Energy Research and Development Division

FINAL PROJECT REPORT

Internet of Things and Ubiquitous Sensing in University Building Energy Management

Design Optimization and Technology Demonstration

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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 CEC and the state's three largest investor-owned utilities—Pacific Gas and Electric Company, San Diego Gas & 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.

Internet of Things and Ubiquitous Sensing in University Building Energy Management is the final report for the Internet of Things and Ubiquitous Sensing in University Building Energy Management: Design Optimization and Technology Demonstration project (Contract Number: EPC-16-033) conducted by California State University, Long Beach, the University of California, Riverside, and Wayne State University. The information from this project contributes to the Energy Research and Development Division's EPIC 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 CEC at ERDD@energy.ca.gov.

ABSTRACT

This project demonstrated, measured, verified and evaluated a pre-commercial Energy Management System based on internet of things to achieve control of lighting, HVAC and plug loads. The researchers monitored a large-scale demonstration at California State University, Long Beach. The demonstration of the energy efficiency technology improvements successfully showed more than a 20 percent reduction to electricity use. The costs and benefits analysis were calculated for a period of 15 years based on the useful life span of the installed system. Some of the highlights of the report include the development of a customized and cost-effective energy efficiency and demand side management system, the development of software interfaces and an analysis of the power quality. The findings from this project can provide other academic institutions and commercial buildings with a comprehensive blueprint for an assessment of an innovative emerging energy management system based on internet of things and ubiquitous sensing and controls and the ensuing energy savings and Green House Gas emission reductions.

Keywords: Smart Building, Internet of Things, Energy Cost Savings, Demand Response, Energy Efficiency, System Optimization.

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EXECUTIVE SUMMARY

Introduction

California’s energy goals, include Senate Bill 350, which requires the state to double statewide energy efficiency savings in electricity and natural gas end uses by 2030. The purpose of this project was to deploy, demonstrate, and test an advanced building energy management system based on Internet-of-Things (IoT). IoT describes physical objects (or groups of such objects) with sensors, processing ability, software, and other technologies that connect and exchange data with other devices and systems over the Internet or other communication networks. The installed technologies included lighting, plug-in, heating, ventilation, and air conditioning loads at a large academic building.

The results from this project can also serve as examples to help rate payers and policy makers set forth plans to increase the energy efficiency in academic buildings. The objective was to facilitate energy efficient technologies and strategies to reduce energy use and reduce greenhouse gas emissions, which is one of California's major energy policy goals. Many academic building energy managers are reluctant to take on brand-new technologies or upgrades due to the need for additional in-house technical personnel and expertise. This agreement attempted to overcome this reluctance by demonstrating state-of -the art energy management technologies in a large academic building.

In addition, conventional energy management systems also often suffer from the lack of a platform which performs the task of integrated energy management with respect to the functionality of the building and occupant behavior. However, upgrading to a modernized building energy management system can be a challenge due to the need for additional in-house technical personnel and expertise. Therefore, a large-scale demonstration and extensive assessment of an innovative energy management system was conducted in this project based on IoT solutions and a ubiquitous number of sensors and actuators. The project site was the 101,670 square feet conditioned space Engineering and Computer Science building, on the campus of the California State University, Long Beach, which is served by Southern California Edison, an investor-owned utility.

Project Purpose

The goal of this project was to remove barriers to achieve widespread deployment of state-of-the-art energy management technologies in academic buildings and achieve 20 percent yearly energy savings by optimizing load operation, load leveling, and shaving peak power demand. The project demonstrated energy efficiency technologies for lighting, heating, ventilation, and air conditioning (HVAC), and plug loads and integrated them with system-level approaches to provide automated demand side management in the university’s Engineering and Computer Science building.

This project can provide California investor owned utilities, academic institutions (including the other 22 California state universities that share similar energy saving objectives), energy management technology developers, and other stakeholders with a detailed customized course of action, an innovative and ubiquitous energy management platform, and comprehensive assessments and documentation of the feasibility of large scale deployment, technical considerations, performance, savings, and other benefits.

Project Approach

To achieve the project goals, the research team took three consecutive actions: 1) characterized the existing equipment, monitoring requirements, and control strategies across classrooms, research labs, teaching labs, offices, and other areas of the Engineering and Computer Science building; 2) installed and tested the IoT network of sensors and actuators, developed software interfaces, assured interoperability, and demonstrated the proposed building energy efficiency and demand side management technologies for the building; and 3) conducted a comprehensive performance evaluation and verification task in terms of energy efficiency and demand response, building operation analysis, and overall costs and benefits assessment.

The project management, system architecture, and planned deployment of technologies allowed for parallel subtasks to be completed simultaneously. The project partners procured and prepared individual components, while the project team defined deployment requirements and system communication, monitoring, controls, component configuration, and energy management platform implementation. The project team also implemented energy and data component connections at the transition points from each deployed technology, component, and module to the overall system.

To properly determine the performance and benefits achieved by the deployed technologies and the building energy efficiency and demand side management platform, the project team implemented a comprehensive measurement and verification plan. The measurement and verification plan had two primary purposes: 1) allow the demonstration sites to calculate and document energy/cost savings by identifying critical performance metrics and by using appropriate analytical methods and procedures; and 2) collect, store, manage and openly share the performance data and analysis procedures with all participating partners to verify savings achieved by this project.

This project included several specific technical tasks in addition to the standard tasks identified in the scope of work:

1. Designing a Comprehensive, Customized, and Cost-Effective Energy Efficiency and Demand Side Management System with an IoT Network of Advanced Sensors and Actuators for the Engineering and Computer Science Building
    - In this task, the project team a) characterized lighting, HVAC, and plug-in load control potential across classrooms, research labs, teaching labs, offices, and other areas of the building; b) developed and designed granular (detailed) IoT-based control strategies to reach maximum energy efficiency and demand response capacity across different areas of the building; c) designed ubiquitous IoT-based sensing and monitoring requirements of the control system across different areas of the building; and d) refined the IoT-based monitoring and control system structure for energy efficiency and demand response.

2. Developing, Deploying, Commissioning, and Testing the IoT Network of Sensors and Actuators, Developing Software Interfaces, and Demonstrating the Energy Management System for the Engineering and Computer Science Building
    - In this task, the project team a) deployed, commissioned, and tested the IoT network of lighting sensors and actuators, HVAC sensors and actuators (a device that moves or controls a mechanism), and plug-in load sensors and actuators across different areas of the building; b) implemented and tested the software and communications interface to collect and store sensor data in a data repository and dispatch command signals to actuators; and c) demonstrated the developed advanced technologies for the building energy management under normal daily conditions and demand response events.
3. Performance Evaluation in terms of Energy Efficiency and Demand Response, Building Operation Analysis, and Overall Costs and Benefits Assessment
    - In this task, the project team a) assessed the benefits achieved by proposed technologies in energy efficiency and demand response flexibility; b) assessed the impact of proposed technologies on user operations across different facilities in the building; and c) analyzed overall costs and benefits of the project and identify the lessons learned.

Project Results

This comprehensive project successfully demonstrated more than a 20 percent reduction to electricity use and holistically covered multiple common load types in an academic building. The project used many state-of-the-art control techniques for electric loads, including automated lighting control, automated dimming control, high granularity zonal occupancy-based lighting control, central temperature monitoring and control, zonal occupancy-based ventilation control, automated variable air volume control, automated fan speed control, automated pre-cooling, temporary non-essential plug load curtailment, and idle load curtailment. The researchers coordinated and optimized advanced controls for lighting, HVAC, and plug loads.

The deployment of technologies directly reduced overall and peak-hour energy consumption (kWh) and energy demand (kW) from the grid. The implemented technologies successfully achieved a reduction in electrical energy consumption of 23.41 percent, which met the initial project target of reducing energy consumption. The installed technologies also have the capability to provide demand response services when required. The results of the project included:

- Lower Costs: The total yearly energy included the HVAC, lighting, and plug-in loads was 264,516 kWh. These savings are summarized here and identified in Table 6. On average, the monthly peak load reduction was .0122 KW, which reduced annual electricity costs by $40,475. Other cost reductions included the annual energy savings for time-of-use pricing rates of $22,114 per year. The researchers estimated that participation of in a demand response program such as critical peak pricing would yield an additional annual benefit of $10,012. The heating thermal energy savings from the implemented HVAC operational changes were estimated at 12.62 percent, translating to 442,054 kBTU annually, or 4,422 therms.
- Lower Greenhouse gas emissions: The project reduced electricity consumption (lighting, HVAC, and plug-in load) and natural gas consumption (HVAC load. The energy savings in this project translated to an annual greenhouse emissions reduction of 60.31 metric tons of carbon dioxide per year.

The project team brought the monitoring and control resolution of a building down to a device level. The sensors used in this project 1) detected and captured many features beyond basic occupancy (they also determine the areas occupied and the extent of occupancy); 2) in addition to motion sensitivity, captured activities and mobile and immobile occupants; 3) monitored the space at much greater spatial detail, which allows fine-tuned zonal control in a single room; and 4) are connected to and coordinated by a central monitoring and data housing system that allows real-time and post analysis. Essentially, this monitoring system represented a breakthrough in the ability to sense and detect activity within a building.

The project team adjusted and customized the technology for the unique features and uses in an academic building. The technology can also be adapted to load patterns in different buildings spanning a wide variety of facilities, for example lecture halls, classrooms, teaching labs, office spaces, simulation rooms, and so on.

Other merits of the implemented technology were the ease of deployment and integration in a variety of existing buildings, interoperability, and the ability to include or work in parallel with existing and conventional energy management systems. Sensors, actuators, and other hardware were plug-and-play devices, deployed without any need of hardwiring or modifications to existing circuits, and the team was able to deploy the fully automated IoT sensor network with minimal labor.

Technology/Knowledge Transfer/Market Adoption (Advancing the Research to Market)

The project team published four papers as part of various conferences including the North America Power Symposium and the IEEE Power & Energy Society Innovative Smart Grid Technologies. In addition, the team published two journal papers as part of the IEEE Transaction on Smart Grid. The team presented the project work in poster presentations and invited talks in five workshops and conferences, including the EPIC Symposium and the IEEE Green Energy and Smart Systems Conference. During the project, project partner, Enlightened Inc.'s IoT lighting with HVAC IoT control was still on its path to market. By the project's end, their IoT-based lighting technologies were implemented in other California universities, including Stanford University, the University of California, Irvine, and California State University Dominguez Hills. Enlighted's IoT-based energy efficiency technologies were also implemented in commercial buildings and facilities at Veeco Services, AT&T, Interface Inc., Agilent Technologies, and Menlo Business Park.

Benefits to California

Currently, utilities must invest in new generation infrastructure capable of handling peak demand. The ability to reduce electricity use during times of peak demand creates an opportunity for utilities (and ratepayers) to reduce capital investment in new electricity generation and make the most of existing equipment. To protect ratepayers, however, technologies that can make the grid more reliable must be rigorously tested in a safe, controlled environment. This project offered carefully controlled demonstration and investigation at multiple spaces within a large academic building environment to ensure safe and effective operation of the technology.

This project provided the following benefits to ratepayers:

- Greater Reliability: The improved energy efficiency could reduce the need for additional electricity generation capacity and transmission system upgrades. The estimated benefit for SCE is $36,906 annually.
- User Comfort Enhancement: The energy management system supports different comfort levels for building occupants by adjusting the setpoints of lighting fixtures and HVAC units.
- Consumer Appeal and Public Awareness: The proposed technologies are turnkey solutions that will be attractive to California's real-estate developers, facility managers, and building owners. Publicity about the project will increase public awareness of the benefits of the project.

The demonstration and validation of the implemented technologies and energy efficiency platform can benefit consumers in commercial buildings.

The total annual economic benefit of this project was $113,715. The achieved economic benefits came from non-overlapping revenue streams listed in Table ES-1. The return of investment over the 15-year useful life span of the system at 1% yearly escalation in energy costs and investor owned utility benefit value is 10.68%.

The total annual electricity and thermal savings were at 264,516 kWh and 442,054 kBTU, respectively. The decarbonization also helped to reduce 60.31 metric tons of CO_2 in greenhouse gas emissions yearly.

Table ES-1: Technology Revenue Streams

Economic Benefit	Annual Amount
Energy cost reduction	$22,114
Peak demand charge reduction	$40,475
Demand response capacity increase	$10,012
Thermal energy saving	$4,208
Transmission and distribution upgrades deferral	$14,844
Improved electric service quality and reliability	$12,852
Electric supply capacity release	$9,210
Total economic benefit	$113,715

Source: California State University Long Beach

CHAPTER 1:
Introduction

Introduction

The purpose of this project was to deploy, demonstrate, and test an advanced building energy management system based on Internet-of-Things (IoT) to reduce energy consumption by 20 percent and increase the use of energy efficient technologies and strategies to reduce energy use to reduce greenhouse gas emissions, which is one of California's major energy policy goals. During this project, a large-scale demonstration and extensive an innovative energy management system based on IoT solutions and ubiquitous sensing and control was installed and assessed at a large academic building in Long Beach, California. The project site was the 101,670 square feet conditioned space of the Engineering and Computer Science (ECS) building, at California State University, Long Beach (CSULB), which is served by Southern California Edison, an investor-owned utility.

Equipment Inventory

The ECS Building is one of the largest buildings at CSULB and includes many different types of facilities. The building's equipment included lighting, plug loads, heating, ventilation, and air conditioning (HVAC) loads. This chapter shows the result of the inventory lighting survey which was performed by visiting every room in the building to determine the total number of different types of fixtures, plug loads, and electrical equipment used in the building. This data was used to define a baseline for the demonstration site. The function of the baseline is to have a pre-deployment case that can be compared directly with the post-deployment performance period.

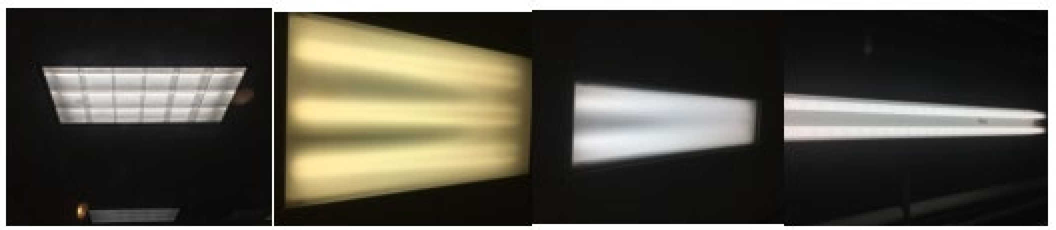
Lighting Fixtures and Plugs

Four types of lighting fixtures were found in the ECS building:

- T8 4' Fluorescent (2 or 3 lamps per fixture)
- Light Emitting Diode (LED)
- High Intensity Diffusion (HID)
- Halogen

These types of lighting fixtures are shown in Figures 1 and 2. Lighting fixture numbers and wattage are reported in Table 1.

Figure 1: Different Types of Fluorescent Lights Based on Number of Lamps per Fixture



Source: California State University Long Beach

Figure 2: Light Emitting Diode (left), High Intensity Diffusion (middle), and Halogen (right)

Source: California State University Long Beach

Table 1: Number of Lighting Fixtures and Wattage by Type

Type	Fluorescent (2/3 Lamps per Fixture)	LED	High Intensity Diffusion (HID)	Halogen	Total
Wattage (W)	59/89	12	190	60	
Count	1,119	139	18	12	1,288

Source: California State University Long Beach

There were also four types of outlets: single, duplex, triplex and power strips (Figure 3).

Figure 3: Outlets in Engineering and Computer Science Building

Outlet types from left to right: single, duplex, power strip, and triplex.

