ENERGY RESEARCH AND DEVELOPMENT DIVISION

FINAL PROJECT REPORT

Smart Plug Load Controls Integrated With Building Energy Management Systems

May 2025 | CEC-500-2025-021

PREPARED BY:

Keaton Chia
Melek Ben-Ayed
Suhas Hebbur Eshwar
Chi Zhang
Eric Chen
Yizhan Gu
Jan Kleissl
Adil Khurram
Jesse Wolf
University of California, San Diego
Primary Authors

Felix Villanueva
Project Manager
California Energy Commission

Agreement Number: EPC-20-009

ACKNOWLEDGEMENTS

We appreciate the support of Xiaohan Fu, Lola Botman, Brandon Salas, Charles Bryant, Matt Winklepleck, Greg Collins, Nicole Lewis, Robert Serocki, Christopher Jones, Krasimir Genov, Zach Dake, Chris Cassidy, Sheila Graves, Mariana Beltran, Vanessa Martinez, Kevin Maley, Eduardo Ramirez, Cory Trusty, Greg Gobiecki, and Bhaskar Mishra. We also acknowledge Home Assistant website user Raphael, whose work with smart plugs and printers inspired our print server control strategy (Raphael 2021), as well as Eduardo Jiménez Miranda and Ricardo Medina Acosta for their work building the prototype in our laboratory. We thank the technical advisory committee members for their input, especially Marco Pritoni, Mani Srivastava, Harold Jepsen, Merry Sweeney, and Eric Eberhardt.

PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission, and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation, and bring ideas from the lab to the marketplace. The EPIC Program is funded by California utility customers under the auspices of the California Public Utilities Commission. The CEC and the state's three largest investor-owned utilities—Pacific Gas and Electric Company, San Diego Gas and Electric Company, and Southern California Edison Company—were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The CEC is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

Smart Plug Load Controls Integrated With Building Energy Management Systems is the final report for EPC-20-009 conducted by the University of California, San Diego. The information from this project contributes to the Energy Research and Development Division's Electric Program Investment Charge Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the Energy Research and Development Division at ERDD@energy.ca.gov.

ABSTRACT

Plug loads comprise more than 50 percent of energy consumption in high-efficiency buildings. Applying intelligent controls to turn off plug loads when unused can provide dynamic load reduction and flexibility. Integration of plug load controls with building energy management systems promises additional energy savings and flexibility. The effectiveness of various control strategies is presented, along with the operational lessons that informed their design. During a 3-year period, more than 600 smart outlets in 12 University of California, San Diego office buildings were operated. The attached plug loads consisted primarily of printers, TVs, water dispensers, and copiers. After recording baseline power measurements for a year, the project team defined plug load control strategies for each plug load type and use, and for different risk tolerance levels, because plug load control can potentially be disruptive to daily work. For advanced controls, smart plugs were integrated with heating, ventilation, and air conditioning systems through the campus building energy management system. The team found static schedules to be the least disruptive and most predictable for occupants, resulting in 38 percent and 66 percent energy savings in two field studies for this project. For printers, print server-triggered plug load control produced 86 percent energy savings, the highest of all strategies, with minimal occupant impact. Scheduling of water dispenser temperature controls, based on occupancy measurements, produced 32 percent savings, which can yield a simple payback of 3 years.

Keywords: Plug load control, Brick Schema, building energy management system, occupancy data

Please use the following citation for this report:

Keaton Chia, Melek Ben-Ayed, Suhas Hebbur Eshwar, Chi Zhang, Eric Chen, Yizhan Gu, Jan Kleissl, Adil Khurram, and Jesse Wolf. 2024. *Smart Plug Loads Controls Integrated With Building Energy Management Systems.* California Energy Commission. Publication Number: CEC-500-2025-021.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Executive Summary

Background

Plug loads are electrical demand from plug-in electric equipment and account for more than 47 percent of energy consumption in commercial buildings in 2020, according to the National Renewable Energy Laboratory's *Assessing and Reducing Plug and Process Loads in Office Buildings* report. Many plug loads have no power management capabilities and are left on all day, every day (24/7). Even if PLs have energy savings settings, often these settings have not been activated or disabled. Plug load control (PLC) is becoming increasingly important as buildings further electrify and the power grid decarbonizes. PLC offers an opportunity for electricity and carbon emission reductions by helping building operators to lower operating costs by eliminating wasted plug load electricity use and reducing peak electricity demand.

Implementing PLC is challenging, because of the numerous devices and types that exist in commercial buildings. Additionally, plug loads are occupant-dependent, and proper engagement with the occupants is vital to the success of PLC. While standalone plug load management programs exist, coupling PLC with other building systems, such as with the building energy management system, creates opportunities for more advanced and effective PLC strategies.

Project Purpose and Approach

The project team explored how PLC strategies can be designed to maximize energy savings while not disrupting the occupants, focusing on how an understanding of heating, ventilation, and air conditioning occupancy data can improve performance.

If occupants arrive late or leave early, occupancy data allows further narrowing of the plug load operating time frame. If occupants arrive earlier than expected, then occupancy data allows early activation of plug loads to prevent occupant interruptions. The team looked at the best practices, infrastructure, and data used in several case studies involving PLCs used on the University of California, San Diego campus.

During a 3-year period, more than 600 PLCs in 12 university office buildings were operated. The attached plug loads consisted primarily of printers, TVs, water dispensers, and copiers. After recording baseline power measurements for a year, the team designed PLC strategies for each plug load type and use, and for different risk tolerance levels, because PLC can potentially be disruptive to daily work. The different levels of PLCs include: 1) Level 0 — no control, which remains on all the time, 2) Level 1 — static control, which is on and off per day, 3) Level 2 — tightened schedule, which changes with a dynamic schedule, 4) Level 3 — usage optimized, which may have multiple on and off times, depending on active states, and 5) Level 4 — special events, which include demand response events and building peak load reductions. The project team used the Brick Schema to facilitate the management of plug load locations and other metadata. The Brick Schema, a standardized ontology and taxonomy for building systems, can streamline PLC integration and development of controls and make the PLC software transferable to other buildings that use the Brick Schema. The project team also created a technical advisory team from Lawrence Berkeley National Lab; the University of California, Los Angeles; the California Energy Commission; Legrand Wattstopper lighting controls; San Diego Gas and Electric Company; and the University of California Office of the President, to review and guide the work.

For advanced controls, the smart plugs were integrated with the campus building energy management systems.

Project Results

The team found static schedules of the PLCs to be the least disruptive and most predictable for occupants, resulting in 38 percent and 66 percent in plug load energy savings in two of the field studies for this project. For printers, print server-triggered PLC produced 86 percent savings, the highest of all strategies, with minimal occupant impact. Water dispensers are thermostatically controlled to maintain water within a certain temperature range. Scheduling water dispenser temperature controls, based on occupancy measurements, produced a 32-percent energy saving.

A key outcome of the project is an open-source Plug Load Management Application software that allows systematic configuration and scheduling of PLC. The software is built upon the Brick Schema to enable seamless coupling of PLC with other building systems. PLC trials with the software were demonstrated.

Benefits to California

The primary future target market for this project is California's higher education sector, which offers stronger economies of scale. The University of California system alone — excluding California State Universities — includes 5,847 buildings spanning 142 million square feet. Capturing just 25 percent of this market would double the current number of PLC deployments nationwide. These economies of scale, along with insights gained, will help mature the product and pave the way for expansion into the California office building market. For static Level 1 control, the overall savings are estimated to be 61 megawatt-hours or $20,000 per year per building. For more dynamic Level 3 control, the savings increase by 14 percent, to 69 megawatt-hours or $24,000 per year per building.

Knowledge Transfer and Next Steps

The principal source of knowledge transfer for this project is the Plug Load Management Application software that was published open source on GitHub. The release was accompanied by a journal paper that describes the software and provides example applications.

Project information was further shared through a webinar with the National Renewable Energy Laboratory and four publications: a best practices brief for PLC, a peer-reviewed journal paper, and two peer-reviewed conference papers, including one for the 2024 American Council on an Energy Efficient Economy Summer Study.

