Installation

When identifying locations for smart outlet deployment, we selected facilities that reflect typical office buildings, such as those with a large number of single or shared office spaces, common areas such as kitchenettes or conference rooms, and reception areas. These buildings provided the largest concentration of desired plug loads, which include printers, copiers, TVs, hot/cold water dispensers, and coffee makers. These device types were chosen as they are products typically found in offices and they continue to draw power when in “standby” or “off” modes. Therefore our results would be representative and impactful. Devices that are safety/life-critical or contain perishables, such as lab equipment and refrigerators, were avoided. At the time of this publication, there were more than 800 smart outlets installed in 16 buildings, spanning more than 50 different departments. For this proof of concept demonstration, we chose a single building with a portion of these smart outlets.

E. Networking

1) Architecture: The smart outlets connect over Wi-Fi to the UCSD-DEVICE network, which is dedicated for wireless hardware owned by the university. Separate networks are available for staff, students, and guests. Since UCSD-DEVICE only allows known media access control (MAC) addresses[1] to join the network, UCSD IT was provided a spreadsheet of MAC addresses prior to the installation. A unique pre-shared key for the smart outlets was also set. The smart outlets come pre-programmed with our network credentials and, once installed at a receptacle, they will automatically attempt to join the network. They are also programmed to communicate using the User Datagram Protocol (UDP)[2] with a server hosted by the campus that runs the BERT BACnet gateway. This gateway translates the smart outlet UDP messages into BACnet by creating virtual BACnet devices. A second server was set up to host a virtual NAE that then discovers these virtual BACnet devices. This NAE is integrated into the central Metasys server where the control points and data collected can be accessed via the site supervisor user interface or the Metasys application programming interface (API).

[1]MAC address is a hardware identification number that uniquely identifies a device on a network.

[2]UDP is a communications protocol under IP that prioritizes speed of data transfer.

2) Security: Security concerns regarding the deployment of these smart outlets have been addressed in several ways. A registry is maintained for the MAC address of each smart outlet. Firewall settings are also set according to the principle of least privilege, which means that only specific Internet Protocol (IP) addresses and ports are allowed for communication. Additionally, a virtual local area network (VLAN)[3] is in use to isolate the smart outlets from other devices on the campus network. This separation helps reduce the impact that a security breach could have such as, for example, MAC spoofing.[4]

F. Integration into Metasys

We imported the smart outlets along with their data and control points as a batch using the Metasys System Configuration Tool. Available points include entries such as power, voltage, and current measurements; relay state; and Wi-Fi signal strength. Each smart outlet can be identified by a unique name that follows the naming convention set by UCSD FM. This includes a standard abbreviation for campus buildings followed by the floor, room number, attached load abbreviation, and point type, all separated by periods. For example, the name of the power measurement of a medium printer would be IRPS.2ND-FLR.RM-1202.MPRNT.PWR-MW. Lastly, we added the devices to the Metasys User Interface, which provides a graphical representation of the building floor plans and the smart outlets (Fig. 1). Device state, control buttons, trend charts, and logs can also be displayed.

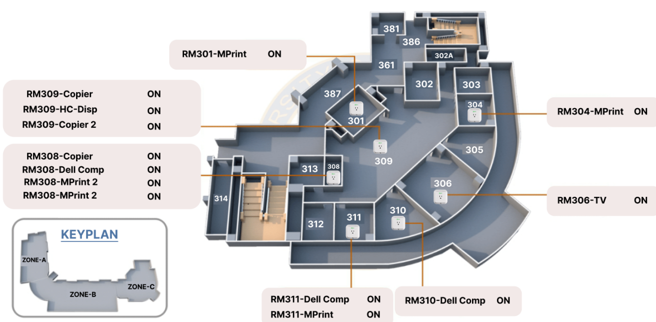

Figure 1. Metasys User Interface with smart outlets.

With the integration complete, we can see from Fig. 2 how the smart outlets are able to transmit data to the Metasys Site Supervisor and receive commands back.