Source: California State University Long Beach

The total number of outlets is shown in Table 2. Of the 2,522 outlets, single, duplex and triplex outlets (total 820) were considered for replacement as power strip plugs are the extensions of these plugs.

Table 2: Number of Outlets and Wattage by Type

Outlet Type	Single	Duplex	Power Strip Plugs	Triplex	Total
Count	4	761	1,702	55	2,522

Source: California State University Long Beach

Plug Loads

The research team conducted a comprehensive plug load equipment inventory throughout the building to determine the different types of plug loads in the ECS building. Table 3 shows the 6 categories of plug loads.

Table 3: Plug Load Inventory

Category	Equipment Type	Total	Wattage
Audio/ Video	Overhead Projector	31	365
	TV/LCD Screen	28	150
Computers & Monitors	Personal Computer	559	165
	Network Switch	1	66
Gym and Training Equipment	Treadmill	1	700
Kitchen/ Breakroom	Refrigerator	11	140
	Coffee maker	5	936
	Microwave	8	1,200
	Water Cooler/Heater	4	602
	Toaster	3	1,500
Lab Equipment	3D printer	9	50
	Oscilloscope/function generator/D.C. Supply	33	50
	Projector control unit	1	47
Printer/Scanner	Personal Printer	112	190
	Small Networked Printer	6	567
	Large Networked Copy/Printer	5	1,500
	Fax machine	2	420
	Paper Shredder	3	146

Source: California State University Long Beach

To determine equipment usage time and energy consumption, the researchers interviewed students of different engineering majors who were occupying the rooms about their equipment usage. The dry and wet laboratories also contain specialized equipment, such as a wind tunnel, laser, absorption column and hood, distribution column, convection dryer and hood, heat exchanger, evaporators, fatigue tester, fume hood, milling machine, welder, radial saw, planer, and an airplane simulator. Table 3 represents the quantity of equipment and its rated wattage. This plug load inventory helped to calculate the leakage current of these loads.

Heating, Ventilation, and Air Conditioning Equipment

The ECS building is served by a central plant with an ice storage system, also referred to as thermal energy storage (TES). Table 4 illustrates the equipment and quantity of the HVAC system equipment. the sizes, manufacturers' names, and model numbers when available.

Table 4: Heating, Ventilation, and Air Conditioning Equipment Inventory

Qty.	Equipment	Size	Manufacturer/Model
7	Air Handling Units	2,600 – 37,260 cfm	Trane Climate Changer/ CCDB
9	Fan Coil Units	1,500 – 6000 cfm	Data-Aire / DTC
2	Refrigeration Compressors	150 – 179 tons	FES / 140
1	Chiller Barrel	535 tons	Repco / BU
2	Evaporative Condensers	2,700 – 5,150 MBH	BAC / VC
4	Ice Storages	58,330 – 71,760 lbs. ice	BAC / TSU (700A / 860A)
1	Heat Exchanger	434 gpm	BAC / B-14
2	Chilled Water Cir. Pumps	427 gpm @ 90 ft.	-
2	Chilled Water Pumps	118 gpm @ 50 ft.	-
2	Hot Water Pumps	31 gpm @ 60 ft.	Paco / 10-15951130001-1562EE
2	Compressor Cooling Pumps	48 gpm @ 24 ft.	Paco / 10127071000611382
12	Fume/Heat Removal Hoods	300 – 3,500 cfm	-
10	Exhaust Fans	700 – 6,100 cfm	Twin City / 105-245

Source: California State University Long Beach

The building is served by 7 air handlers. The air handling units use chilled water from the central plant, and a refrigeration compressor/ice storage system provides chilled water when the central plant cannot meet the load. The terminal unit reheats are served by medium temperature hot water, which is produced from the campus central loop. Ten pumps in total serve the various systems: chilled water, hot water, cooling compressor, and ice storage systems. The exhaust fans are on the roof and serve areas such as restrooms and classrooms that have fume hoods.

Potential Energy Savings from Engineering and Computer Science Building Current Systems

Baseline Energy Consumption for Sensing and Monitoring

The baseline energy consumption was determined by identifying lighting circuits, distribution panels, and bus load. According to the ECS building single line diagram, there were 3 types of buses feeding different distribution panels on each floor: 2500 A, 277/480V AC, 3 phase buses, 2000 A, 120/240V AC Bus, and 2000A, 120/208V AC, 3 phase buses. Table 5 lists each distribution panel and Kw per bus and floor.

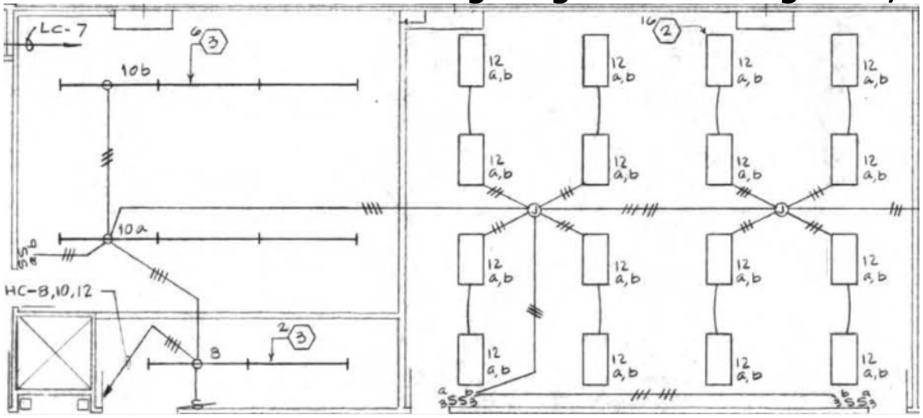
Table 5: Lighting Distribution Panels

Panel	Total Panel Lights	Total Panel kW	Floor
HA	171	20.425	1st Floor
HB	161	18.68	2nd Floor
HC	191	22.6	3rd Floor
HD	201	23.64	4th Floor
HE	108	15.12	5th Floor
HF	134	19.54	6th Floor
LA	103	9.14	1st Floor
LB	59	3.27	2nd Floor
LC	64	5.05	3rd Floor
LD	50	3.64	4th Floor
LE	9	0.68	5th Floor
LEA	89	11.34	5th Floor
LF	11	0.68	6th Floor
LFA	91	11.04	6th Floor

Source: California State University Long Beach

The lighting panel boards were metered next to identify only the lighting energy consumption. The researchers assumed the lighting had a dedicated source, so the electrical circuits were traced to identify the location for the meters using the lighting plan drawings and lighting schedule. Figure 4 shows the third-floor lighting plan and that circuits HC-8,10,12 were connected to fixtures located in room 310, 311, 312, 313, and 314.

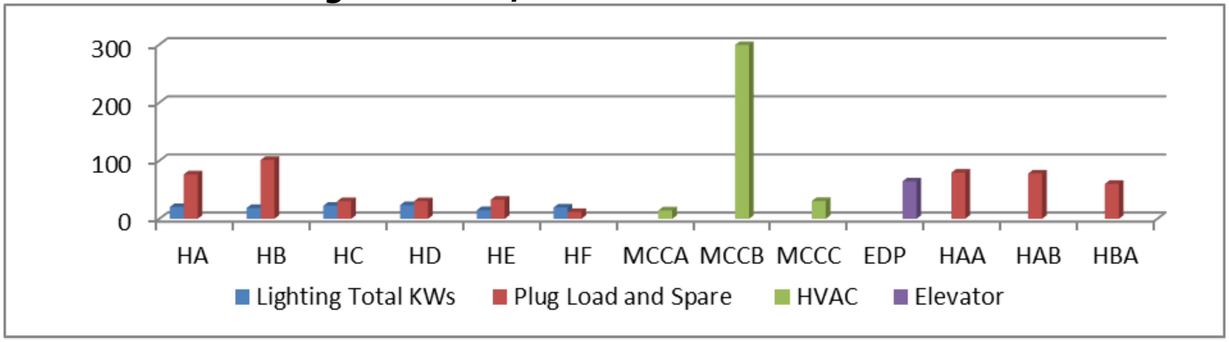
Figure 4: Section of Third Floor Lighting Plan Showing HC-8,10,12



Source: California State University Long Beach

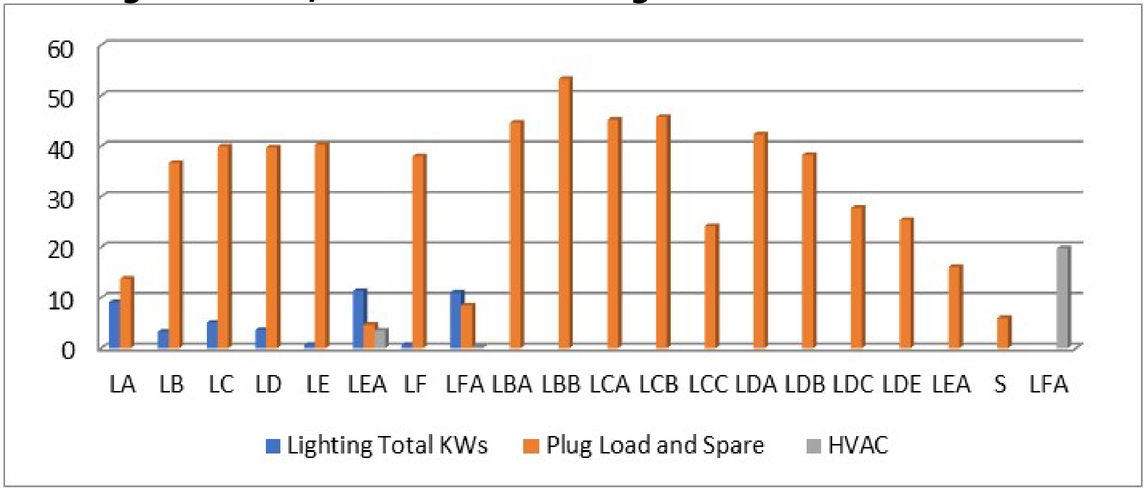
In this way, the researchers were able to identify the distribution of loads. Figures 5 and 6 show the distributions. Figure 5 shows all the loads connected to the 277/480V AC bus, and Figure 6 shows the panels connected to the 120/208V AC bus.

Figure 5: 277/480 Volt Bus Panel Loads



Source: California State University Long Beach

Figure 6: 120/208 Volt Alternating Current Bus Panel Loads

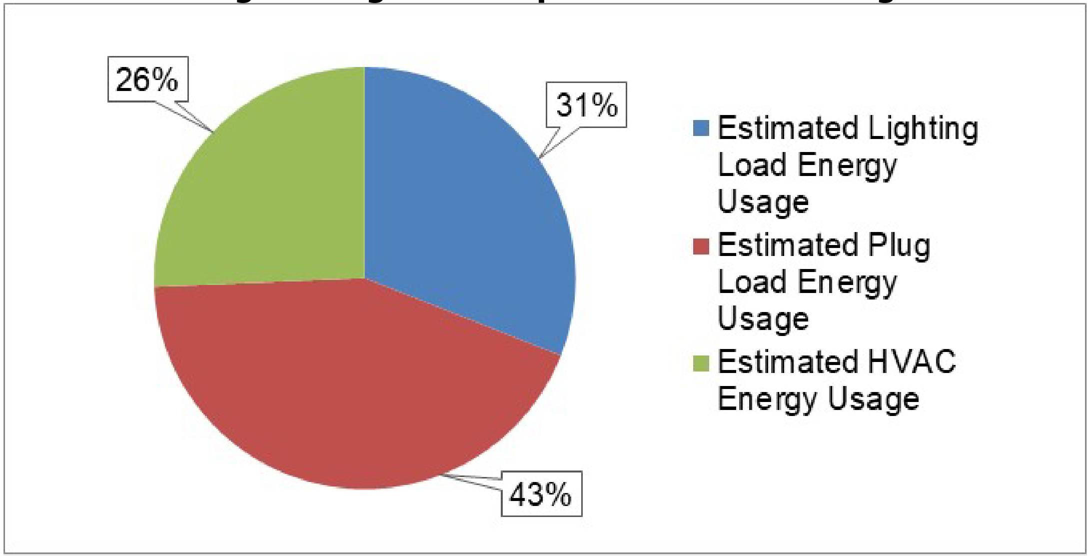


Source: California State University Long Beach

Potential Energy Savings Analysis

Two smart meters collected the energy consumption data. The average load of the ECS building in 2016 was 128 kW, and the peak load of the building was 456 kW. The average plug load demand of the building was 56 kW, while the average lighting load and HVAC load demand was 39 kW and 33 kW respectively. Based on the comprehensive inventory, Figure 7 shows the estimated energy usage breakdown of the building in 2016.

Figure 7: Estimated Energy Usage Profile of Engineering and Computer Science Building



Source: California State University Long Beach

The project's objective was to reduce energy consumption in the ECS building by 20 percent. Table 6 shows the potential energy savings for each system.

Table 6: Potential Energy Savings for Engineering and Computer Science Building

	Lighting Load	Plug Load	HVAC	Total
Estimated Energy Usage (kWh/year)	350,000	490,000	290,000	1,130,000
Proposed average 20% Reduction (kWh/year)	280,000	392,000	232,000	904,000

Source: California State University Long Beach

CHAPTER 2:
Design a Customized, and Cost-Effective Energy Efficiency and Demand Side Management System

This chapter discusses the energy management system (EMS) used in the California State University at Long Beach building prior to this project as well as the system installed as part of the project. The upgraded system combined two networks (Enlighted and Siemens), and used an integrated and interoperable control and communication platform with an open protocol (BACnet).

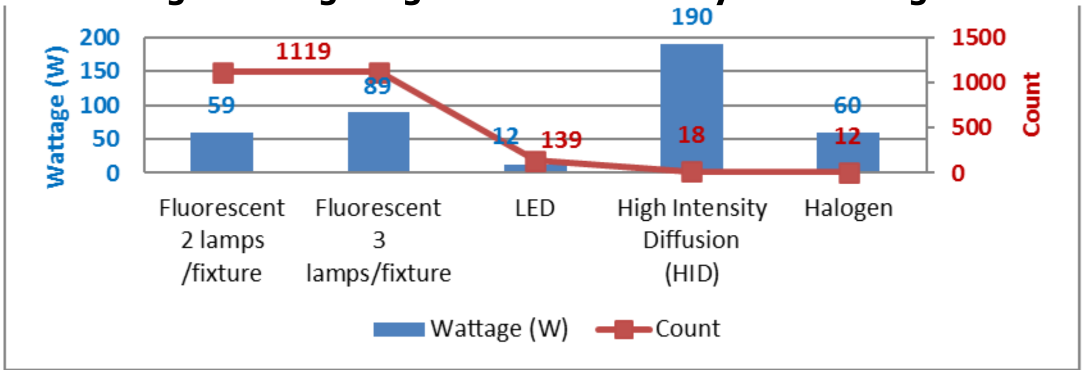
Characterize the Lighting, Heating, Ventilation, and Air Conditioning, and Plug-In Load Control Potentials

The previous EMS is subdivided into two sections: HVAC and lighting systems. Plug loads were not part of the previous EMS. The outlets were not smart devices and did not interface with a controller or a network manager.

Previous Lighting Systems

As discussed in chapter 1, the project team categorized the lighting fixtures into 5 distinct types with corresponding wattage. The building has 1,288 fixtures, 86 percent (1,119) which were fluorescents. There were two types of fluorescent fixtures: those with 2 lamps at 59 watts per fixture, three lamps with 89 watts per fixture. Figure 8 shows the inventory of lighting fixtures and wattage, and Figure 9 shows two-lamp fixtures installed in room ECS-411.