Further research should use the Plug Load Management Application software to develop a library of plug load management tools and to increase broader uptake of the software.

CHAPTER 1: Introduction

Twenty-seven percent of California commercial electricity consumption in 2018 was due to plug loads (PLs). PLs include all plug-in loads in a building that are not associated with: heating, ventilating, and air conditioning (HVAC); lighting; water heating; or other major equipment. In office buildings, PLs include devices such as computers, monitors, printers, projectors, cell phones, task lights, vending machines, and office kitchen equipment (Langner and Trenbath 2019). Many PLs have no power management capabilities and are left on all day, every day (24/7). Even if PLs have energy savings settings, often these settings have not been activated or disabled.

Integrating different building end uses and data can be achieved through building energy management systems (BEMS). Integrating plug load controls (PLCs) into BEMS platforms allows integrated control of multiple building systems and automated and dynamic load control, such as during demand response events (Langner and Trenbath 2019). Integration also advances operations through more comprehensive data monitoring and analysis, such as occupancy data triggers, streamlined controls, and fault detection and diagnostics.

PLC is becoming increasingly important as buildings further electrify and the power grid decarbonizes. PLC offers an opportunity for electricity and carbon reductions. It enables building operators to reduce operating costs by eliminating wasted PL electricity consumption and reducing peak electricity demand. Baseloads, the lowest constant power often occurring during unoccupied times, can also be reduced to allow for the electrification of other building systems. Implementing PLC is challenging due to the large number and many types of devices that typically exist in commercial buildings. Additionally, PLC is highly occupant-dependent, and proper engagement with occupants is vital to the success of the system. While standalone PL management programs exist, coupling PLC with other building systems, such as via BEMSs, creates opportunities for more advanced and effective PLC strategies. Lack of interoperability between heterogeneous systems is a well-documented issue in commercial BEMS (Hardin et al. 2015); the lack of integration is due to varying data formats and protocols, inconsistent data quality, and the need for complex integration processes.

Semantic interoperability is the ability to exchange data in a manner that ensures shared comprehension and a clear understanding of the data's meaning, thereby maintaining data semantics consistently across different systems. The Brick Schema (Balaji et al. 2016), a standardized ontology and taxonomy software for building systems, was developed to provide structure to the basic metadata commonly found in BEMS, including for PLC, to achieve semantic interoperability (Bergmann 2020). Not only does the Brick Schema streamline PLC integration and development of controls but it also makes the PLC software transferable to other buildings that use the Brick Schema.

The project team explored how PLC strategies can be designed to maximize energy savings while not disrupting occupants.

The project goals were to:

- Reduce total building plug load energy use by 20 percent.
- Install PLC in at least nine buildings of 100,000 square feet or more.
- Achieve simple payback of less than five years from savings in energy and electrical load when compared to no controls.
- Automate configuration and reconfiguration of PLC.

The infrastructure, data, results, and best practices for PLC through several case studies at the University of California, San Diego (UCSD) campus is described.

CHAPTER 2: Project Approach

Plug Load Control Levels

A challenging aspect of PLC is striking a balance between energy savings and the risk of interrupting occupants if plug loads are off when needed. To manage this balance, controls were classified into different levels that represent the risk of disrupting occupants. These levels are defined in Table 1. The control level is typically chosen by the PLC operator based on the desired number of on/off events per day and whether the schedule of those events repeats weekly or is dynamic. Higher levels offer greater energy savings but at a higher risk. Defining these levels helps align the controls with the risk tolerance of the building occupants.

Table 1: Description of Plug Load Control Levels

Control Level	Description
Level 0 — No Control	PLC remains on to provide uninterrupted power to its attached load.
Level 1 — Static Schedule	Only one on and off event per day. A static, weekly schedule is used that starts before and ends after occupants are typically in a building. For example, the facility manager programs PLCs to turn on at 7:30 a.m. and off at 5:30 p.m. every day.
Level 2 — Tightened Schedule	Only one on and off event per day. The schedule may change weekly and have a reduced time buffer before occupants arrive. For example, the front door contact sensor turns PLCs on when the first person arrives and turns them off at 5:30 p.m.
Level 3 — Usage Optimized	May have multiple on and off events per day to align power consumption more closely with actual plug load usage. For example, the print server turns a PLC on when a print job is received and turns it off after 30 minutes of inactivity.
Level 4 — Special Events	Similar to Level 3 but more aggressive, for cases such as demand response events, building peak load reduction, or islanded operation when the economic benefits of load shedding are orders of magnitude greater than in regular operation.

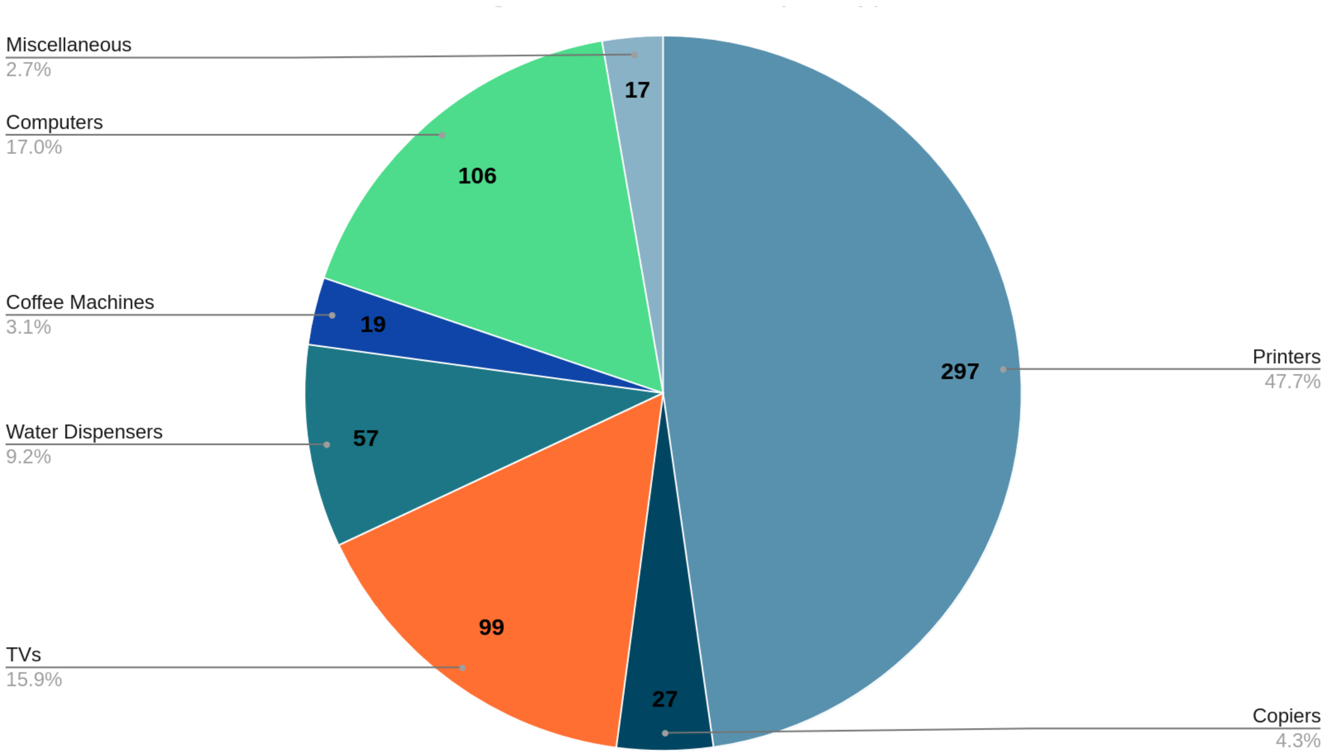
Source: University of California, San Diego

Deployment

Installing the PLCs in departments across the UCSD campus provided valuable insights into the diversity of occupant preferences and the operational constraints that PLCs must work within. The team used PLCs made by Best Energy Reduction Technologies (BERT). These are commercial PLCs with the capability to integrate with a BEMS via a Buildings Automation Control Network (BACnet) gateway. BACnet is the American National Standards