III. Demonstration Methodology

In our demonstration, we verified two aspects of system integration, data collection from the smart outlets to the BAS and the control of smart outlets by the BAS.

[3]A VLAN is a grouping of devices on a network that restricts the inter-transmission of data packets to just the devices it encompasses.

[4]MAC spoofing is a practice that allows one to impersonate a device and send packets over the network that will be recognized as the spoofed device. A bad actor could potentially submit erroneous readings on behalf of a plug load with this technique.

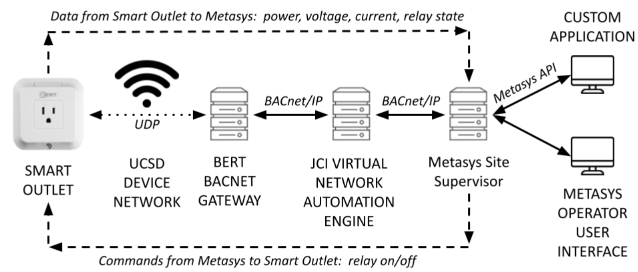

Figure 2. Architecture for connecting smart outlets to the building automation system.

A. Case Study

We conducted the demonstration in Robinson Hall. This building has a single department, the School of Global Policy and Strategy, which made coordination with occupants much simpler as it provided a single point of contact. The smart outlets were located in the administration area, which includes offices, conferences rooms, break rooms, and a lobby. Operating hours and facility usage are consistent with typical business offices, with occupants arriving no earlier than 07:00 and leaving before 18:00. The 25 plug loads in the demonstration represent seven device types: hot/cold water dispensers, TVs, copiers, small and medium printers, projectors, and coffee makers (Table I).

Prior to applying PLC, notice was given to occupants along with a flyer that included an overview of the study, its research value, contact information, and instructions for how occupants can manually override the smart outlet in the event that it is off when the attached device is needed.

TABLE I
PLUG LOAD TYPES AND COUNTS INCLUDED IN DEMONSTRATION

Device Type	Number of Devices
Medium Printer	13
Water Dispenser	4
Copier	3
Small Printer	2
Coffee Maker	1
Projector	1
TV	1

B. Data Collection

We configured the BAS to record the baseline power measurements of the 25 plug loads from June 20 to June 26, 2022. We set the BAS to capture measurements every 15 minutes, as this is the standard rate for other systems in Metasys, like HVAC systems, which have slow response times. During the week controls were applied, July 11 to July 17, we changed the data collection frequency to 5 minute intervals to better identify plug load usage, which requires more granularity. To align the two data sets, we interpolated the baseline data to

5 minute time stamps using nearest-neighbor interpolation. Five percent of the data was missing values due to server interruptions. We cleaned the data by inserting the last known power measurement. These specific weeks are expected to have comparable occupant activity as they are both in the summer quarter and they have no anomalies such as holidays.

C. Scheduled Control

To demonstrate the ability of the BAS to control the smart outlets, we set up Metasys to send "on" and "off" commands to the smart outlets according to a set schedule. This approach also shows how building systems can share common information, which provides time savings and ease of use to the operator. For example, a building may have standard operating hours that dictate when HVAC and plug loads are turned on and off. If these systems were operated independently, redundant work would be required to input and update these schedules in each individual system.

For UCSD buildings, the HVAC systems are actuated using occupancy schedules that repeat weekly. These schedules do not use actual occupancy data, but rather periods of time are marked as "occupied", "unoccupied", "standby", or "not set". Air handlers or variable air volume (VAV) boxes will adjust their operation based on the occupancy mode. For example, in occupied mode, a VAV will increase airflow and narrow the temperature band around the comfort temperature.

To implement the scheduled controls, we created a multiple command object in Metasys because smart outlets use an "on/off" command whereas a VAV uses occupancy mode. The occupancy schedule feeds the current occupancy mode into the multiple command object, which links each occupancy mode in an action table to which command points can be added for the smart outlets. For example, when the system is in an occupied state, the multiple command object will issue an "on" command to smart outlets and "occupied" command to the VAV. During weekdays, the smart outlets were turned on at 07:00 and turned off at 18:00. On weekends, the smart outlets remained off. Due to COVID policies that required 24/7 outside air supply, we were not able to include VAV control in the demonstration. However, the integrated scheduled control approach shows how additional energy management can be achieved through system integration.