Figure 8: Lighting Fixtures Inventory and Wattage



Source: California State University Long Beach

Figure 9: Room Engineering and Computer Science-411 with Old Lighting Fixtures

Source: California State University Long Beach

The previous lighting system was not automated and did not interface with a controller or network manager. The system had motion sensors that turned lights on or off in a particular room, but did not have a scheduler so the lights typically remained on until the motion sensor stopped detecting movement.

Previous Heating, Ventilation, and Air Conditioning System

The HVAC system of the building had six control zones composed of multizone controllers for heating and cooling, variable frequency drivers for fan motor control to increase and reduce air duct pressure, and a Java Application Control Engine (JACE) (a physical device that connects the controllers and network manager).

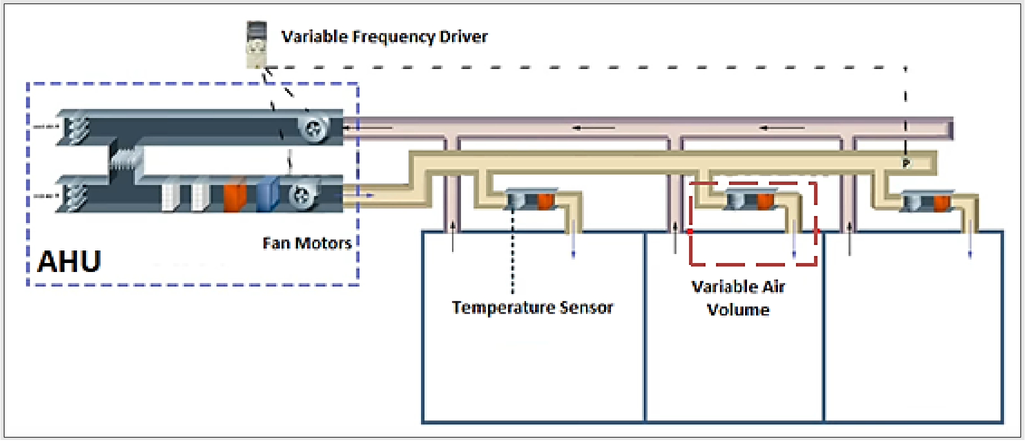
For data exchange, the system used a building automation and control network (BACnet), a data communication protocol that provided a set of rules for data exchange between devices. For data control, the system used Niagara Framework, an application programming interface (API) to build a custom Web application for accessing, automating, and controlling devices in real time over the Internet.

Control Zones

Control zones were used to modulate the damper of the variable air volume (VAV) and open the hot water return system to increase the temperature.

The HVAC system also had pressure sensors located in the air ducts that communicated with the variable frequency driver (VFD) to slow down or speed up the fan motors on the air handling unit (AHU) to reduce or increase the air pressure in the air ducts. Figure 10 provides a simplified overview of the VAV and VFD.

Figure 10: Variable Air Volume, Variable Frequency Driver, and Air Handling Unit



Source: California State University Long Beach

Java Application Control Engine

The ECS building's previous HVAC system was controlled by the temperature set-point of the system. The AHU, VFD, VAV, and temperature sensors worked together to provide the desired temperature to the building according to pre-determined set-points.

The previous HVAC system was controlled by the JACE-600, a compact, embedded controller and server platform. The platform combined integrated control, supervision, data logging, alarming, scheduling and network management functions with Internet connectivity and web serving capabilities in a small, compact platform. The JACE-600 made it possible to control and manage external devices over the Internet and present real-time information to users in web-based graphical views.

The JACE-600 is ideal for smaller facilities, remote sites, and for distributing control and monitoring throughout large facilities. Optional input/output modules can be plugged in for applications where local control is required. The JACE-600 also supports a wide range of field busses for connection to remote I/O and standalone controllers and its features included:

- Embedded PowerPC Platform@ 524MHz.
- Support for open and legacy protocols.
- QNX real-time operating system.
- Web user interface (standard) serving rich graphical browser presentations.
- Running stand-alone control, energy management, and integration applications within the JACE-600 series controllers.
- Supporting two optional communications boards.
- Optional 16 and 34 point I/O modules.

New Energy Management System in the Engineering and Computer Science Building

The new EMS consisted of 2 networks, Enlighted IoT Architecture (controlling lighting system and plug load system) and the Siemens embedded IoT controller and server platform for connecting multiple and diverse devices and subsystems (controlling HVAC system). Both networks provided internet connectivity and web-based capability to interface directly with the devices, sensors, and controllers.

Enlighted Network (Sensors, Gateways, Energy Manager)

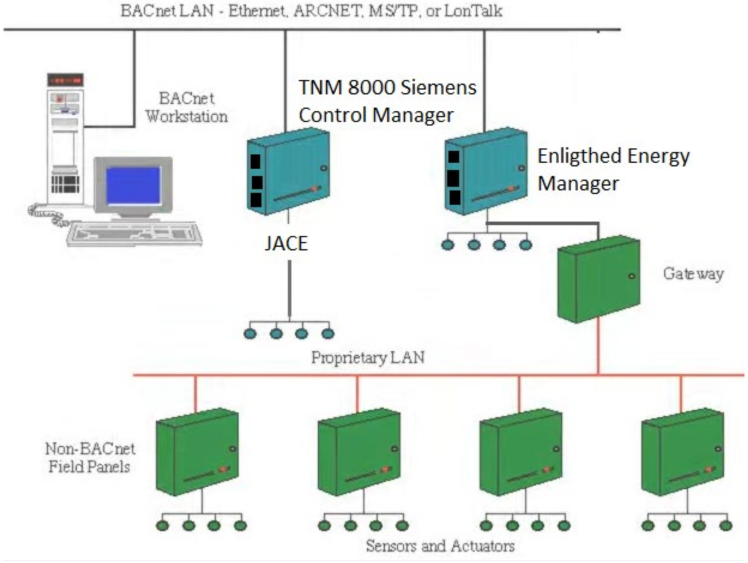
The implementation of the new lighting system required a retrofit of lighting fixtures, replacement of fluorescent lamps and ballast with LED tubes and control drivers, replacement of every light fixture with the Enlighted occupancy sensor, and the removal or disabling the existing wall switches. Energy loads were a maximum 4.25 A, 120 VAC or 277 VAC.

The Enlighted Internet of Things (IoT) architecture consisted of a network of LED lights with smart occupancy sensors that connected to form the sensor and analytics platform. Data is collected 65 times/second to detect environmental and occupancy changes and act on lighting.

Building automation and control network

Building automation and control network (BACnet) was the protocol that most devices (including sensors and actuators) within the ECS building network used to facilitate interoperability, visibility, and control. The protocol was created to provide a single efficient solution for all the building systems to communicate to a single workstation. The devices communicated mainly using master slave/token passing (MS/TP) and standard internet protocol (IP). The communication between the different network types was through routers. Figure 11 shows the BACnet system used for ECS building networks.

Figure 11: Engineering and Computer Science Building Automation and Control Network System

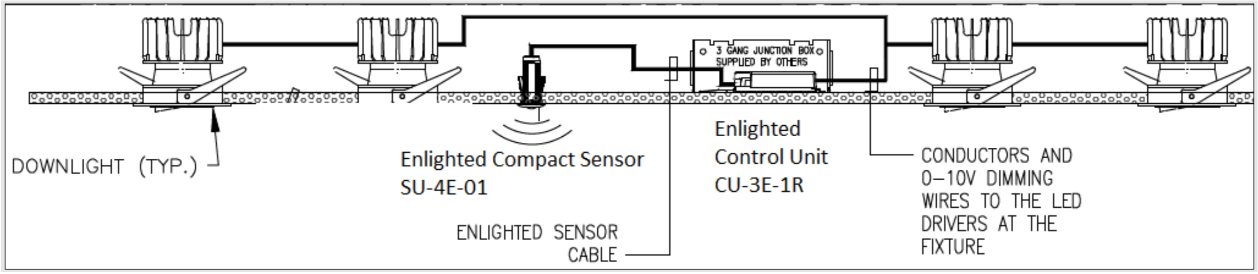


Source: California State University Long Beach

Network Architecture

Enlighted sensors were installed in every lighting fixture in the ECS building. When the sensors were installed, the team also installed the control units CU-3E-1R together to interface with the Enlighted sensor units and connect to a ballast or LED driver to control light behavior, or receptacle relays to provide on/off controls. Each sensor contains a power metering chip that enables the control network to measure power in real time as well as energy consumption over time. Figure 12 shows the layout of the connection between an Enlighted sensor and a control unit.

Figure 12: Connection Between Enlighted Sensor and Control Unit



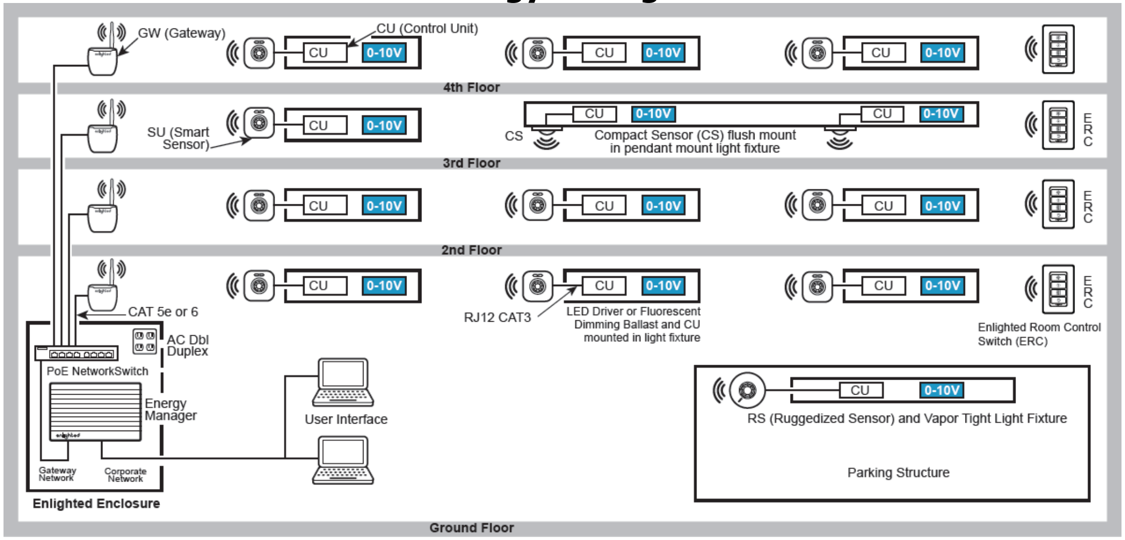
Source: California State University Long Beach

The team used GW-2-01 Gateways as the intermediary device between the Energy Manager and the control network. The gateways relay energy, environmental, and occupancy data captured by the Smart Sensors to the energy manager for analysis and reporting. They also communicate configuration changes from the energy manager to sensors and other network devices.

The gateways were deployed on each floor to relay information between the sensors and the Energy Manager, which translates data from the sensor network into detailed energy, temperature, and occupancy insights around the clock. The team mounted the gateways to the ceiling at the same height as an individual sensor device, with the antenna pointed down.

CAT5e cable was run from the Enlighted Gateway to the Enlighted PoE switch. Figure 13 shows the connection and configuration between Enlighted sensors, gateways, and Energy Manager.

Figure 13: Connection and Configuration Between Enlighted Gateway, Switch, and Energy Manager



Source: California State University Long Beach

Sequence of Operation

The sequence of operations for the interoperability of the Enlighted network included:

- Task tuning: A control strategy to set the light output to a specific foot-candle level and maintain that light level for specific tasks. Lighting is typically designed with a greater initial quantity of light so that over time, as lamps depreciate and collect dust, more power is required to maintain the desired light level. Task Tuning allows the maximum energy savings to be realized while providing lighting levels that meet the needs of most individuals working within a space. LED lighting sources typically can be dimmed 70-80 percent before there is a noticeable drop in the lighting level.
- Lumen maintenance: Lumen maintenance allows the adjustment of the light output of a lighting fixture so that the present level of light can be maintained during the life of the fixture.
- Demand response (DR): The Enlighted system can support demand response programs from local utilities, with selectable manual initiated lighting load reductions. The control system allows selection of up to 4 operating modes. These operating modes can be edited as needed. There are 3 types of response levels that reduce maximum light output:
    - Automatic demand response (ADR) (voluntary): A power reduction agreement between the owner and utility for cost reduction. When the utility signal is present, the building automatically dims by an agreed percentage(s).
    - ADR (mandatory): Title 24 in California requires that buildings larger than 10,000 sq. ft. can respond to a standardized signal to reduce load by 15 percent.

    - DR (voluntary): Power reduction that is manually initiated to reduce power consumption during peak demand.
- Automatic daylight control: The lighting system can support daylight savings by using daylight sensors incorporated into the Sensor Unit. When daylight changes during the day, light levels in the daylight areas react slowly to changes in the exterior light levels (to prevent lights increasing or decreasing in response to passing clouds or light reflection from a passing vehicle, for example) and then slowly increase or decrease to maintain the desired foot-candle level. The dimming occurs automatically and increases the energy savings when there is ample sunlight.
- Operating modes: The sensors or switches can respond differently based on a schedule. For example:
    - Operating hours: During normal business hours, the lighting can be set at the levels indicated under task tuning. When the space is occupied, the lighting will automatically turn on to preset lighting levels. Once the space is unoccupied, after 10 minutes (the timing is adjustable) lights will dim to 20 percent which saves substantial energy while allowing the ceiling to have a consistent visual appearance.
    - After hours: After normal business hours, the lighting can be set at levels indicated under task tuning. When the space is occupied, lighting will automatically turn on to preset lighting levels. Once the space is unoccupied, after 5 minutes (also adjustable), the lights will dim to 20 percent. After an additional 5 minutes, the lights will turn off.
- Occupant Sensor/Vacancy Sensor Behavior:
    - Occupancy sensors can be programmed to automatically bring the lighting up to the levels established under task tuning. Generally, after 15 minutes of the space being unoccupied, the sensor will dim the lighting to 20 percent during normal business hours. After hours, the sensor will dim the lighting to 20 percent for 5 minutes. After an additional 5 minutes, the lighting will turn off.
    - Vacancy sensors will be programmed to require manual activation of an Enlighted wall control to bring the lighting up to the levels established under task tuning.
    - Partial-ON sensors will be programmed to automatically bring specific lighting fixtures up to the levels established under task tuning. Generally, after being unoccupied for 15 minutes, the partial-ON sensor will dim the lighting to 20 percent during normal business hours. After hours, the sensor will dim the lighting to 20 percent for 5 minutes. After an additional 5 minutes, the lighting will turn off.
    - Partial-OFF sensors will be programmed to raise the light level to full when occupied. When no occupancy is detected for 20 minutes, the partial-OFF sensor will dim the lighting to level between 50 percent and off during normal business hours. After hours, the sensor will dim the lighting to 15 percent for 5 minutes. After an additional 5 minutes, the lighting will turn off.