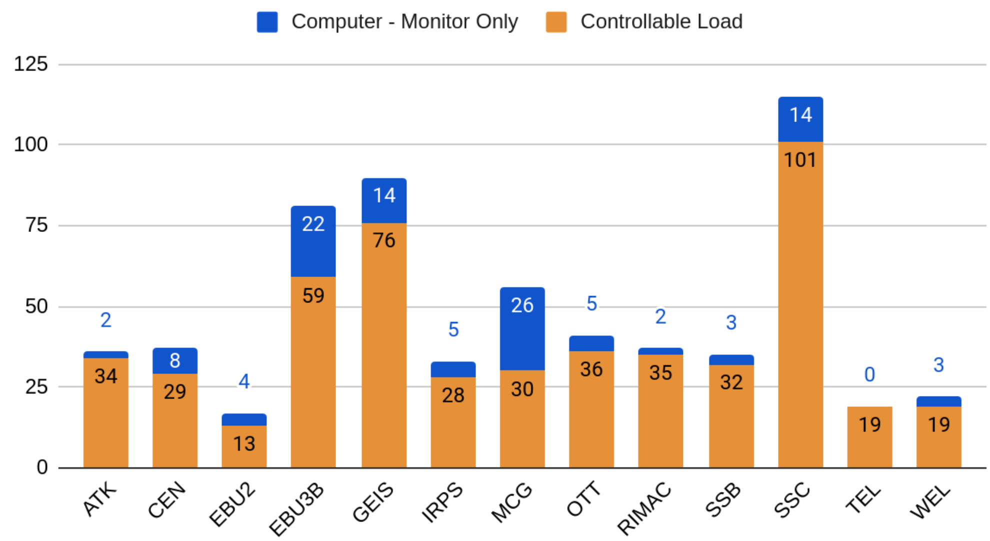
Institute/American Society of Heating, Refrigerating and Air-Conditioning Engineers standard for Building Automation and Control networks (ASHRAE 2016). PLCs are installed directly into existing wall outlets and have power metering capability, relay control, Wi-Fi connectivity, and a button to manually override a control if the PLC is off. The team installed 765 PLCs on office equipment such as TVs, printers, computers, copiers, scanners, hot/cold water dispensers, coffee makers, and portable air conditioning units (Figure 1). These types of PLs usually consume power at all hours, even when in standby or off mode. The PLCs were in 12 different UCSD campus facilities that reflected standard office buildings (Figure 2). The buildings are used primarily for administration and are composed of spaces such as private offices, shared offices, shared workspaces, storage rooms, conference rooms, and kitchenettes. Out of the 765 PLCs, 134 were connected to computers. Computers were not controlled due to concerns about interrupting user workflow; only the remaining 631 PLCs were used for the study.

Figure 1: Distribution of Plug Load Types



Source: University of California, San Diego

Figure 2: Number of Plug Loads by Building



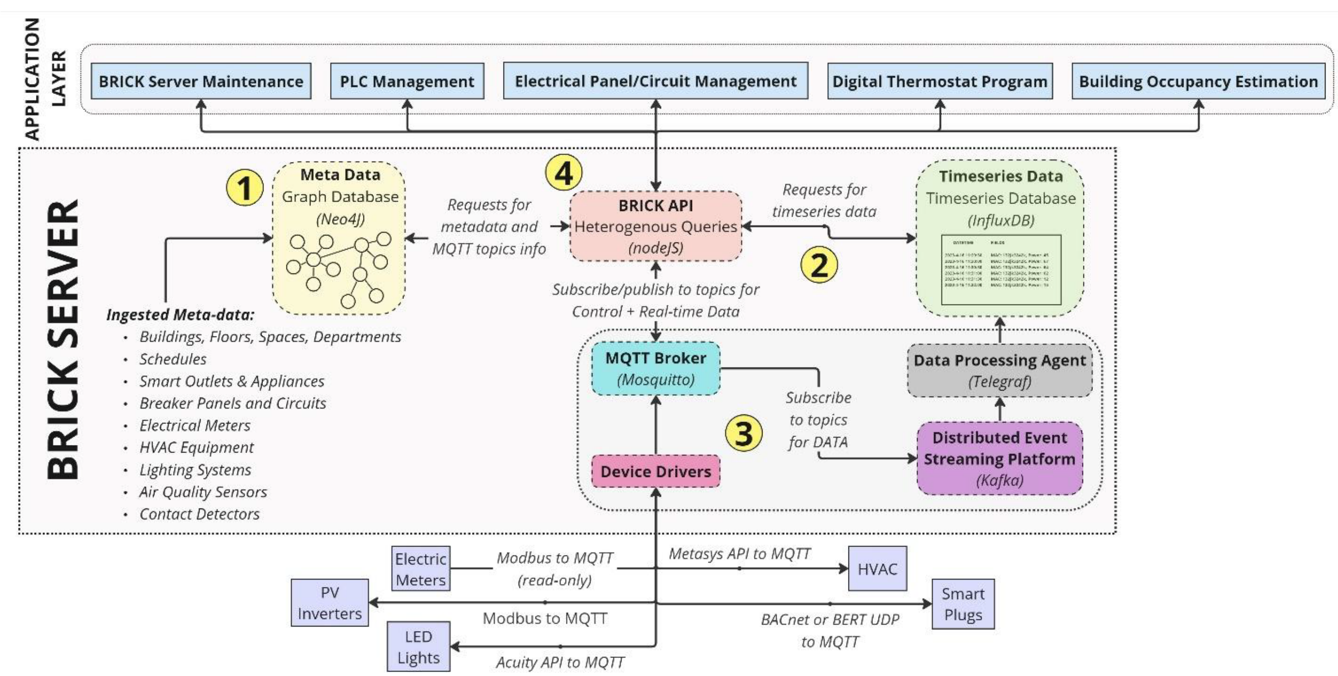
Plug loads are split into computers (blue) and controllable plug loads (orange).

Source: University of California, San Diego

Brick Server

The potential benefits of the Brick Schema are realized through a Brick Server. The software stack of this system consists of four main components, as shown in Figure 3: (1) graph database, (2) time series database, (3) data pipeline, and (4) Brick Application Programming Interface (API).

Figure 3: Block Diagram of the Brick Server Architecture



Source: University of California, San Diego

Graph database. This database stores all metadata related to the PLCs, including device properties, which appliance they control, and their spatial relationship to the building as well as to other relevant equipment such as thermostats and lighting systems. All entities are created as nodes, each with a label that comes from the Brick Schema as well as standard Brick relationships to other nodes such as 'hasLocation' or 'feeds.'

Time series database. The data generated by the sensors is stored in a time series database at its native resolution. PLC data is recorded in one-minute intervals.

Data pipeline. To get data into the Brick Server, different software device drivers communicate with the devices using their native communication protocol and convert it into MQTT (Message Queuing Telemetry Transport). These messages are then queued using Kafka, an event streaming platform, and formatted using Telegraf, a data processing agent, before being stored in InfluxDB, the time series database.

Brick API for applications. A primary challenge of equipment interoperability is interfacing with the different communication protocols that heterogeneous devices use. Providing a common framework and point of interaction is one of the key values that Brick provides. Users interface with Brick and its underlying data through an API (Application Programming Interface). There are API calls that enable exploration of the metadata, retrieval of desired time-series data, and control. The Brick Schema standardization streamlines development and increases the portability of applications.

PLC Management Application

The PLC Management Application software runs at the application layer and interfaces with the Brick Server via the Brick API. The PLC Management Application is custom software developed by the project team that is designed for PLC at scale and with the advantage of leveraging data from all other systems integrated into the Brick Server. Key features of the application include:

- Management of PLCs by grouping them into accounts and assigning points of contact. PLC highly depends on the preferences and risk tolerances of the users, so taking a people-first approach to organizing PLCs is beneficial.
- The ability to filter, sort, and configure PLCs in batches.
- A library of control strategies.
- The ability to draw from metadata stored in the Brick Server, such as relationships to departments and operating schedules.
- The ability to develop custom alerts and automation.