IV. Results and Discussion

A. Baseline Results

We successfully recorded power measurements from the 25 plug loads in the Metasys server. From these historical data, we can gain insights into the power consumption of different plug loads. In Fig. 3, six example load profiles are shown for a 24-hour period on June 21. Plug load use is inconsistent during the summer at universities. Thus, a specific day and set of devices were chosen for their active use. This enabled us to observe standby and active patterns. For water dispensers, we can see that it consumes power consistently throughout the time period. The other devices have more distinct peaks that likely correspond to active use, which indicates that their standby power is in the range of 2 to 60 watts. Energy savings can be gained by eliminating this standby power consumption.

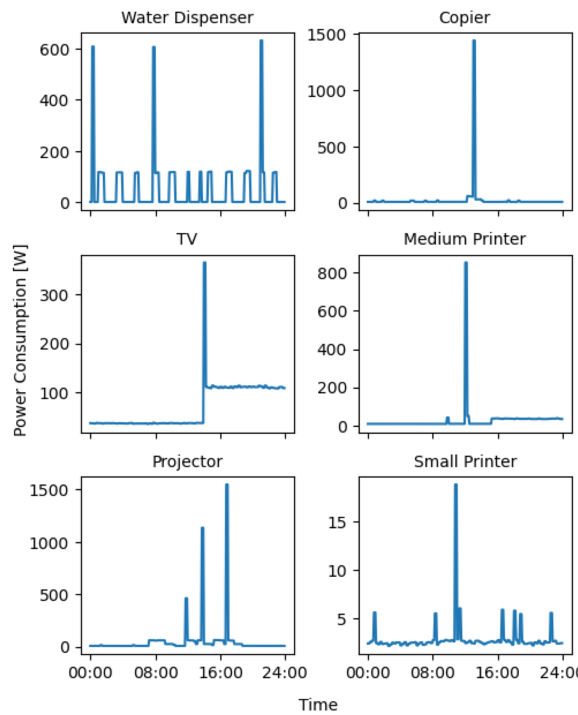

Figure 3. Example one-day load profiles for six of the plug loads included in the demonstration.

B. Control Results

In Fig. 4, the aggregate power consumption of the 25 plug loads is shown for the baseline week in blue and controls week in orange. The periods during which the orange line drops to zero correspond with the control schedule, which confirms that the BAS was able to turn off the smart outlets at the expected times. There were no increases in power consumption during these "off" periods, which means that occupants did not have to manually override the smart outlets to restore power. This is important because occupant satisfaction is crucial for long-term implementation of PLC.

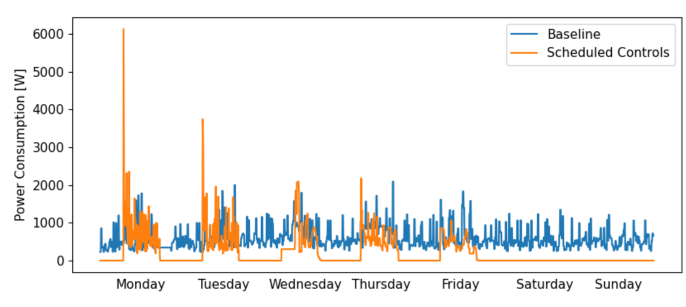

Figure 4. Daily power consumption of one week baseline (June 20-26) versus one week controls (July 11-17).

Fig. 5 shows the amount of energy saved. In total, the controls week used 66% less energy than the baseline week.

During weekdays, we see an average savings of 53%. These savings will vary depending on active use of the plug loads. However, savings from evening and weekend controls are likely more predictable.