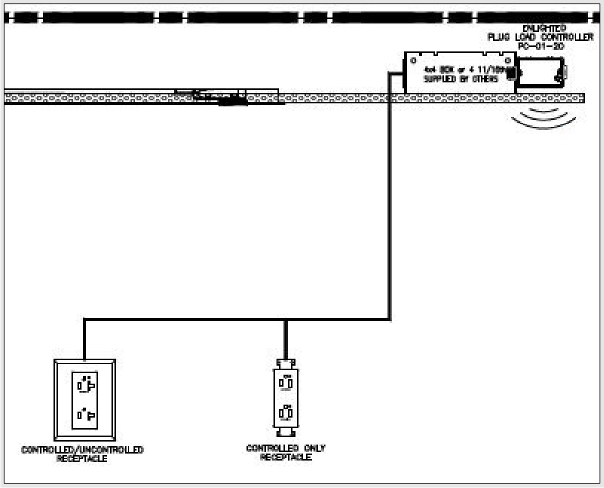
- Egress lighting: Egress lighting is defined as lighting along interior paths of egress to reach the exterior of a building or from the exterior building door to a public right-of-way. During operating hours, the egress lights turn on according to local energy codes (usually on automatic control) and remain on (dimmed to a lower light level when unoccupied) for the duration. Egress lighting provides a minimal level of lighting for safety and comfort.
    - Generally, after 15 minutes, the sensor will dim the lighting to 20 percent during normal business hours. After hours, the sensor will dim the lighting to 20 percent for 5 minutes. After an additional 5 minutes, the lighting will turn off.
    - For exterior egress lighting, Enlighted ruggedized exterior sensors will be programmed to automatically bring the exterior egress lighting up to a minimum average level of 1.0 foot-candles at dusk. After midnight, the exterior egress lighting will turn off. If occupancy is detected after midnight, the exterior egress lighting will turn on to an average level of 1.0 foot-candles for 20 minutes. After 20 minutes, the exterior egress lighting will turn off.
- Enlighted wall control: The wireless wall control has four buttons: on/raise, off/lower, automatic return, and scene tap. The wall control serves as a 1-way, 3-way, and 4-way switch and dimmer. It does not require line voltage or low voltage wiring since it is powered by a lithium battery and allows wireless control of lighting.

Internet of Things-Based Plug Load Controller

Figure 14 shows how the plug load controller connection and configuration with the sensors to transform common power outlets into smart receptacles. It can be managed from the energy manager, which turns off power to selected outlets (like task lights, fans, and heaters) at scheduled times, or when a room becomes unoccupied. This reduces passive energy use from idle devices and opens the new room for saving energy. The plug load controller also:

- Collects and aggregates data on plug load electricity usage via the Enlighted energy manager for better analysis and decision-making.
- Reduces waste heat from idle plug loads (which decreases HVAC costs).
- Helps meet Title 24 obligations by providing an additional reduction source when a DR signal arrives from the local utility.
- Leverages Title 24 obligations by integrating DR and the building automation system (BAS) for maximum cost saving.

Figure 14: Plug Load Controller Connection and Configuration



Source: California State University Long Beach

Optimal Placement of Smart Plug Controllers

As mentioned previously, the ECS building had 820 electrical outlets (not including the power strip outlets). The funding for this project funded up the replacement of 400 smart plug controllers from the original outlets. To maximize the overall energy reduction, the research team needed to identify the optimal location of the replacement smart plugs.

The researcher team prepared a complete inventory of the building and classified the outlets based on electric plug loads. There were five types of plug loads in the building: 1) schedulable plug loads, such as projectors, printers, and LCD screens; 2) non-critical plug loads, such as computers in laboratories and classrooms; 3) open plugs, not connected to any fixed load; 4) critical plug loads, such as severing must-run machines, specialized equipment in the laboratories, and clusters that are always operating; and 5) non-replaced plugs, those not considered to be replaced since only one smart plug was being replaced for each faculty room on 5th and 6th floors.

Based on the plug load classification, the project team developed a weighted matrix that prioritized the installation of smart plug controllers. The schedulable loads had the highest priority because they are not frequently used and can be turned on and off during demand response events and for energy efficiency measures. Non-critical loads were the second priority because they can be turned off when not in use. Critical plug loads were the lowest priority since they served must-run loads. Plug loads in these 5 categories were in 7 different building zones classified by how the space was used (classroom, lecture hall, research/technical lab, faculty office, conference room, department office, and restroom). Table 7 shows the type and number of plugs in each category, and the installation-priority weight for each category.

Table 7: Engineering and Computer Science Building Plug Load Inventory

Plug Load Category	Schedulable Plug Loads Energy Efficient	Schedulable Plug Loads Demand Responsive	Non-Critical Plug Loads Energy Efficient	Non-Critical Plug Loads Demand Responsive	Open Plugs	Non-replacing Plugs (on 5th/6th floor)	Critical Plug Loads
Numbers of Plug Loads	154	17	57	0	228	306	58
Installation-Priority Weight	4	4	3	3	2	1	0

Source: California State University Long Beach

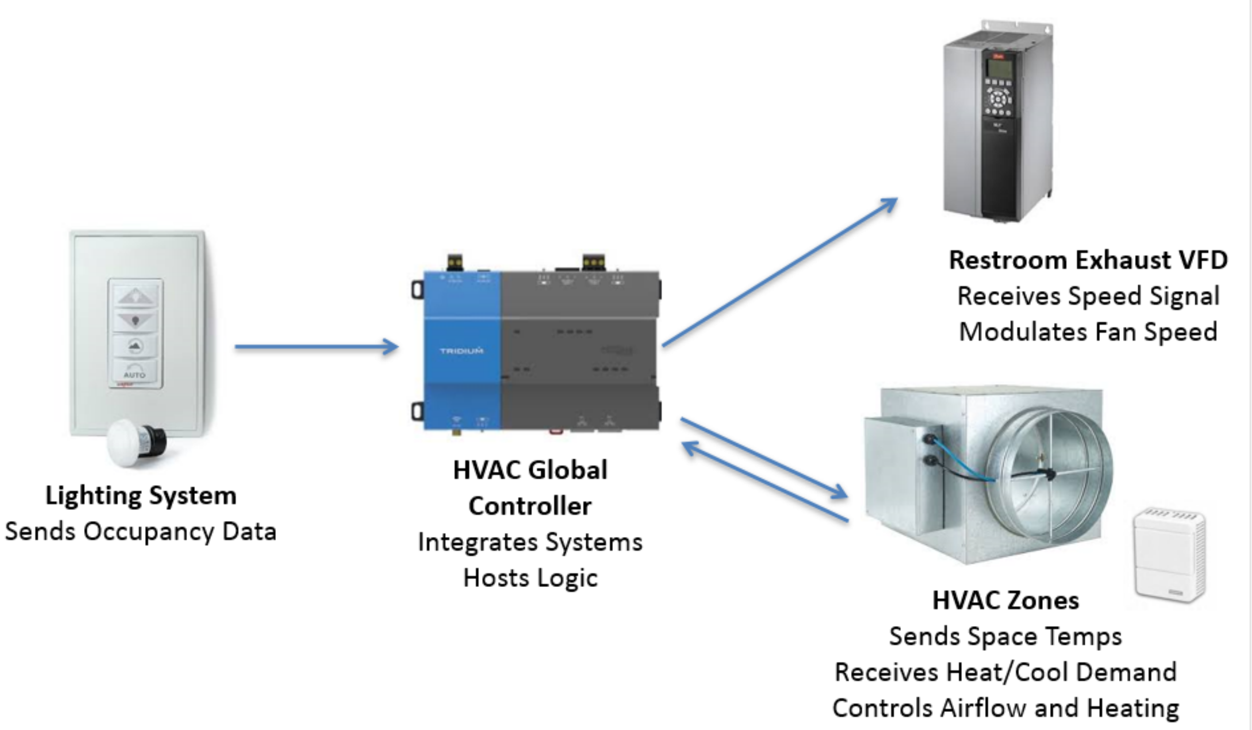
The project team developed a model-based optimization approach based on the installation-priority weight matrix. Zones affected the installation-priority weight since classrooms, laboratory rooms, and lecture halls had higher priority than other zones, and restrooms had the least priority. Zones with schedulable plug loads should have at least one controllable plug and at most 50 percent of all plugs in the rooms belong to those zones.

The model-based optimization method allowed the researchers to narrow and limit the search to 3 plug load categories: schedulable plug loads, noncritical plug loads, and open plugs. The project team prioritized open plugs based on their location in the building. For instance, classrooms, lecture halls, and lab rooms had high priority, because these plugs were used frequently for charging student laptops, phones, and other portable electronic devices. Using the plug loads inventory as the input, half of the schedulable and noncritical plug loads were replaced by smart plug load controllers because these categories were available in all the rooms (except restrooms and exhibition room), which were 114 smart plugs. Excluding 42 open plugs in the exhibition room, and 12 open plugs in restroom since they were seldom used, 87 open plugs could be replaced. Therefore, there were 201 smart plugs that could provide maximum energy efficiency, demand response capability and cost savings.

Heating, Ventilation, and Air Conditioning System

The new network for the HVAC system was built on the existing HVAC system automation by adding a Siemens TNM 8000 controller with Niagara Framework that uses APIs to build custom, web applications for accessing, automating, and controlling devices in real time over the Internet. Figure 15 provides an overview of the new HVAC system.

Figure 15: New Heating, Ventilation, and Air Conditioning System Overview



Source: California State University Long Beach

The previous network for the HVAC system used a static schedule and was the sole means of driving occupancy for the entire building based on time of day. Based on the schedule, when occupied, all zones in the building were controlled to provide comfort heating or cooling, and all zones were ventilated based on temperature demand. In addition, the air handling units and restroom exhaust fans ran at full speed, any time the building was occupied.

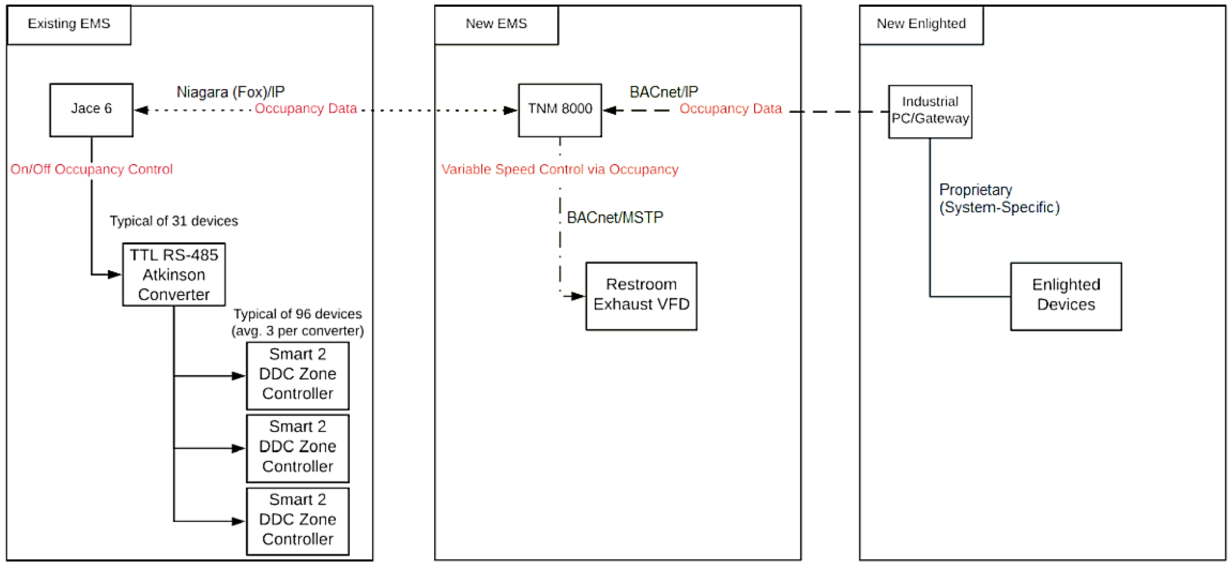
The new network for the HVAC system still utilizes a static schedule, but utilized added occupancy data of the building zones based on time of day. Data from the Enlighted system was integrated to the existing EMS through the TNM 8000 controller, recognizing un-occupied zones among 96 zones in the building, via the 31 media converters. In this way, temperature in unoccupied areas can be relaxed (heat 68˚F, cool 76˚F) to save HVAC energy. A VFD was added to the air handling units and restroom exhaust fan, further reducing energy use by allowing the fan to run at a lower, more efficient speed when the restrooms are unoccupied.

The new network for the HVAC system architecture us composed of 3 main controllers (Figure 16): the Siemens TNM8000, the Tridium JACE 6, and the Enlighted Network Controller. The Tridium TNM 8000 controller received data from Enlighted Network Controller (occupancy data) and from Control Works' Tridium JACE 6 (HVAC sensors and actuators). The TNM8000 controller then processed the data and sent commands to the JACE 6 and VFDs. The occupancy data came from the smart sensors installed at fixtures and was already processed by the Enlighted system for controlling the smart lighting system. The data transfer process emphasized how data from Enlighted system integrated, supported, and enhanced the new smart HVAC system.

The main trunk of the network architecture depicted in Figure 16 was mainly based on BACnet protocol; however, multiple routers were used to interface the MS/TP, IP, and Ethernet. The

Atkinson Converter was used to convert transistor/transistor logic into RS485 or EIA 485 from the JACE 6 to the direct digital control (DDC) zone controller. The Siemens TNM 8000 ran on the Niagara 4 operating system (OS).

Figure 16: Architecture of New Network for Heating, Ventilation, and Air Conditioning System



Source: California State University Long Beach

Siemens TNM 8000 Controller

The TNM 8000 controller provided integrated control, supervision, data logging, alarming, scheduling, and network management. Figure 17 shows a picture of the controller, which can stream data and rich graphical displays to a standard web browser via Ethernet, LAN, or Internet.

Figure 17: Siemens TNM 8000 Controller

Source: California State University Long Beach

The controller had optional IO and field bus expansion modules for ultimate flexibility and expandability, used a power supply of 24 VDC/VAC, ran the Niagara 4.1 or later operating system, and used a real time clock.

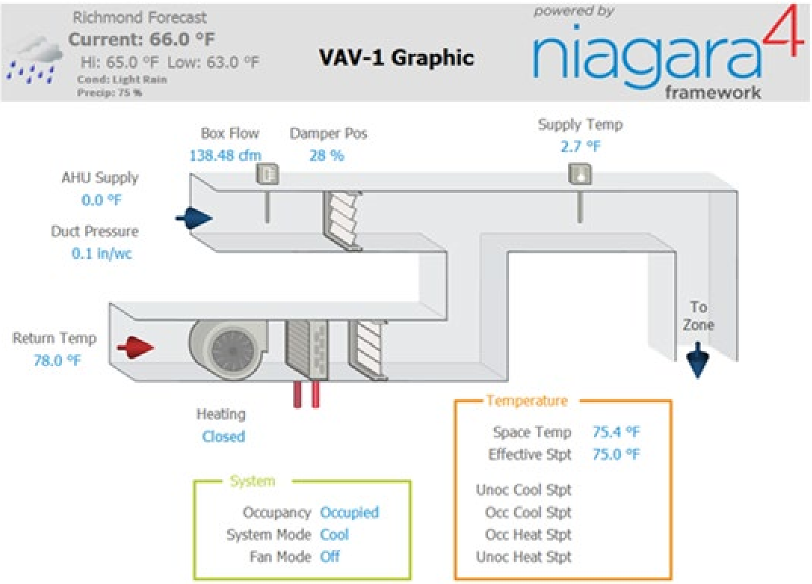
Niagara 4 Framework

The framework also integrated diverse systems and devices of different manufactures and protocols into a unified platform that could be easily managed and controlled in real time over the Internet using a standard web browser that integrates HVAC, lighting, and security systems.

The Siemens TNM 8000 ran on the Niagara 4.1 framework, an open framework that provides management and control for building automation, energy, and security by taking full advantage of the IoT. The framework makes managing all buildings at an enterprise level possible, giving facilities managers the ability to quickly respond to problems and insights to optimize their systems.

The Niagara 4 User Interface UI offered an intuitive interface that uses HTML 5 to provide rich features such as markups, new APIS, XHTML5, error handling, popularity browser plug-ins. The interface also used scalable vector graphics (SVG). Figure 18 shows the user interface display for the status of the system. The displays show the location, current weather, system status with occupancy, system mode, and fan mode information, damper information, AHU pressure, supply temperature, heating, and occupied set point.