Plug Load Control Design

Input Data Types

When designing PLC strategies, it is helpful to first identify what information and data is available. PLC strategies may use a combination of the categories of data and information shown in Table 2.

Table 2: Types of Information and Data Used When Designing PLC Strategies

Information Type	Description
Static Schedules	These are schedules that are repeated weekly and are typically defined by the building or department managers. Schedules for HVAC zones are typically programmed into the BEMS and can be reused for PLC if there is a mapping between PLC locations and HVAC zones.
User Input	User input can be used as a trigger for PLC. Examples include users sending print jobs, pushing a specially programmed button, or using another related plug load.
Plug Load Use	Power measurements can be used to detect when certain plug loads are used to generate schedules that align with the usage.
Environmental Data	This includes data such as binary occupancy data from thermostats or lighting systems or CO_2 measurements.

Example Controls

Table 3 presents an example of how different levels of controls can be designed based on the types of information available as well as what strategy is most appropriate given the appliance type, its use, and the risk tolerance of its users. These strategies are demonstrated as case studies.

Table 3: Example Progression of Control Strategies for Different Plug Loads

	Control Level		
Load Type	**Level 1**	**Level 2 — Schedule Tightening**	**Level 3 — Usage Optimized**
Shared Printers	Static Schedule	User Input: Connect the printer to a central print server that triggers the PLC to turn on when the first print job of the day is received. The PLC can be scheduled to turn off at the end of the business day. Alternatively, usage data can be used to determine a better OFF time.	User Input: Connect the printer to a central print server that can trigger PLCs to turn on when a print job is received. Turn the printer off after 30 minutes of inactivity.

	Control Level		
Load Type	**Level 1**	**Level 2 — Schedule Tightening**	**Level 3 — Usage Optimized**
Individual and Shared Water Dispensers	Static Schedule	Occupancy-Driven Schedule: Use historical occupancy data from BEMS to generate a tightened schedule for the dispenser to be on, based on when people are nearby.	Occupancy-Triggered: Turn on 60 minutes before the area is forecasted to be occupied. Turn off after 60 minutes of inactivity in all areas.

Note that, as the levels increase, so do the savings and corresponding risks.

Source: University of California, San Diego

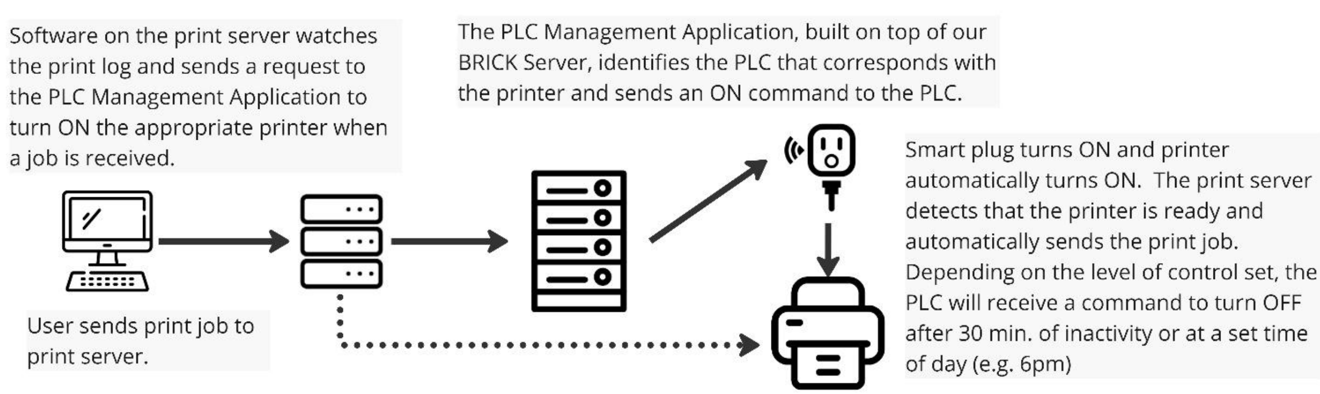
Case Studies

Case Study 1: Print Server

Motivation. Printers are of high interest for PLC as they comprise nearly 50 percent of the installations, with 363 printers attached to a PLC. The team developed Level 2 and Level 3 control strategies that leverage user input to turn a printer on when a print job is received.

System architecture. The system operates by monitoring the print log of a print server (Figure 4). When a user submits a print job to the server, the software installed on the print server detects the new job and identifies the relevant printer. It then requests the PLC Management Application to turn on the appropriate printer. The print server queues the print job until the printer is in Ready mode and then sends the job to be printed. The PLC Management Application and the Brick Server store the mapping between the printer's name and its associated PLC.

Figure 4: Architecture of the Print Server + PLC System



Source: University of California, San Diego

Pilot test. A business department on campus agreed to participate in a two-week pilot study with an HP Color LaserJet in the lobby. This lobby printer is used primarily by staff in the business office as well as some other staff in the building. Prior to starting controls, the project team posted an instructional flier at the printer, and it sent emails to department staff to configure staff computers.

Controls. Two control strategies were tested:

Week 1 (January 22 to 28, 2024) — Level 2: The printer starts OFF and turns ON when the first print job is received. It then turns OFF at a preset time of 18:00 h.

Week 2 (January 29 to February 4, 2024) — Level 3: The printer starts OFF and turns ON any time a print job is received. It turns OFF after 30 minutes of inactivity.

Case Study 2: Water Dispenser

Motivation. Water dispensers are thermostatically controlled devices that maintain water within a certain temperature range. Water is cooled/heated until reaching the target temperature; then the cooling/heating is turned off until the water reaches the higher/lower end of the temperature deadband and the cycle repeats. Water dispensers on campus have the second highest average daily energy consumption, as the dispensers maintain hot and cold water 24/7.

The project team selected a water dispenser in an administrative department for the study and collected baseline power measurements from January 2 to January 19, 2024, as well as from February 20 to February 27, 2024. From January 19 to February 2, the team applied Level 1 and Level 2 controls and collected ground truth data by placing a clipboard on the dispenser and instructing occupants to write down the day and time they used the dispenser and whether it was hot or cold water. From May 28 to June 4, 2024, Level 3 controls were applied and occupancy data from thermostats in the department was collected from the campus BEMS through the Brick Server. Additionally, three portable motion detectors were installed near key entrances to validate the thermostat occupancy data.

Controls. Initially, a static control strategy was applied:

Level 1. The department contact provided a static schedule of 8:00 a.m. to 4:00 p.m. Monday to Friday. Since water dispensers need up to an hour to cool/heat the water, a buffer was added, resulting in a schedule of 7:00 a.m. to 5:30 p.m. Monday through Friday.