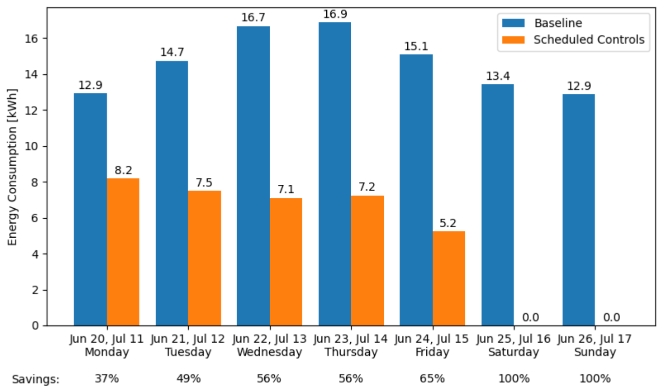

Figure 5. Daily energy consumption of one week baseline (June 20-26) versus one week controls (July 11-17).

V. Limitations

Several limitations impacted the design and scope of the demonstration.

1) COVID HVAC Policies: To create a healthy environment, the HVAC system for all campus buildings is currently locked in occupied mode to maintain a high level of fresh air indoors. This limits our ability to demonstrate further building optimizations and integration benefits until these restrictions are lifted.

2) Academic Summer Quarter: These initial demonstrations were performed during the summer quarter, which typically sees a decrease in campus activity and onsite presence of staff.

3) Lack of Lighting Integration: The lighting system was not integrated into the BAS, which limits occupancy data and system integration. Future connected lighting upgrades to campus buildings through DERConnect [6] will allow for additional integration.

VI. Conclusions and Future Work

This work proved that communication among and integrated control between building systems is possible. Smart outlet power measurements can be collected and stored in the BAS. Scheduled controls from the BAS were successfully communicated to the smart outlets. Static schedule controls saved 66% of the energy consumed by 25 plug loads compared to a week of baseline data. The value of system integration could be further realized if the BAS used this same schedule to also set HVAC systems into an unoccupied mode for even greater savings. Beyond energy savings, system integration can also enable more specific localized controls through the sharing of sensor data as well as the whole-building response to grid signals. The integration demonstrated in this work is a step towards making GEBs a reality.

In future work, we will expand the scheduled controls to additional UCSD buildings. This will enable us to evaluate the impact of PLC with different types of user groups and plug loads. We will also test new control strategies aimed at predicting usage of building systems to further reduce energy consumption during business hours. Once COVID HVAC policies are lifted, we will have the opportunity to include VAV control in our demonstrations and to further showcase the benefits of integrating HVAC, lighting, and plug load control in commercial buildings.

Acknowledgment

We acknowledge funding from (a) the California Energy Commission under grant EPC-20-009 and agreement manager Felix Villanueva and (b) the National Science Foundation under ECCS-1947050 DERConnect. We appreciate the support of Charles Bryant, Greg Collins, David Rapp, Ryan Sullivan, Nicole Lewis, Robert Serocki, Christopher Jones, Scott Yetter, Eduardo Ramirez, Cherise Paramore, Greg Gobiecki, and Bhaskar Mishra.

References

[1] M. Neukomm, V. Nubbe, and R. Fares, "Grid-interactive efficient buildings technical report series: Overview of research challenges and gaps," Dec. 2019. [Online]. Available: https://www1.eere.energy.gov/buildings/pdfs/75470.pdf

[2] M. R. Langner and T.-K. L. Trenbath, "Integrating smart plug and process load controls into energy management information system platforms: A landscaping study," June 2019. [Online]. Available: https://www.nrel.gov/docs/fy19osti/74080.pdf

[3] "Lighting the Way to Whole-Building Energy Savings," https://neea.org/news/lighting-the-way-to-whole-building-energy-savings.

[4] J. Zirnstein, "Intelligent Building Management with Holistic Digital Lighting," March 2020. [Online]. Available: https://www.serdp-estcp.org/Program-Areas/Installation-Energy-and-Water/Energy/Conservation-and-Efficiency/EW-201720

[5] "Integrated controls for plug loads and lighting systems," March 2022. [Online]. Available: https://www.osti.gov/biblio/1855909

[6] UC San Diego DERConnect. https://sites.google.com/ucsd.edu/derconnect/home.