Figure 18: Scalable Vector Graphics Library of Niagara 4 Framework



Source: California State University Long Beach

Anytime Demand Response Capability of the Developed Energy Management System

This section discusses the test plan and results for the dedicated field experiment at the CSULB ECS building to demonstrate the anytime DR capability of the developed EMS for the lighting system as well as for the HVAC system. A detailed quantitative analysis of the opportunities to increase the DR capacity of the EMS is also presented. As for the plug-load system, the building operators decided not to include this type of loads in any DR program due to the very low power consumption of these types of loads in the ECS building at CSULB; yet their high impact on building occupants; which does not justify DR participation.

Field Test Demonstration of Anytime Demand Response Capability - Lighting

For practical purposes, the field test (conducted by the UC Riverside team) focused on adjusting key parameters with the greatest effect on reducing lighting load: the active motion window and the maximum light level. The team defined the set-up of the DR test in two ways, manual and automatic setups.

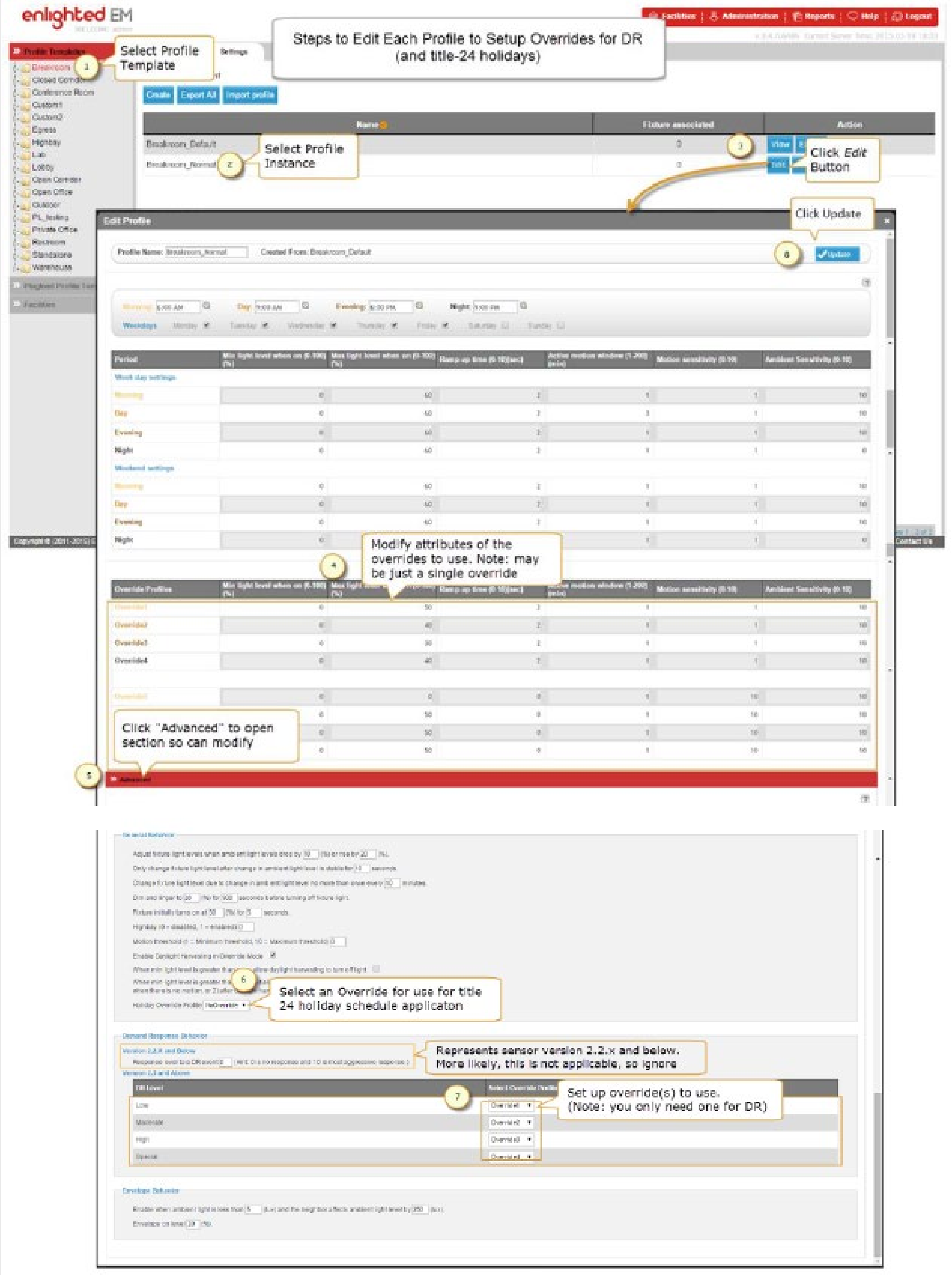
Test Setup and Configuration

By default, the Enlighted energy manager supports DR and holiday overrides to contribute to energy load reduction savings during peak demand time and public holidays. Configuring and demonstrating the DR and holiday overrides feature in EM requires two steps:

- Configure the DR and holiday behavior in the profiles section of profile templates.
- Schedule a DR or holiday override event in Administration > Override schedules menu

Figure 19 shows the five steps taken to configure DR and holiday behavior.

Figure 19: Steps to Edit Each Profile to Set Up Overrides for Demand Response



Steps to Edit Each Profile to Setup Overrides for DR (and title-24 holidays)

1 Select Profile Template

2 Select Profile Instance

3 Click *Edit* Button

4 Modify attributes of the overrides to use. Note: may be just a single override

5 Click "Advanced" to open section so can modify

6 Select an Override for use for title 24 holiday schedule applicaton

Represents sensor version 2.2.x and below. More likely, this is not applicable, so ignore

7 Set up override(s) to use. (Note: you only need one for DR)

8 Click Update

Source: California State University Long Beach

After configuring the DR and holiday behavior for fixture profiles, the second step performed is scheduling a DR and holiday override event.

At the scheduled time, the EM sends the events to the sensors with the selected DR level and holiday overrides for the required duration at the assigned facility. The sensors then run the appropriate override profile instead of the time of the day profile.

The Open ADR is a custom feature that is not available by default. When activated by Enlightened customer support, the ADR feature can result in a new option named *Open ADR Configuration under Administration* in EM GUI. After it is enabled, the user register as an ADR user with their local utility company. The utility company's ADR server will communicate with the EM and will schedule Open ADR events in EM. The EM will respond to ADR signals in real-time to reduce demand.

Scheduled Demand Response Test Event and Test Result

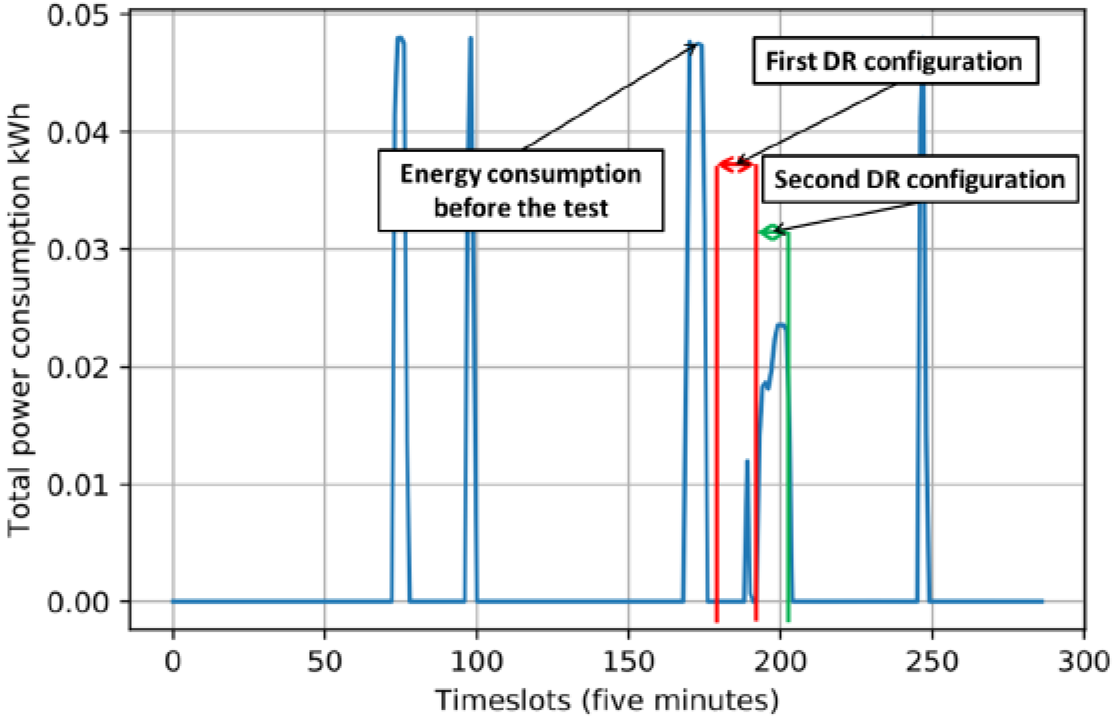
The ADR capability of the ECS building is not available yet because it has not been registered to an ADR program through the utility or an aggregator. However, there does exist a key feature in the system to emulate the DR event to investigate whether and how the lighting fixtures respond to a DR event and how much power consumption is reduced.

In the test, the UC Riverside team used manual DR and conducted the test from 3 p.m. to 5 p.m. on December 20, 2018 for whole building. The duration of the DR test was 120 minutes, and the override level was set to high. Although the test was for the whole building, for in-detail analysis the UC Riverside team considered classroom 411 as a test and compared the lighting fixture performance before and during the DR event.

Two steps were considered to analyze the DR test data. First, the team analyzed energy reduction of the whole building during the scheduled DR event. Second, the team conducted a detailed analysis of classroom 411. For the latter, the researchers showed the energy consumption before and during the test period to demonstrate the effectiveness and performance of the system as it responded to the DR event.

During the test, the sensors had two main parameter configurations for the DR override. The difference in these two configurations was the active motion window, which in the first was set to 6 seconds and in the second 1 minute. As illustrated in Figure 20, there was a considerable reduction in both DR tests; however, the reduction in the first test was more than expected and was undesirable. This huge initial reduction was due to a very low active motion window, which caused light flickering and made the occupant uncomfortable. When the active motion window was set to 1 minute, the issue was resolved, and the light level appeared to be normal. Therefore, by analyzing the real energy consumption data for the DR event test, the effectiveness of any time DR test can be readily seen.

Figure 20: Actual Energy Consumption of Classroom 411 at 12/20/2018



Source: California State University Long Beach

Sensitivity Analysis

The UC Riverside team expanded the analysis and investigated the amount of power reduction that could be achieved when manipulating the setting of the parameters. The key was to use the real-world granular occupancy data available to the team from the lighting fixture installations in room 411 of the building. The most important and critical data in the analysis was the motion detected column, which provided occupancy data.

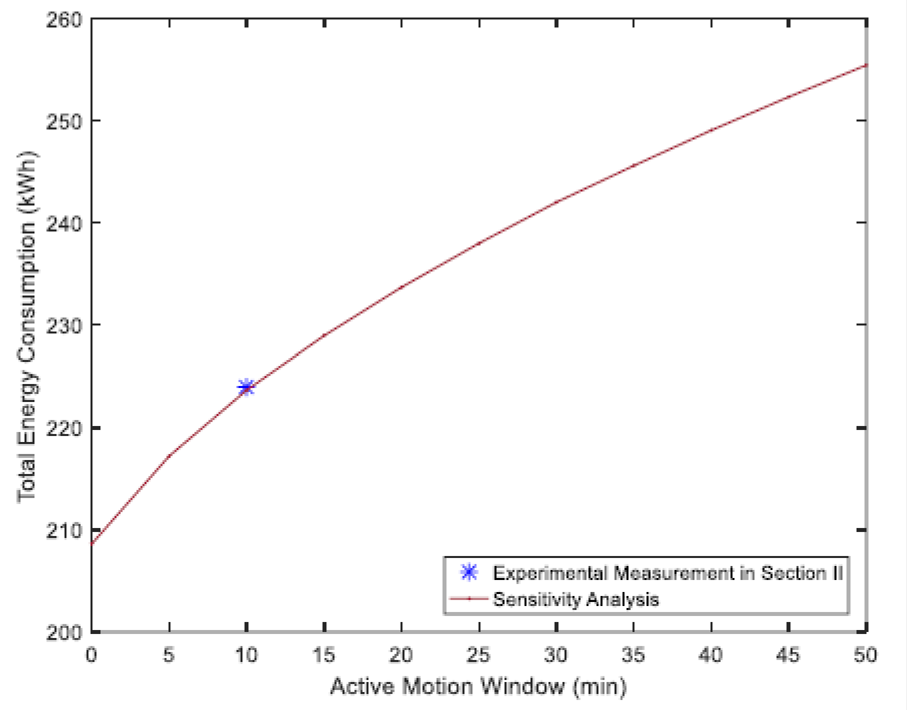
Variety sensitivity analysis had been investigated for the collected data for test classroom and can be easily extended to all classrooms, offices, and corridors. These analyses were based on the sensors control method, which could be controlled by group or individual and based on parameters that can be manipulated to determine the impact on energy consumption.

Impact of Changing Active Motion Window

The lighting fixtures are controlled by group, turning on the 20 lighting fixtures when any sensor in the group senses occupancy. Therefore, the total energy consumption must be multiplied by the number of sensors. To implement such a control structure in the analysis, the UC Riverside team defined a moving window, with its size being equal to the active motion window. This moving window swept through the motion detected column for each sensor in a group and if there were any added the consumed energy to the total.

Figure 21 shows the sensitivity analysis on the effect of the changing active motion window on total energy consumption in room 411. As expected, increasing the active motion window resulted in further reduction in energy consumption, thus expanding the DR capacity of the lighting loads. However, the curve in Figure 21 is not linear. That means there is a sharp advantage in decreasing the active motion window from 10 minutes to 5 minutes to almost immediate inactivation at zero minutes. Energy consumption drops from 223 kWh to 217 kWh and further down to 208 kWh. Figure 21 also shows that the actual energy consumption (223.9 kWh) was close to the calculated energy consumption (223.6 kWh).

Figure 21: Impact of Changing Active Motion Window and Experimental Verification



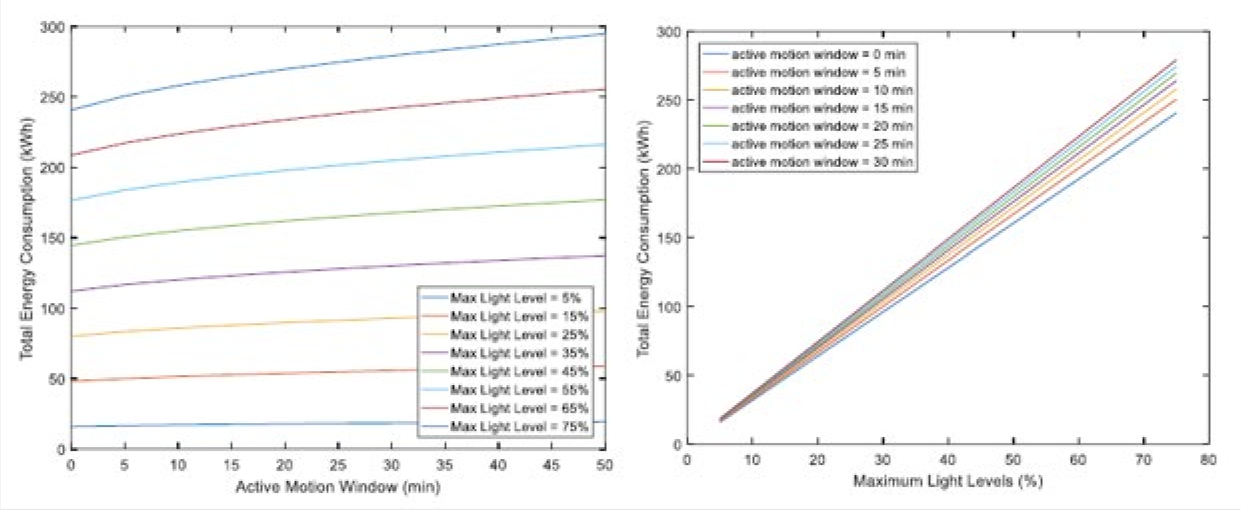
Source: California State University Long Beach

Impact of Changing Maximum Light Level

The team also investigated the effect of changing the maximum light level. The maximum level was set to 65 percent and 35 percent during normal operation and during DR operation, respectively.