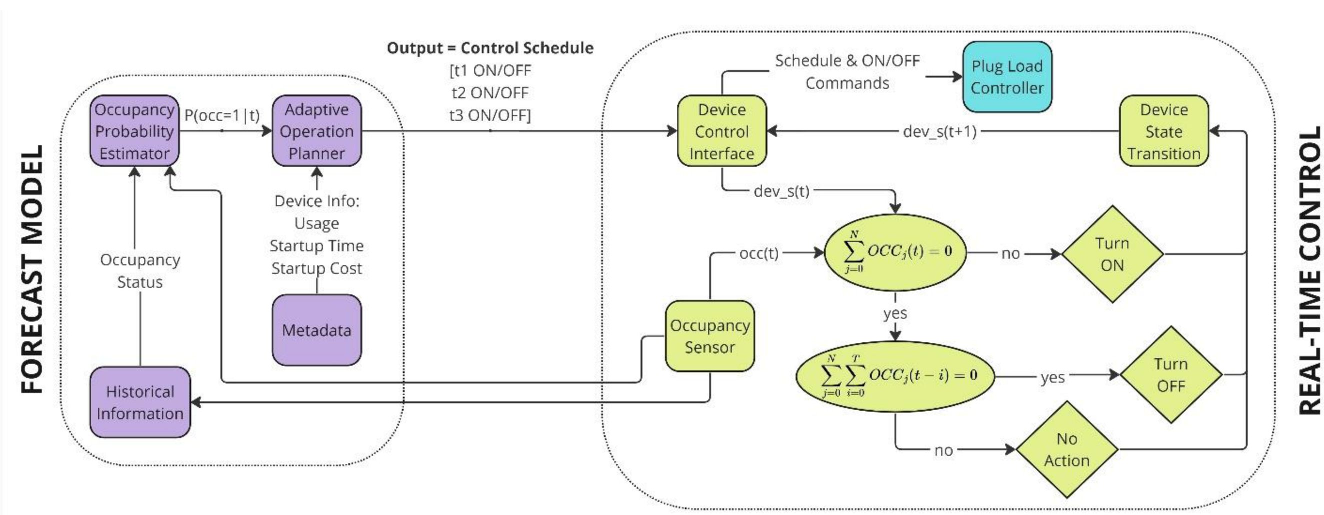
Subsequently, an alternative approach used passive infrared occupancy data collected from HVAC thermostats to trigger PLCs on and to determine when it was appropriate to turn them off. This strategy took full advantage of the Brick infrastructure, as it had to programmatically identify which thermostats were relevant (those in the same department and floor of the PLC) and retrieve the appropriate historical and real-time occupancy data. Two versions of this control strategy, with increasing complexity, are defined:

Level 2. With this approach, the PLC was turned on when any occupancy was detected from thermostats in the department or at 8:00 a.m., whichever occurred first (alternatively, PLC ON could be only on first occupancy). The PLC was turned off at a preset time of 6:00 p.m. This strategy ensured that the plug load would be on during the times provided by the department contact, but also accounted for edge cases where people may arrive early, which was observed during the Level 1 case study. This strategy is like the Level 2 print server controls and automatically accounts for changes in staff arrival times.

Level 3. This version, shown in Figure 5, addressed the issue of water dispensers needing additional time before they are ready for use. A startup time is defined. Water dispensers require one hour of startup time to pre-condition water. The control algorithm then uses historical occupancy data from a defined area (such as a group of spaces that are interconnected and associated with the same department) to forecast daily occupancy for that area. If any part of that area is occupied, then plug loads should be on and ready for use. For each hour of the day, the probability of occupancy is calculated. To determine the time to turn on a PLC, the algorithm finds the first 15-minute increment that has a probability for occupancy above a set threshold. The plug load startup time is then subtracted. To forecast the turn-off time of the plug load, the algorithm identifies sequential hours where occupancy is consistently below the probability threshold. Additional control logic is added to account for unexpected occupant behaviors, including logic to automatically turn on PLCs if a thermostat detects any motion, as in the case of people arriving unexpectedly early. Also, if no motion in the department is detected for 45 minutes, PLCs can be turned off early. A blackout period was established from 10:30 p.m. to 4:30 a.m. for the device to remain off, independent of occupancy detection.

Two primary challenges impacted the Level 3 strategy. (1) The quality of the occupancy data affects the reliability of this control strategy. Thermostats are not always positioned in the ideal spots to consistently track occupancy. Also, thermostats in private offices are likely not as useful as those placed in shared workplaces. (2) Water dispensers require time to pre-condition water before use. Thus, there needs to be sufficient time between the occupancy trigger and the first use.

Figure 5: Control Block Diagram for Level 3 Thermostat Occupancy-Triggered PLC



A PLC incorporating occupancy forecasting. Here, 'dev_s' represents the state of the water dispenser (with 1 indicating on), occ(t) is the binary occupancy measurement at time t with indicating occupied, and j = 1, . . . , N indexes occupancy sensors in N rooms.

Source: University of California, San Diego

CHAPTER 3: Results

Technical Barriers

The principal technical barrier of the project was the ability of existing BEMS to manage plug load controllers. The project first explored the capabilities of the existing campus BEMS to manage plug load controllers and to identify what features are needed for PLC management. After identifying the limitations of the BEMS, a parallel system was developed to prototype and demonstrate an alternative architecture and the features that can better support the integration of plug-load controllers with a BEMS.

The existing campus BEMS is used by UCSD Facilities Management to manage the HVAC of campus buildings. Each building has a network engine with which HVAC components communicate. To add the PLCs, a server was set up to act as an additional network engine for all PLCs to communicate via the BACnet protocol. A network engine is capable of supporting only a limited number of data points, so the large number of PLCs necessitated a dedicated engine for them. The capabilities and limitations of this architecture are noted in Table 4.

The parallel system uses the Brick Schema, which provides a standardized ontology and taxonomy for building systems. This schema, along with the system's architecture of using a graph database in conjunction with a time-series database, enables greater levels of interoperability between heterogeneous devices.

Table 4: Comparison of Standard BEMS and Brick Server Capabilities

Function	Existing Campus BEMS	Brick Server and PLC Ops Application
Adding and Removing PLCs From the System	Adding and removing PLCs is a lengthy, manual process. Discovery of new devices on the network can take hours, due to all the other HVAC components on the network. Adding a new PLC requires individual data points to be manually mapped and added.	The Brick Server receives messages directly from the PLCs through the User Datagram Protocol. New PLCs can be automatically added to the database if the PLC's MAC address does not already exist in the database.
Meta-data Management	Meta-data such as the device location and what appliance is attached to the PLC are stored only in the name given to the PLC. PLCs were named following the standard format that UCSD uses for HVAC, such as SERF-136-PRINTER (building-room-appliance). The limitation of this approach is that PLCs cannot be easily	The Brick Server's graph database enables PLCs to relate to all necessary meta-data and to use it for sorting and management purposes. A graph database works by creating a node for each entity, such as the building, room, plug load controller, and appliance. Relationships can then be created

Function	Existing Campus BEMS	Brick Server and PLC Ops Application
	sorted by this meta-data, which is crucial for managing PLCs in batches. Also, the BEMS lacks additional spatial information, such as how rooms are connected or which rooms belong to certain departments. While this information may not be needed for HVAC, it is more important for PLC.	between nodes such as giving the PLC a "hasLocation' relationship to the room in which it is installed. The Brick meta-data includes critical elements such as which rooms a variable air volume box feeds and how rooms are physically connected. A graphical user interface was created to easily manage this information.
PLC Management	In the BEMS, equipment is primarily organized by its location and what parts of the building it serves. The BEMS graphical interface illustrates where PLCs were located on the floor plan, which was helpful. However, other contextual information is not as readily available.	The PLC Operations App focuses on the stakeholders. PLC impacts occupants more directly, so their preferences and input are important. The app allows the operator to create accounts and then associate people and relevant PLCs to the account. Each PLC can then be set to the desired control strategy per the input from occupants.
PLC Use of HVAC Data	Attempts were made to actuate PLCs using occupancy data from the BEMS. But occupancy data is limited, as the campus does not use occupancy data for HVAC controls since it operates on a static schedule. Also, despite using the BEMS interlock feature to actuate a PLC based on data from an occupancy sensor, we were unable to transfer data between network engines.	In addition to storing HVAC, PLC, and metadata, the Brick Server also has an API, which enables the team's PLC Operations App to access all this data, allowing for interoperability between heterogeneous devices. While the BEMS also has its own API, it lacks the additional historical and metadata needed.
Scheduling	Integrating PLC with a BEMS offers the convenience of reusing schedules for multiple systems. At UCSD the HVAC system operates from static weekly schedules. This same schedule was used to turn PLCs on and off at the same times as HVAC. However, since PLCs are wireless, connectivity was an issue. There were several instances where PLCs failed to receive the signal to turn on due to loss of	The Brick Server is designed to store a schedule for the building and departments, and a custom one for each device. This allows the operator to select a batch of PLCs and to easily apply the stored schedule to them. In this way, the information can be reused for all building systems that rely on schedules.