Figure 22 shows that there were significant changes in the energy consumption when the maximum light level was changed. For example, when the active motion window was 10 minutes, the total energy consumption dropped from 258 kWh to 224 kWh, 189 kWh, 154 kWh, 120 kWh, 86 kWh, 52 kWh, and 17 kWh when the maximum light level dropped from 75 percent to 65 percent, 55 percent, 45 percent, 35 percent, 25 percent, 15 percent and 5 percent, respectively. This result explained how much the energy consumption reduced once one adjusts both the active motion window and the maximum light level.

Figure 22: Impact of Changing Maximum Light Level versus Active Motion Window (left), and Vice Versa (right)

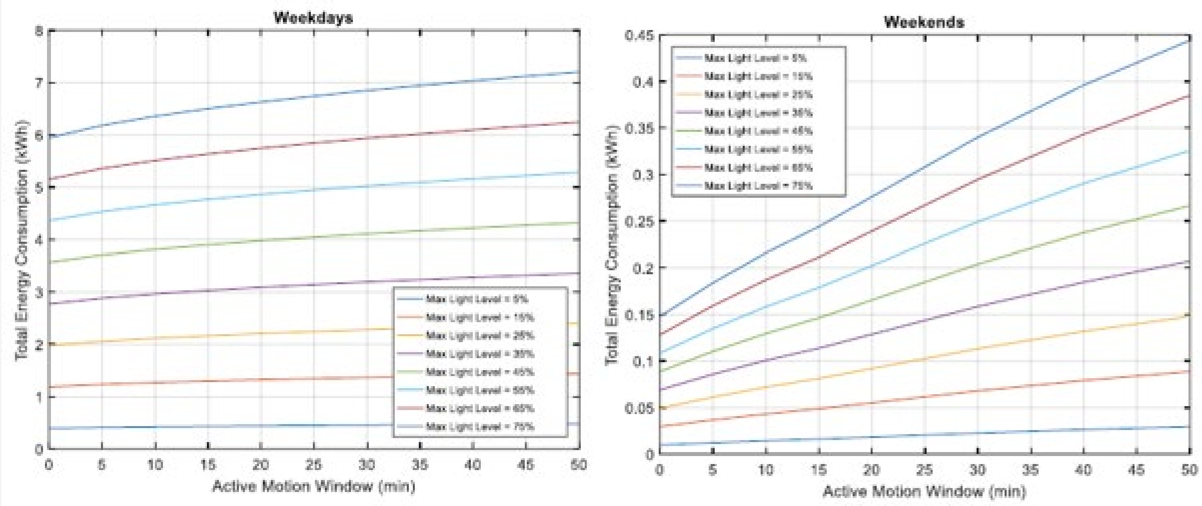


Source: California State University Long Beach

Weekdays versus Weekend

To further study the potential DR capacity of the advanced lighting systems, the project team separated data into weekends and weekdays to determine the share of the total energy consumption. Figure 23 summarizes this analysis based on changing the active motion window and maximum light level. The results show that the trends for the weekdays are the same. For weekends, however, the curves are noticeably different. At different light levels, the total energy consumption was much more sensitive to the changes in the active motion window during weekends. This is a useful insight for DR events that may occur during weekends.

Figure 23: Impact of Changing Lighting Parameters on Weekday



Source: California State University Long Beach

Different Segment of Day

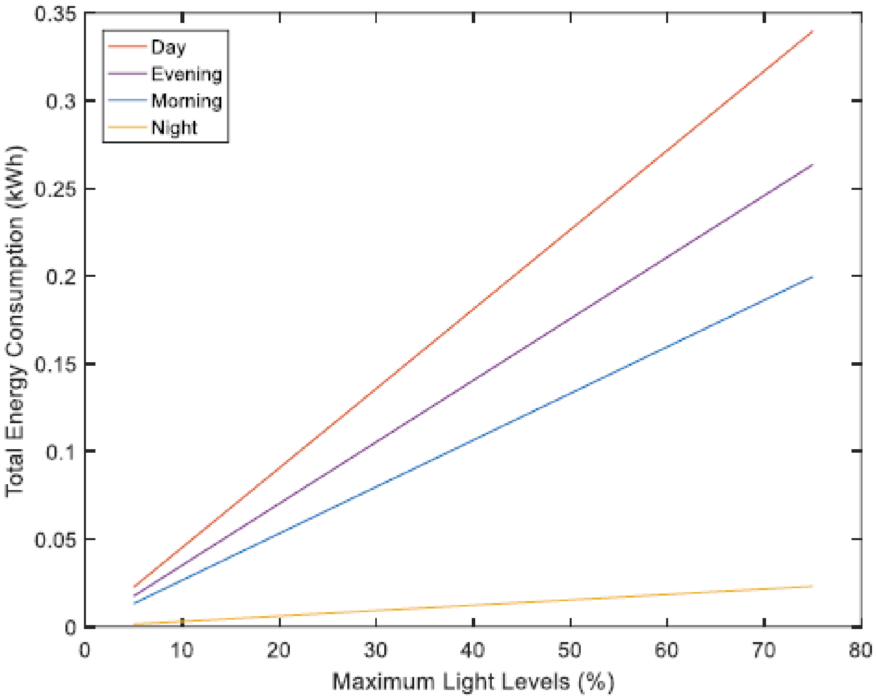
The researchers also conducted a sensitivity analysis of the load with respect to different time segments of a day, which were defined by the EM software as:

- Morning: 6 a.m. – 9 a.m.

- Day: 9 a.m. – 10 p.m.
- Evening: 10 p.m. – 11 p.m.
- Night: 11 p.m. – 6 a.m.

The active motion window was 10 minutes. All the curves were normalized per-hour energy consumption to avoid misleading results due to a longer or shorter period of certain time segments during the day. The results suggested that the maximum load flexibility for DR purposes was available during the day or during the evening.

Figure 24: Impact of Changing Lighting Parameters During Different Segment of Day



Source: California State University Long Beach

Field Test Demonstration of Anytime Demand Response Capability - HVAC

The project team also conducted experiments and analysis to examine the role of HVAC control system in creating load flexibility to enhance demand response capability.

Experiment Set Up

Occupant comfort level is the most important factor for the HVAC system, so one cannot reduce the comfort level for any energy efficiency or DR purposes. The building operators at CSULB, therefore, established the requirement that the HVAC system participation in the DR program had to be limited to unoccupied rooms. As a result, the focus of the experimental tests in the HVAC system also focused on unoccupied zones.

There were two available adjustments that could be used for the DR test: adjusting the setpoint temperature (target temperature for the HVAC system defined based on comfort level) and adjusting the setback or dead band (amount of freedom and deviation for the temperature). However, because changing the setpoint temperature would affect other occupied zones and their comfort levels, the only adjustment that could be used for the DR test was changing the setback.

In the ECS building, to save energy the setback temperature for the HVAC system for unoccupied zones was 2˚F. The DR test aimed to see how much energy the researchers could save by changing the setback from 2˚F to 3˚F when wanting to participate in DR programs.

During the COVID-19 pandemic, CSULB was closed and the ECS building was completely unoccupied, providing a good situation in which to test the DR capacity of the entire building. The UC Riverside team arranged a two-week test from April 1 to April 14, 2020. In the first week, the setback temperature for the HVAC system for unoccupied zones was 2˚F and in the second week they changed the setback for unoccupied zones to 3˚F.

Experiment Results

In the ECS building, there were two measurements for the HVAC system and elevators. As the building was unoccupied during the DR test, the summation of measured energy consumption can be assumed to be from the HVAC system. The resolution for these measurements was 15 minutes and captured different parameters such as voltage, active power, reactive power, and power factor. The team focused on active power to analyze the DR capacity of the HVAC system in kW.

In the first week, the UC Riverside team fixed the setback for all the zones equal to 2˚F. Table 15 shows the value of setbacks for each zone before the test. The setback of some of the zones was not equal to 2˚F because of some override plans for specific zones with a high comfort level or some false occupancy detection in the building. The UC Riverside team made all the setbacks equal to 2˚F in the first week. The setback was then set to 3˚F in the second week to measure the impact of changing the setback of the HVAC system from 2˚F to 3˚F.

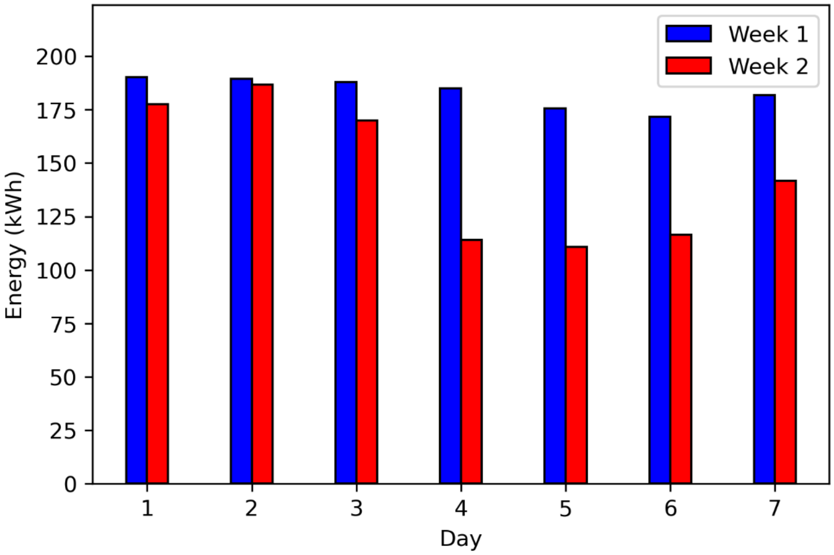
Table 8: Setback of Engineering and Computer Science Building Zone before Demand Response Test

Zone	Setback	Zone	Setback	Zone	Setback	Zone	Setback
Zone 01	2	Zone 23	2	Zone 45	2	Zone 67	0
Zone 02	2	Zone 24	2	Zone 46	2	Zone 68	0
Zone 03	2	Zone 25	2	Zone 47	2	Zone 69	0
Zone 04	2	Zone 26	0	Zone 48	2	Zone 70	0
Zone 05	2	Zone 27	2	Zone 49	2	Zone 71	0
Zone 06	2	Zone 28	2	Zone 50	2	Zone 72	0
Zone 07	2	Zone 29	2	Zone 51	2	Zone 73	0
Zone 08	2	Zone 30	2	Zone 52	1	Zone 74	0
Zone 09	2	Zone 31	2	Zone 53	2	Zone 75	0
Zone 10	2	Zone 32	2	Zone 54	2	Zone 76	2
Zone 11	2	Zone 33	2	Zone 55	1	Zone 77	0
Zone 12	2	Zone 34	2	Zone 56	1	Zone 78	0
Zone 13	2	Zone 35	2	Zone 57	1	Zone 79	0
Zone 14	2	Zone 36	2	Zone 58	1	Zone 80	0
Zone 15	2	Zone 37	2	Zone 59	1	Zone 81	0
Zone 16	2	Zone 38	2	Zone 60	1	Zone 82	0
Zone 17	2	Zone 39	2	Zone 61	1	Zone 83	1
Zone 18	2	Zone 40	2	Zone 62	1	Zone 84	1
Zone 19	2	Zone 41	2	Zone 63	1	Zone 85	1
Zone 20	2	Zone 42	2	Zone 64	1	Zone 86	0
Zone 21	1	Zone 43	2	Zone 65	1	Zone 87	2
Zone 22	2	Zone 44	2	Zone 66	2		

Source: California State University Long Beach

Analysis of the collected power consumption data of the ECS building after the DR test showed that changing the setback of the HVAC system from 2˚F in the first week to 3˚F in the second week reduced its average power consumption by 20.62 percent. Considering a scenario in which the building receives the DR signal at a time that 50 percent number of zones are unoccupied, then by switching to the suggested DR mode, there will be about 10 percent reduction in the total amount of energy consumption for the HVAC system. Figure 71 shows the daily energy consumption in kWh for the first and second week of the DR test.

Figure 25: Daily Amount of Energy Consumption in Heating, Ventilation, and Air Conditioning During Demand Response Test



Source: California State University Long Beach

As shown in Figure 71, energy consumption for each day of week 2 compared to week 1 was reduced. The average daily HVAC energy consumption decreased from 183.1 kWh to 145.3 kWh. Because HVAC is a thermostatic load and its operation is on and off, this decrease could not be directly converted to kW load reduction. However, based on the HVAC load measurements, it was known that the HVAC load cycles are typically between 5 kWh and 17 kWh based on 15 minute measurement intervals, so it is simple to multiply these results by 4 (60/15) to convert to average kilowatts. That means the HVAC load cycles changed between 20 kW and 68 kW during the DR test. The 48 kW difference could be considered as the load flexibility associated with the HVAC system.

Although the amount of energy consumption for the HVAC system was directly related to the outside temperature, during this test the outside temperature did not fluctuate significantly so the research team considered it as fixed. The main point is that even with some fluctuations in the outside temperature, there were energy savings on each day during this test.

CHAPTER 3:
Developing Software Interfaces and Demonstrating the Energy Management System

This chapter discusses the full-scale deployment of new equipment for lighting, plug load, and HVAC systems including type, configuration, number of lighting fixtures, smart sensors, plug load controllers, the HVAC global controller, VFD controller, etc. The chapter also discusses accessing and managing the profiles of lighting fixtures, smart sensors, and plug load controllers through web-based graphical user interface (GUI) energy manager software.

Deployment, Commissioning, and Testing of the Internet of Things-Based Lighting System

The previous lighting system in the ECS building did not interface with a network manager controller. The system was not automated even though it had motion sensors to control the lighting in rooms based on occupancy. Most lighting fixtures in the ECS building were replaced with LED lights equipped with smart sensors. The sensor attached in each light allowed control and monitoring using IoT and enabled near-real-time demand response.

The implementation of the new lighting system included retrofitting lighting fixtures, replacing fluorescent lamps and ballasts with LED tubes and control drivers, installing smart sensors at each lighting fixture, and replacing existing wall switches with the Enlighted room control switch.

Enlighted IoTs architecture consists of a network of LED lights and connected smart sensors that formed the sensor and analytics platform. Data was collected 65 times per second to detect environmental and occupancy changes and act on lighting. Using the IoT-based system was expected to have the following results. The IoT based system provided the following benefits:

- Energy savings of 72 percent from the lighting installation.
- Improved overall light quality with LED and sensor light fixtures.
- Lowered lighting maintenance costs up to 25 percent.
- Collected large volume of data for lighting and other applications.
- Task tuning, occupancy data and daylight harvesting increased savings.
- Initial installation and services paid for out of energy cost savings.
- Unlimited scalability for the enterprise.

Type of Installed Enlighted Lights and Sensors

Enlighted Light-Emitting Diode Lighting Fixtures

The following types of LED lights with the listed characteristics were previously used in the ECS building:.

a) ILP LANCE 2’ X 4’ & LANCE 1’ X 4’ (LED-Latch and Close):
  - LED retrofit kit for recessed lighting application.
  - One-piece unit with universal mounting brackets for rapid installation.
  - 3000K, 3500K, 4000K, and 5000K available.
  - Prepainted aluminum.
  - Acrylic frosted lens easily removable for cleaning.
  - Toolless access to driver.
  - 0-10V dimmable driver.
    - LANCE24 – 35W (100 percent - 5 percent).
    - LANCE14 – 30W (100 percent - 5 percent).

Figure 25 shows a photo of the LANCE LED lighting used in the classrooms and hallways. The fixture on the left is the hallways LANCE14 and LANCE24 is the fixture on the right.

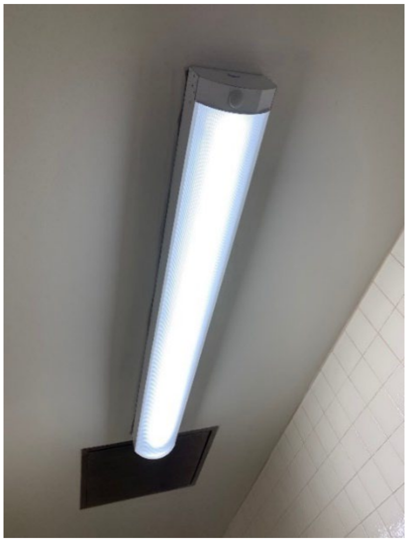
Figure 26: Light-Emitting Diode Latch and Close Fixtures

Source: California State University Long Beach

b) ILP SQ4 curved wrap 4ft – 30W LED:
  - 3,000k-5,000k color options.
  - Ceiling, wall, or suspension mounting options.
  - Multiple dimming and control options.
  - 0-10V dimming driver.
  - Suitable for installing in continuous runs.

Figure 26 is a photo of the restroom lighting.

Figure 27: ILP-SQ4 Curved Wrap Light-Emitting Diode Installed in Restrooms



Source: California State University Long Beach

c) ILP RZ4A-30W and RZ8C-60W:
  - Multiple dimming & sensor options to fully control occupied and unoccupied.
  - 0-10V dimmable driver (100 percent - 5 percent).
  - Dry and damp location listed.

- Figure 27 is a photo of the laboratory lighting.

Figure 28: ILP RZ Light-Emitting Diode installed in lab rooms

Source: California State University Long Beach

d) ILP UFO low bay:
  - Motion and daylight harvesting available.

  - Sensor ready for grouping/zones & IoT (provided by others).
  - 0-10V dimming driver.
  - 120-277V universal voltage.

Figure 28 is a photo of the Chemical Laboratory room lighting

Figure 29: ILP UFO LED Installed in Engineering and Computer Science 111 (Chemical Lab Room)

Source: California State University Long Beach

The specifications of above types of LED light are listed in Table 8.

Table 9: Specifications of Utilized Light-Emitting Diode Lights

Type of LED light	LED System Info	Calculated L70 (TM-21)	Delivered Lumens	Total Input Watts	Luminaire Efficacy Rating (LER)	Correlated Color Temperature	Color Rendering Index	Ambient Temperature Range	Universal Driver
LANCE14	30W	>100K	3,704 lm	30W	122 lm/W	4000K	>80	110°F	120 – 277 V
LANCE24	35W	>100K	4,400 lm	34W	131 lm/W	4000K	>80	110 °F	120 – 277 V
SQ4	30W	>100K	3,694 lm	30W	123 lm/W	4000K	>80	-4 °F to 115 °F	120 – 277 V
RZ4A	30W	>100K	4,365 lm	30W	146 lm/W	4000K	>80	-4 °F to 115 °F	120 – 277 V
RZ8C	60W	>100K	8,760 lm	60W	146 lm/W	4000K	>80	-4 °F to 115 °F	120 – 277 V

Source: California State University Long Beach

Table 9 provides an inventory of LED lights installed and used in the ECS building.

Table 10: Inventory of Utilized Light-Emitting Diode Lights

Product Code	Description	Quantity
CUST-1	ILP:LANCE24-35WLED-UNIV-40-CSCU4-ENLHOLE	597
CUST-2	ILP:LANCE24-35WLED-UNIV-40-CSCU4-ENLHOLE-Cxxx	222
CUST-3	ILP:LANCE14-30WLED-UNIV-40-CSCU4-ENLHOLE-Cxxx	65
CUST-4	ILP:LANCE14-30WLED-UNIV-40-CSCU4-ENLHOLE-ILBCP10-Cxxx21	21
CUST-5	ILP:SQ4-30WLED-UNIV-40-CSCU4/SU5E	9
CUST-7	ILP:RZA-30WLED-UNIV-40-FRAL-CSCU4/SU5E	2
CUST-8	ILP:RZ8C-60WLED-UNIV-40-FRAL-CSCU4/SU5E	38
CUST-9	ILP:SQ4-30WLED-UNIV-40-CSCU4/SU5E	45
CUST-10	ILP:LANCE24-35WLED-UNIV-40-CSCU4-ENLHOLE	4
CUST-11	NaturalLED:LED-FXHBL100/22/FR/840	18
CUST-12	ILP:LANCE24-35WLED-UNIV-40-CSENL-SU5E-Cxxx	7
CUST-13	ILP:SQ4-30WLED-UNIV-40-CSCU4/SU5E-ILBCP10	2
CUST-14	ILP: UFO-75WLED-UNIV-40-LB	18

Source: California State University Long Beach

Enlighted Smart Sensors

Figure 29 shows a photo of the types of Enlighted sensor that were used. Table 10 shows installed equipment amount (smart sensors, power over ethernet [PoE] switch, gateway). Figure 30 shows the sensor coverage pattern. Also, Figure 31 shows sample Enlighted Smart Sensors, installed at lighting fixtures in the building.

Figure 30: Different Types of Enlighted Smart Sensors (left to right): MicroSensor, Surface Mount Sensor, Fixtureless Compact Sensor

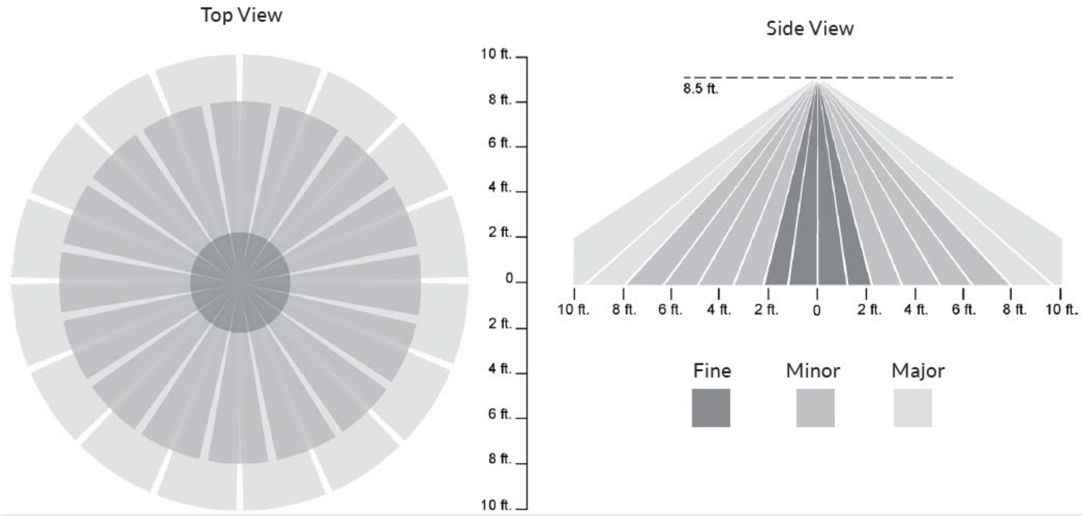
Source: California State University Long Beach

Table 11: Inventory of Installed Smart Sensors, Gateway, PoE Switch, and Energy Manager

Product Code	Part Number	Description	Quantity
SU-5E-01	01-01961-XX	Enlighted – Kona Embedded Sensor	1,023
CU-3E-1R	01-00405-XX	Enlighted - Control Unit - 1% extra included	19
WS-2-00	01-01034-XX	Enlighted - Wireless Room Control (ERC)	155
SU-4S-H	01-01616-XX	Enlighted - Sensor Unit (High Bay) - w/BlueTooth - 1% extra included	19
CBL-2-7F	12-00028-02	Plenum Rated Cable - 7 ft. - for SU2 - 1% extra included	19
BRKT-SU-2-00	11-00057-01	Gen 2 - Sensor Bracket Mount - 8.875" Flat Metal	58
CU-4E-FM	01-02296-03	Enlighted - Fixture Mount Control Unit - for SU5 - 1% extra included	1,023
CBL-5E-CU4-30N	12-02290-01	Enlighted - Sensor Cable - 30 In - for SU5 - 1% extra included	1,023
WING-CS-D2	05-01315-01	Enlighted - Wing Nut for tile mount sensor - Plastic - (Bag of 100)	1
CS-D2-FL	01-02210-01	Enlighted - 2-Wire Tile Mount Sensor (Sensor Grid Only) - 1% extra included	7
GW-2-01	01-00671-XX	Enlighted - Gateway V2	15
SW-POE-8-8	18-01918-01	8 Port, Managed, PoE Network Gigabit Switch	2
AT-4G-00	06-00540-01	Modem, Wireless, Rugged AL. Casing, 1Eth, 1 USB, 1 RS-232 ports	1
ENCL-EM/FAN	40-00420-02	NEMA 1 Enclosure - w/Fan - for Energy Manager and POE switches	1
EM-2-02	01-01453-XX	Enlighted - Energy Manager - Base sensors = 1,000	1
EM-SW-1	90-01906-01	Per Sensor License	36
PWR-NF	01-02511-01	Enlighted - Power Supply for Sensor Grid Sensors, Max (20) CS-D2-FL sensors, daisy chained	1
FSC-85-RFK-48-132-NB-W-RS	05-00776-01	1x4 1L Strip retrofit Kit (Kit Only & Un-shunted sockets/No Ballast-No pre-wire)	2

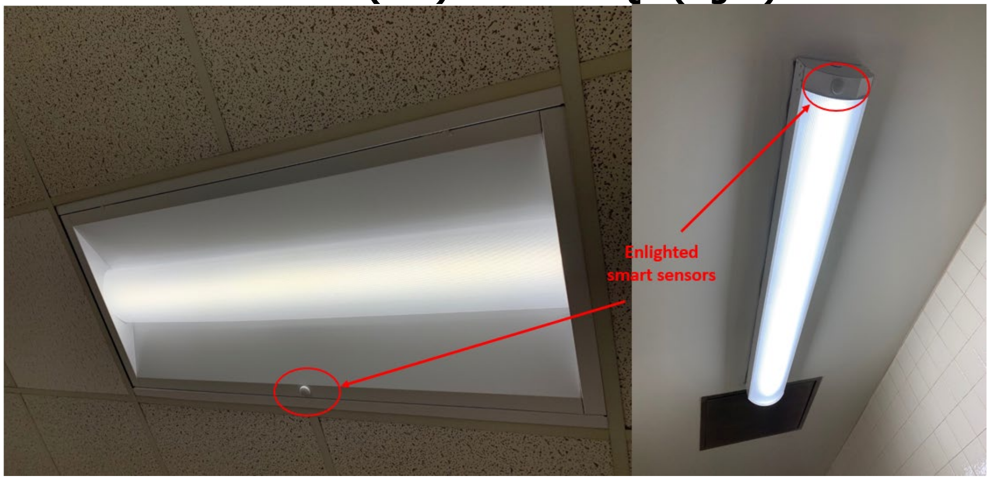
Source: California State University Long Beach

Figure 31: Enlighted Smart Sensor Coverage Pattern



Source: California State University Long Beach

Figure 32: Enlighted Smart Sensors (Red Circle) Installed at Lighting Fixtures: LANCE24 (left) and ILP-SQ4 (right)



Source: California State University Long Beach

Accessing and Managing Fixture and Sensor Profiles using Graphical User Interface Software

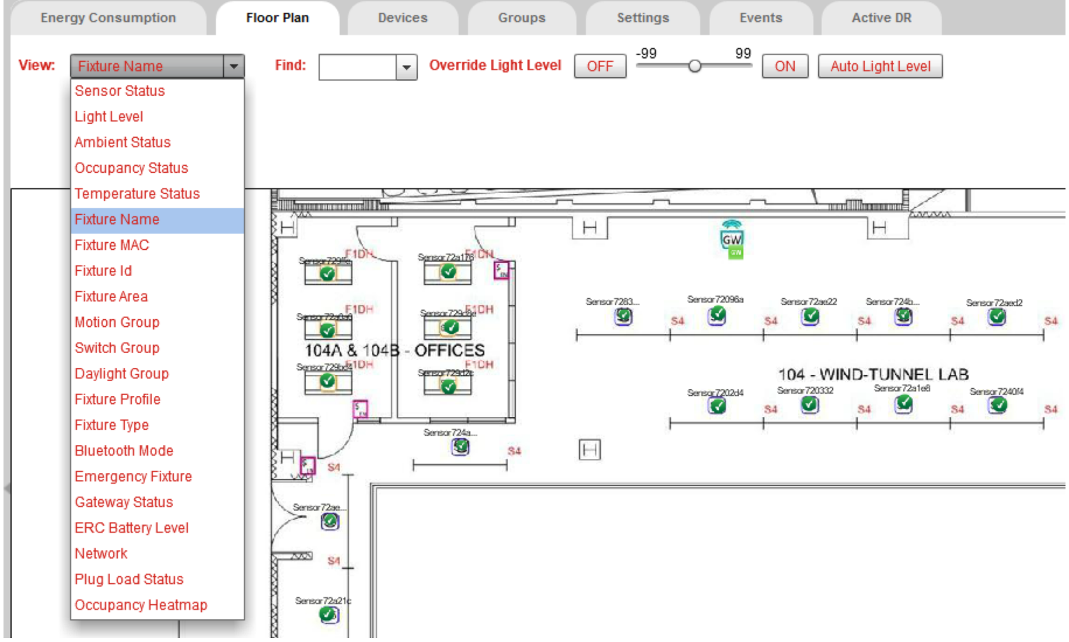
Figure 32 shows the access to the floor plan display of lighting fixtures in ECS-411. After choosing the floor plan option, the left column on Figure 32 allows a choice of the location to be observed, which in this case was classroom 411 in ECS building. Moving the cursor to one of the fixture icons in this room, the status of that fixture at real time will pop-up. The green box in Figure 32 displays the status of the middle lighting fixture in the first line. This lighting fixture was in the auto mode, which varied the light level of the luminaire using sensor input, time of day, day of the week, and values from its operational configuration. The fixture operated at a 55 percent light level and consumed 22W at the time it was checked. There is also information regarding occupancy and ambient temperature in the room. The status shown in the fixture icon was updated every 5 minutes.

Figure 33: Floor Plan Display of Lighting Fixtures in Engineering and Computer Science 411

Source: California State University Long Beach

In the floor plan sub-panel, there are different options for viewing information related to the lighting fixtures such as light level, fixture name, fixture Media Access Control (MAC), fixture ID, fixture area, fixture profile, fixture type. Figure 33 displays the option of viewing the fixture name, which shows the name of the lighting fixture on that floor plan. In this case, Enlighted named the lighting fixtures based on the sensor name for easy management.