Function	Existing Campus BEMS	Brick Server and PLC Ops Application
	Wi-Fi connectivity, due to changes from the IT department that unintentionally disrupted communications, or because the PLC server rebooted and failed to restart the gateway software. These experiences highlighted the advantage of PLCs that can store and operate using a schedule uploaded to them, rather than relying on signals from a central source. This approach was attempted with the BEMS; however, this was not practical, as the schedule object for each individual PLC had to be updated manually and could not be connected to or copied from the existing HVAC schedule. Therefore, algorithms that generate updated schedules daily would require manual updates each time. This BEMS limitation made scheduling time-consuming to create and update.	Based on the lessons learned about operating PLCs with stored schedules instead of receiving commands from a central server, most of the control strategies use stored schedules. For example, an algorithm that processes historical occupancy data daily outputs a one-week schedule that can be stored on the PLC. Anytime the algorithm receives new information, it will generate a new one-week schedule and upload it to the PLC. In that way, if communication is functional, only the first (most accurate) day will actually be used for scheduling; but, if communication fails, six additional days are available for the PLC to use as a failsafe.
Alerts	A BEMS has standard alerts that can be applied, such as if a PLC is off or offline. The OFF alert was useful only to confirm that the PLCs did turn off at the correct times. Other alerts, such as those listed in the right column, could not be developed.	The Brick system supports any program logic. Therefore, the following alerts, which are critical for operating a large fleet of PLCs, were created: • PLCs that were offline for more than 24 hours, which could indicate that the PLC was removed. • PLCs that were reporting 0 watts for more than 48 hours, which could indicate that the attached appliance was removed. • PLCs that had a different appliance attached to them are based on analysis of power signatures for device types.

Source: University of California, San Diego

Case Studies

Case Study 1: Print Server

Four weeks, November 6 through December 3, 2023, were averaged to form the baseline with an average energy consumption of 3,870 watt-hours (Wh) per week (Table 5).

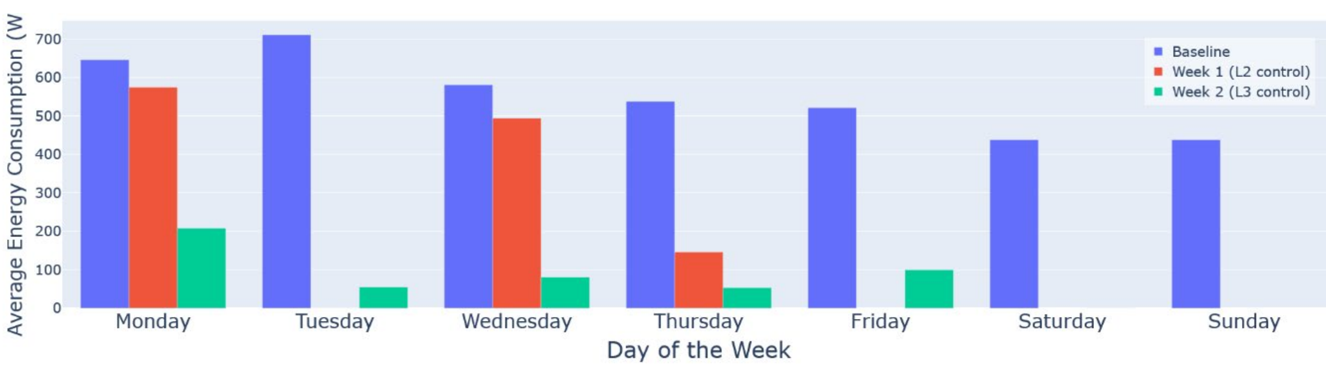
Table 5: Summary of Energy Savings From the Application of Level 2 and Level 3 PLC on a Printer

Week	Energy Consumed	% Saved Versus Baseline	Annual $ Saved Per Printer	Energy Per Print Job
Baseline	3,870 Wh	----	----	184 Wh
Level 2 Control	1,215 Wh	69%	$47	110 Wh
Level 3 Control	496 Wh	86%	$60	33 Wh

Source: University of California, San Diego

During the week-1 pilot with Level 2 control (Figure 6), the printer was not used at all on Tuesday and Friday, and therefore no energy consumption was recorded on those days. On Monday and Wednesday, the printer was used early in the day and more frequently and it remained on until 6:00 p.m., resulting in energy consumption similar to that of the baseline. During the week-2 pilot with Level 3 control, the printer was used every day, but, since it turned off after 30 minutes of inactivity, the energy use was minimal. During both pilots, the printer was never used on the weekend and remained off then.

Figure 6: Comparison of Daily Energy Consumption of One Printer in a Business Department for Baseline Weeks and Control Weeks



Source: University of California, San Diego

Level 2 controls resulted in an energy consumption of 1,215 Wh for one week, which is 69 percent less than the baseline and equates to an estimated annual savings of $47 per printer.

Level 3 controls resulted in a consumption of 496 Wh for one week, which is 86 percent less than the baseline and equates to an estimated annual savings of $60 per printer. However, the printing process took longer, 2 minutes compared to 15 to 20 seconds without PLC, which resulted in a reported issue where an occupant mistook the delay for an equipment fault. Four other reported issues were likely caused by occupants who did not follow the posted instructions for sending print jobs to the print server instead of directly to the printer.

Case Study 2: Water Dispenser

Without any controls, the water dispenser used an average of 9.48 kilowatt-hours (kWh) per week. Level 1 control resulted in an ON-time of 52 hours (31.2 percent) and an energy consumption of 5.10 kWh for the week, a 46-percent savings compared to the baseline.

The Level 2 and Level 3 control strategies rely on robust occupancy detection. In particular, false negatives should be avoided. False negatives refer to no occupancy detection even though there was occupancy, as indicated by the water use log. The robustness of occupancy detection for the water dispenser located in the kitchenette, room 361 (Figure 7), was tested by analyzing the relationship between thermostat occupancy (o) and water usage (u). The team calculated the probability of occupancy within 15 minutes of water usage, as in [P (o|u = 1)]. There is a high (97 percent) probability that occupancy in room 361 was detected within 15 minutes of water dispenser use; probabilities are even higher for the centrally located thermostats. This confirms that the occupancy sensors operated as intended and that there are enough well-placed thermostats in this department to execute PLC strategies based on occupancy.

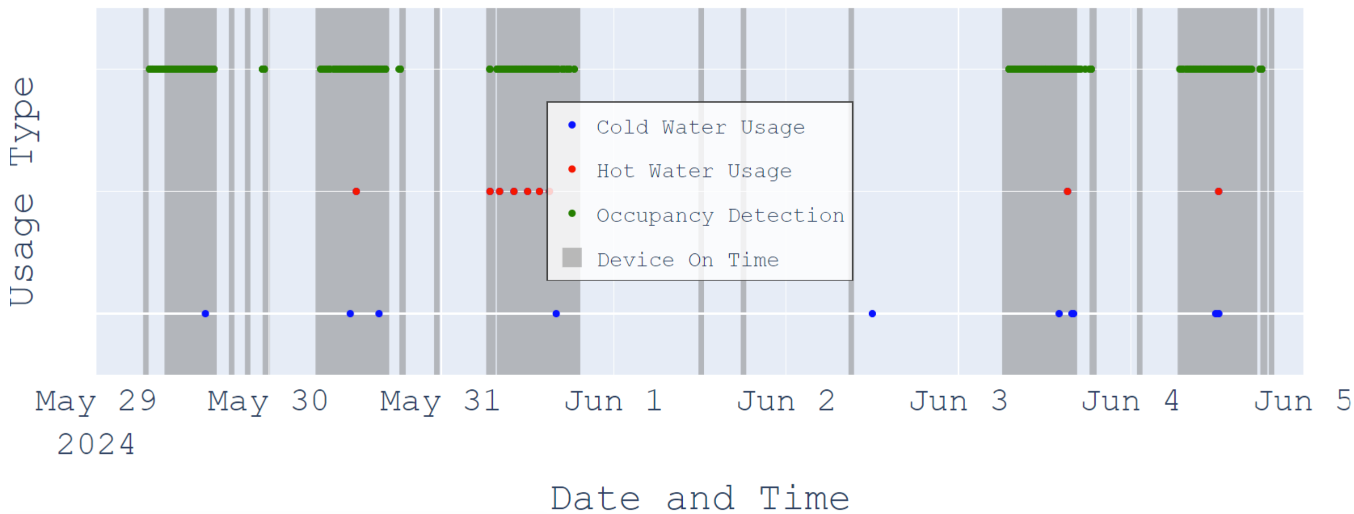
Figure 7: Floor Plan Showing Thermostat Locations in the Administrative Department

Location in the administrative department and the probabilistic relationship to water dispenser (wd) usage in room 361. P(o|u) indicates the probability of an occupancy event within 15 minutes of the water dispenser usage.

Source: University of California, San Diego

The Level-3 control strategy was then field-tested to validate the simulation (Figure 8). During the controls week, the water dispenser used 5.79 kWh, a 32-percent energy savings compared to the baseline. The data shows that the dispenser was on appropriately during all water usage events except one on June 2. However, neither the thermostats nor the portable sensors detected motion during that time. Lastly, there were 10 instances where the thermostats detected motion but the portable sensors did not, which may indicate false positives from the thermostats or insufficient coverage by the portable sensors.

Figure 8: Field Testing of the Level 3 Control



With actual water usage and occupancy data from thermostats and portable motion detectors (green).

Source: University of California, San Diego

The field test shows that the implemented control logic does conserve energy by avoiding unnecessary operation in the absence of demand, but it also ensures the availability of pre-conditioned water in alignment with actual usage patterns, thereby substantiating its efficacy and adaptability.

Cost Benefit Evaluation

For the 765 commercial plug load controllers used in this project, the costs totaled $109 per controller, including hardware, vendor support of the installation, the license for the BERT Software required for integration with the campus BEMS, two virtual machines, 131 hours of installation support by the UCSD project, and support costs from BERT.

The cost for integrating the Johnson Controls and the PLCs into the campus BEMS, including configuration of the virtual network engine, was $299,434, including importing the PLCs and adding them to the BEMS user interface graphics. The final cost of the PLCs was $408 per controller.

The average commercial electricity rate in San Diego at this point was $0.34 per kWh. For a 3-year payback period, this would require 400 kWh of savings per year or 7,692 Wh of savings per week. Assuming typical UCSD business hours, PLCs could be turned off for 103 hours per week (7:00 p.m. to 6:00 a.m. on weekdays and all day on weekends). For the electricity cost savings to equal the installation costs in three years, each PLC would need to turn off an appliance that would normally consume at least 75 watts during those time periods. Large TVs that are used as digital signage and older copiers that are left on 24/7 would meet this requirement, but most smaller appliances and devices that are on standby would not.

If more affordable consumer PLCs are used, ranging in cost from $10 to $25, and the project team's Brick software was used instead of a commercial BEMS, then appliances that use between 10 to 15 watts could meet the 3-year payback period.

Table 6 shows projected energy savings for different PLC levels and buildings. The energy savings are projected, since PLC has been implemented only at relatively small scales due to challenges with onboarding departments. Potential savings are presented for PLC implementation on all printers, TVs, and water dispensers currently monitored. Level 1 controls assume a typical static schedule for turning PLs off evenings and weekends. Level-3 controls use the percent savings demonstrated in the case studies. Rates of $0.34 per kWh are used to convert kWh of energy savings into cost savings.

Table 6: Estimated Energy and Cost Savings Across All Plug Load Controllers

Building	Level 1 Savings per Year	Level 3 Savings per Year	Percent Saved From Level 1 to Level 3
Atkinson	5,724 kWh | $1,946	6,387 kWh | $2,172	12%
Center Hall	4,132 kWh | $1,405	4,565 kWh | $1,552	10%
EBU3B	5,981 kWh | $1,901	6,949 kWh | $2,363	24%
Geisel Library	9,760 kWh | $2,016	11,096 kWh | $3,773	87%
GPS (Robinson)	2,820 kWh | $1,519	3,224 kWh | $1,096	29%
McGill Hall	5,062 kWh | $1,721	5,538 kWh | $1,883	9%
Otterson Hall	4,493 kWh | $1,528	5,221 kWh | $1,775	16%
RIMAC	4,060 kWh | $1,380	4,716 kWh | $1,604	16%
Social Sciences Building	2,784 kWh | $947	3,299 kWh | $1,122	19%
Student Services Center	11,104 kWh | $3,775	12,861 kWh | $4,373	16%
Telemed	1,364 kWh | $464	1,655 kWh | $563	21%
Wells Fargo	3,482 kWh | $1,184	3,896 kWh | $1,325	12%
TOTAL	60,766 kWh | $19,786	69,407 kWh | $23,598	14%

Source: University of California, San Diego

For static Level 1 control, the overall savings are estimated to be 61 megawatt-hours (MWh) or $20,000 per year across the 12 buildings, with 631 plug load controllers. Level 3 control increases savings by 14 percent, to 69 MWh or $24,000 per year.

Plug Load Control Operator and Plug Load User Considerations and Recommendations

Plug Load Control Operator Considerations

Having a single interface for PLC and HVAC provides convenience for PLC operators. It also promises time savings by consolidating information into a single system, such as schedules for buildings. Limitations within the project team's particular BEMS and the approach of storing schedules in the PLC limited this benefit.

Integration of PLC into the BEMS allows the operator to create more effective controls by using BEMS data, such as occupancy from thermostats, for PLC.

A primary concern for the BEMS operator is the additional workload that PLC introduces. IT departments also share this concern, since many plug loads fall under their responsibility.

The addition of plug loads adds many more devices that the operator is responsible for. It also makes troubleshooting more complex, as the fault could be with the plug load controller or have something to do with how occupants are using the plug load.

Whereas HVAC equipment does not change often, plug loads are more susceptible to changes (appliances being moved, removed, or added). While automated alerts can be set up, operator time is still required to keep the system updated.

The priority for BEMS operators is to meet occupant needs. HVAC changes or even failures are generally less disruptive to occupant work, especially in San Diego, where there are small differences between indoor and outdoor temperatures. Plug loads, on the other hand, are directly used by occupants for work and thus require a higher level of reliability.

PLC requires adoption by the occupants that use it; therefore, the BEMS operator must invest time to coordinate with more individual users and communicate frequently.

To mitigate the time-burden concerns, BEMS operators can first focus on plug loads that are not as relied on for work, such as water dispensers and digital signage. From there, shared equipment such as copiers and shared printers can be targeted, as they are less likely to be moved. Level 1 strategies can be implemented first to also reduce the risk of disruption. As occupants become more aware of and comfortable with implementing smart plugs, more energy-effective strategies can be used.

Plug Load User Considerations

Most occupants are supportive of energy-saving measures. Some are skeptical of the savings, claiming that their plug loads are already energy efficient. Generally, occupants do not see a direct value added from PLC (other than the potential for automation) and it is more likely that PLC will disrupt their work. Thus, the value of energy savings and environmental impact must be communicated to occupants regularly to keep them engaged in their efforts.

Outreach and Dissemination Activities

The principal source of knowledge transfer is the Plug Load Management Application software that was published open source on GitHub. The release was accompanied by a journal paper that describes the software and provides example applications.

Project information was further shared through four publications, including a best practices brief for plug load control, a peer-reviewed journal paper (Botman et al. 2024), and two peer-reviewed conference papers (Chia et al. 2023, 2024), including one for the 2024 American Council on an Energy Efficient Economy Summer Study.

The project team delivered a webinar for the United States Department of Energy Better Buildings initiative on March 22, 2022 entitled *Better Together: Integrating Plug Load Management into Lighting and Building Management Systems.* The recording is accessible here: https://betterbuildingssolutioncenter.energy.gov/webinars/better-together-integrating-plug-load-management-lighting-and-building-management-systems.

CHAPTER 4: Conclusion

Plug load control (PLC) demonstrated contributions to California's climate goals and ratepayer benefits. The benefits include annual electricity and energy cost reductions, peak load reduction, contributions to infrastructure reliability, and greenhouse gas emission reductions. PLC energy savings in commercial buildings accrue primarily in the evenings and at night when power grid carbon emission factors are highest. Certain plug loads that are rarely used (printers), are noncritical (most displays), or provide thermal storage (water dispensers) can also provide for immediate load curtailment during demand response events and other grid emergencies. PLC, therefore, represents a powerful tool to enable load flexibility in support of grids with substantial variable renewable penetrations.

PLC trials yielded the following findings. Level 1 (static) control is the simplest control strategy to implement. Level 1 control can be applied to most plug loads and it generally goes unnoticed by occupants if the schedule has sufficient buffer time before and after typical occupancy periods. Occupants also prefer predictable controls, so that PLC can fit naturally into their daily routines. Also, regular training and awareness are required to maintain the PLC deployment, since, on several occasions, the project team found that occupants removed PLCs, ignored the manual override buttons, or assumed the PLC was malfunctioning when it was off at a needed time. Static PLCs are readily available and can realize a 3- to- 5-year payback period if used on plug loads that consume 75 watts or more during unused periods.

An effective PLC for printers was achieved by coupling a print server with PLC. Large energy savings were achieved and the process of turning printers on was fully automated. The print server is robust enough to handle changes in occupant behavior, such as printing at odd hours. Level 2 controls are ideal for printers that are used frequently and for copiers that have a longer bootup time. Level 3 control requires more education and communication with occupants; it is ideal for printers that are used less frequently. There continue to be concerns about PLC degrading printer health due to the hard stop of power. The project team reached out to printer manufacturers, and the general feedback is that PLC does not affect printer health if power is not cut while the printer is actively printing, which the project team's control successfully avoided. Additional work is required to get the print server system to a production and commercialized level that can be used in daily operations. A key improvement that must be developed is to transition to a different print server that can support Windows, Apple, and mobile devices. Additional fail-safes must be developed, such as the ability to default PLCs to ON if connectivity is lost to the control system, whether due to the Wi-Fi network or to server error.

Level 1 control of water dispensers and digital signage TVs provided reliable savings. Schedules provided by department contacts are useful; however, due to holidays and variable work schedules, they may not reflect true occupancy patterns or appliance use. To achieve greater energy savings with Level 2 and Level 3 control, occupancy data is required. The concept of using occupancy data with PLC was successfully demonstrated. For water dispensers, occupancy forecasting is necessary to account for the long startup time needed to precondition water before use. Generally, PLCs do not inherently have occupancy data, so the interoperability that the Brick Schema provides is crucial for the scalability and portability of occupancy-driven control strategies. Future work will be performed at a building with a connected lighting system that has near-complete coverage of all rooms with occupancy detectors.

The main future target market is the California higher education market, as this market has better economies of scale. The University of California market alone (not including California State Universities) consists of 5,847 buildings with 142 million square feet of floor area. A 25-percent adoption in this market would double the existing PLC deployments in the country. The economies of scale and lessons learned would then result in product maturity, which will enable targeting the California office buildings market.

GLOSSARY AND LIST OF ACRONYMS

Term	Definition
24/7	all day, every day
API	Application Programming Interface
BACnet	Building Automation Control Network
BEMS	Building Energy Management System
BERT	Best Energy Reduction Technologies
HVAC	heating, ventilation, and air-conditioning
kWh	kilowatt-hour
MQTT	Message Queuing Telemetry Transport
MWh	megawatt-hour
PL	plug loads
PLC	plug load control
UCSD	University of California, San Diego
Wh	watt-hour

References

ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers). 2016. "Standard 135-2016, BACNET™ — A Data Communication Protocol for Building Automation and Control Networks." Available at www.ashrae.org/technical-resources/standards-and-guidelines/standards-addenda/standard-135-2016-bacnet-a-data-communication-protocol-for-building-automation-and-control-networks.

Balaji, B., A. Bhattacharya, G. Fierro, J. Gao, J. Gluck, D. Hong, A. Johansen, J. Koh, J. Ploennigs, Y. Agarwal, M. Berges, D. Culler, R. Gupta, M. Kjaergaard, M. Srivastava, and K. Whitehouse. 2016. "Brick: Towards a Unified Metadata Schema for Buildings." BuildSys '16: Proceedings of the 3rd International Conference on Systems for Energy-Efficient Built Environments: 41–50. Available at https://doi.org/10.1145/2993422.2993577.

Bergmann, H., C. Mosiman, A. Saha, S. Haile, W. Livingood, S. Bushby, G. Fierro, J. Bender, M. Poplawski, J. Granderson, and M. Pritoni. 2020. "Semantic Interoperability to Enable Smart, Grid-Interactive Efficient Buildings." LBL Publications, Lawrence Berkeley National Laboratory. Available at www.escholarship.org/uc/item/1325d5j3.

Botman, L., J. Lago, X. Fu, K. Chia, J. Wolf, J. Kleissl, and B. De Moor. 2024. "Building plug load mode detection, forecasting and scheduling." *Applied Energy*, 364: 123098. Available at https://doi.org/10.1016/j.apenergy.2024.123098.

Chia, K., A. LeBar, V. Agarwal, M. Lee, J. Ikedo, J. Wolf, K. Trenbath, and J. Kleissl. 2023. "Integration of a Smart Outlet-Based Plug Load Management System with a Building Automation System." 2023 IEEE PES Grid Edge Technologies Conference & Exposition (Grid Edge): 1–5. Available at https://doi.org/10.1109/GridEdge54130.2023.10102749.

Chia, K., M. Ben-Ayed, S. Hebbur Eshwar, C. Zhang, E. Chen, Y. Gu, J. Kleissl, A. Khurram, J. Wolf, A. Van Sant, and K. Trenbath. 2024. "Brick Schema Standardized Plug Load Control: Strategies for Load Reduction." ACEEE 2024 Summer Study on Energy Efficiency in Buildings. Available at https://www.aceee.org/sites/default/files/proceedings/ssb24/assets/attachments/20240722163153344_43b23c53-9a47-44f2-b01d-aa5f9d3d18ce.pdf.

Hardin, D. B., E. G. Stephan, W. Wang, C. D. Corbin, and S. E. Widergren. 2015. *Buildings Interoperability Landscape*. Pacific Northwest National Laboratory. Report Number: PNNL–25124. December, 2015. Available at www.osti.gov/servlets/purl/1234792/.

Langner, R., and K. Trenbath. 2019. *Integrating Smart Plug and Process Load Controls into Energy Management Information System Platforms: A Landscaping Study*. National Research Energy Laboratory. Technical Report Number: NREL/TP-5500-74080. June, 2019. Available at https://betterbuildingssolutioncenter.energy.gov/sites/default/files/attachments/NREL_PPL_Landscaping_Study.pdf.

Lobato, C., S. Pless, M. Sheppy, and P. Torcellini. 2011. "Reducing Plug and Process Loads for a Large Scale, Low Energy Office Building: NREL's Research Support Facility." Presented at the ASHRAE Winter Conference, Las Vegas, Nevada, January 29 – February 2, 2011. Conference Paper: NREL/CP-5500-49002. Available at https://docs.nrel.gov/docs/fy11osti/49002.pdf.

Raphael. 2021. "Turn on printer with a print job (printer power saving)." Home Assistant website. July 18, 2021. Available at https://web.archive.org/web/20241103224728/www.community.home-assistant.io/t/turn-on-printer-with-a-print-job-printer-power-saving/323154.

United States Utility Rate Database. 2024. "Open Energy Information, Data and Resources." Available at https://web.archive.org/web/20240427135710/www.apps.openei.org/USURDB/.

Project Deliverables

The high-value Project Deliverables include:

- Data Taxonomy Glossary
- Advanced Plug Load Operation Strategies in Building Energy Management Systems
- Best Practices for PLC Brief

Project deliverables, including interim project reports, are available upon request by submitting an email to pubs@energy.ca.gov and at http://gridlab.ucsd.edu/plcxbms/.