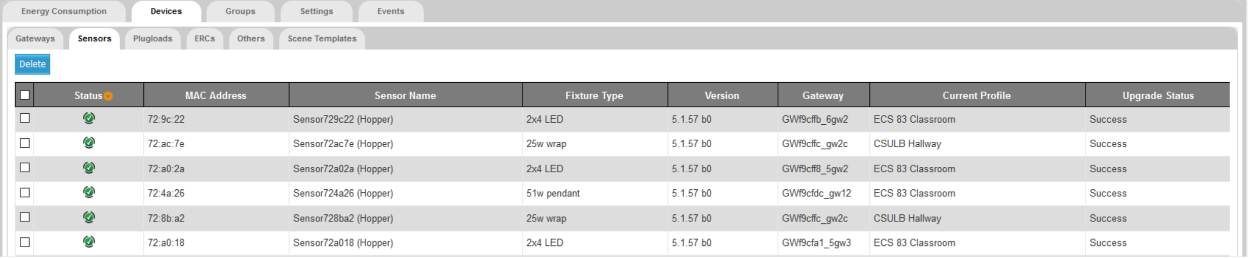
Figure 34: View Option for Lighting Fixtures under Floor Plan Subpanel



Source: California State University Long Beach

The display of sensors installed in the building provides information such as status, MAC address, sensor name, fixture type to which the sensor was attached, the gateway to which it was connected, and so on. For example, as shown in Figure 34, the status of Sensor72aedc was healthy, had the MAC address, was attached to a 2X4 LED, and was connected with the Gateway.

Figure 35: Example of Sensor Information Provided on Energy Manager Graphical User Interface Software



☐	Status	MAC Address	Sensor Name	Fixture Type	Version	Gateway	Current Profile	Upgrade Status
☐	✓	72:9c:22	Sensor729c22 (Hopper)	2x4 LED	5.1.57 b0	GWf9cffb_6gw2	ECS 83 Classroom	Success
☐	✓	72:ac:7e	Sensor72ac7e (Hopper)	25w wrap	5.1.57 b0	GWf9cffc_gw2c	CSULB Hallway	Success
☐	✓	72:a0:2a	Sensor72a02a (Hopper)	2x4 LED	5.1.57 b0	GWf9cff8_5gw2	ECS 83 Classroom	Success
☐	✓	72:4a:26	Sensor724a26 (Hopper)	51w pendant	5.1.57 b0	GWf9cfdc_gw12	ECS 83 Classroom	Success
☐	✓	72:8b:a2	Sensor728ba2 (Hopper)	25w wrap	5.1.57 b0	GWf9cffc_gw2c	CSULB Hallway	Success
☐	✓	72:a0:18	Sensor72a018 (Hopper)	2x4 LED	5.1.57 b0	GWf9cfa1_5gw3	ECS 83 Classroom	Success

Source: California State University Long Beach

Collected Data from New Lighting System

The subpanels in the energy manager GUI software also show the current load, period peak load, and current baseline load. Figure 35 shows the display of energy used by the new lighting system from 1 p.m. on January 21, 2019 to 12 p.m. on January 22, 2019 was 180.66 kWh. Occupancy savings during this time were 394.79 kWh, daylight harvesting was 3.08 kWh, and task tuning savings were 1.29 MWh for a total savings of 1.69 MWh.

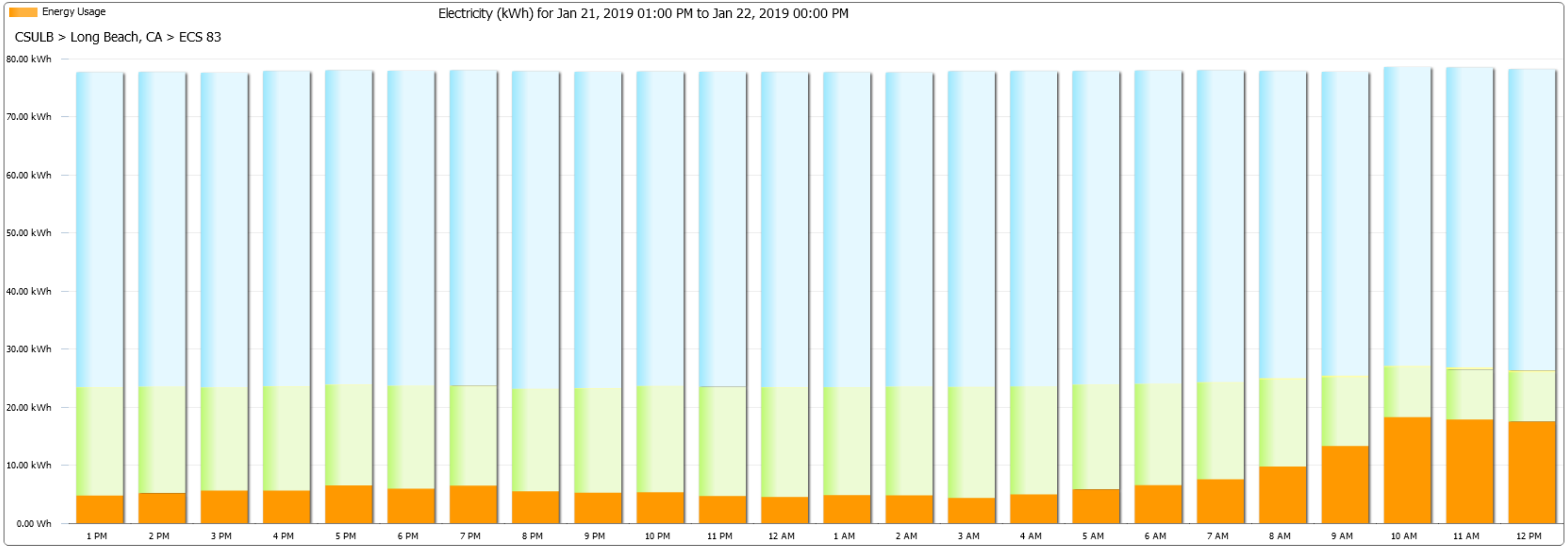
Energy usage can be displayed in the following ways (for the whole building or a separated zone, see Figure 8):

- Hourly over the last 24 hours (has label "day").
- Daily over the last 7 days (has label "week").
- Daily over the last 30 days (has label "month").
- Monthly over the last year (has label "year").

The upgraded energy manager records each event that has occurred on the system. Some events are for an action initiated by the administrator. There may be a separate event for when the action started, for when it completed successfully or failed, or when it was aborted. Other events occur due to periodic actions performed on the Enlighted energy manager or fixture. The energy manager can also supports demonstrating DR execution.

In addition to energy consumption data, smart sensors also provide data on occupancy, temperature status, and so forth. On the floor plan display, in the floor plan tab, selecting the occupancy status in the drop-down list labeled "view" provides information about floor occupancy at any time.

Figure 36: Energy Consumption of Engineering and Computer Science Building New Lighting System from 1-21-2019 (1 p.m.) to 1-22-2019 (12 p.m.)



Source: California State University Long Beach

The energy manager has an advanced option provided by GUI software that is capable of viewing the occupancy heat-map. The heat-map provides a color map to show the relative amount of activity on the floor of the building based on occupancy. The visualization makes it easy to identify floor areas with the highest activity as well as areas not in use.

Heat maps are generated by tracking occupant motion and activity in the area around each sensor. Activities such as moving hands while seated, waving hands, walking, or typing are registered by the sensors. The maps use different colors to represent different levels of activity: orange and red indicate more activity, while green and blue indicate less. Figure 36 shows a recorded example of the heat map for the 4th floor January 20, 2019 at 8:30 a.m. to January 23, 2019 at 5:30 p.m and showed that the most occupied areas (those with the dark red circles) were classrooms 408 and 412, along with the hallway in front of classroom 411.

Figure 37: Occupancy Heat-Map of Floor 4
from 1-20-2019 (8:30 a.m.) 1-23-2019 (5:30 p.m.)

Source: California State University Long Beach

Deployment, Commissioning, and Testing of the Internet-of-Things-based Plug Load Controller System

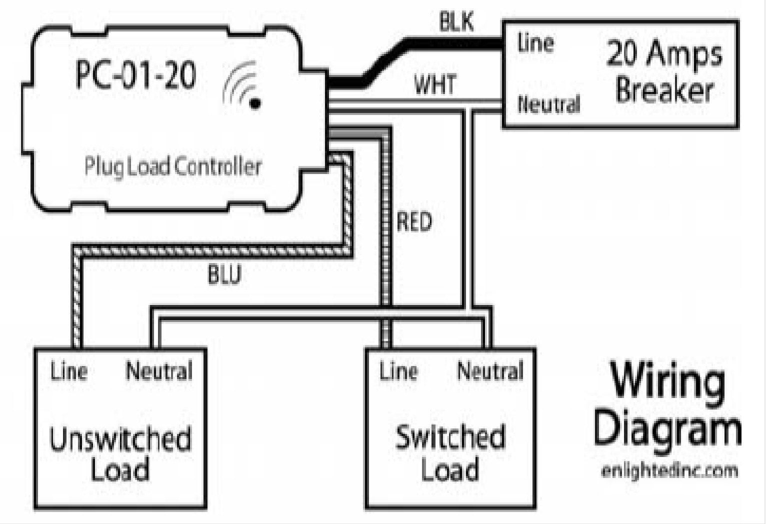
Based on the results of the model-based optimization approach, the researchers determined 201 original outlets in the building could be replaced with the smart plug controllers to provide maximum energy efficiency, demand response capability, and cost savings. However, based on an internal survey of faculty, students, and staff, there was little interest in replacing the smart plug controllers because building users did not want to completely turn of their devices during unoccupied periods. Users needed their devices (such as computers and laboratory equipment) to be continuously on for software updates, simulations that required extended run time, or for remote access. Therefore, the researchers installed only 30 plug load controllers in the ECS building, mostly at the overhead projectors and printers in classroom and laboratory rooms. Figure 37 shows an Enlighted plug load controller installed at a printer in classroom 411.

Figure 38: Enlighted Plug Load Controller Installed at Engineering and Computer Science 411

Source: California State University Long Beach

The Enlighted's PC-01-20 plug load controller has an input voltage range from 120-277VAC and a maximum current rating of 20A. It can operate at input frequency of 50 or 60Hz with an operating temperature from 32˚F to 122˚F The controller communicates with the energy manager and the sensors using wireless communication facilitated by the Enlighted's Gateway using the IEEE 802.12.4 protocol with communication radio frequency of 2440-2438.5 MHz and has a range of 150 feet radially. Figure 38 shows the controller configuration and Table 11 summarizes the technical specifications.

Figure 39: Enlighted Plug Load Controller Configuration



Source: California State University Long Beach

Table 12: Technical Specifications of Enlighted Plug Load Controller PC-01-20

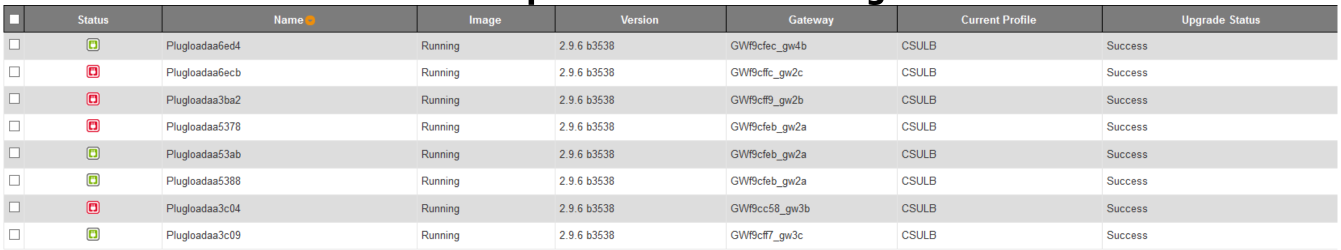
Specification	Value
Input Voltage	120 to 277 VAC
Input Frequency	50/60 Hz
Maximum Output Current	20A
Operating	0 to 50 C
Radio Frequency	2400 to 2483.5 MHz
Wireless Protocol	IEEE 802.15.4
Wireless Range	150 ft. radius (46m) open field

Source: California State University Long Beach

Accessing and Managing Plug Load Controller Profiles using Graphical User Interface Software

The devices subpanel includes the full list of plug load controllers installed in the building (Figure 39). The list provides controller information such as name, image (working condition), and the gateway to which it is connected. For example, as shown in Figure 22, the status of Plugloadaa6ed4 is "healthy," it is running, and is connected to Gateway GWf9cfec_gw4b.

Figure 40: Part of List of Plug Load Controllers Installed in Engineering and Computer Science Building

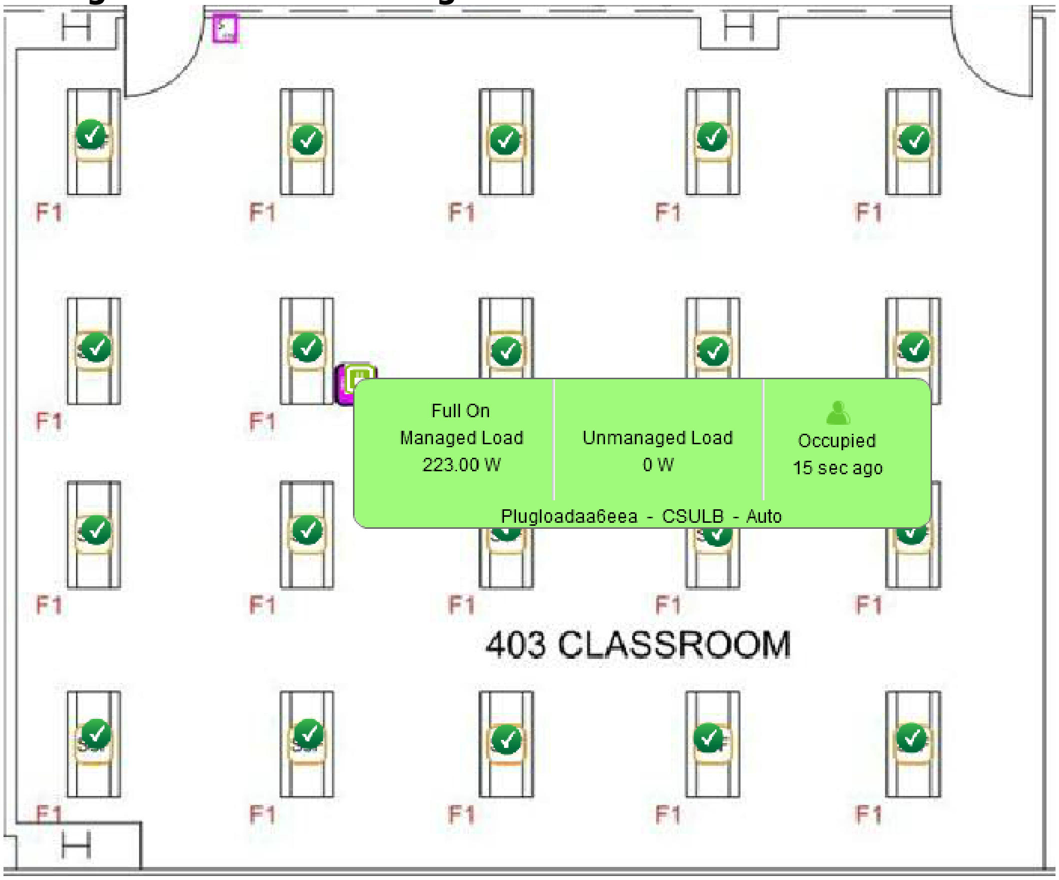


■	Status	Name	Image	Version	Gateway	Current Profile	Upgrade Status
☐	🟩	Plugloadaa6ed4	Running	2.9.6 b3538	GWf9cfec_gw4b	CSULB	Success
☐	🟥	Plugloadaa6ecb	Running	2.9.6 b3538	GWf9cffc_gw2c	CSULB	Success
☐	🟥	Plugloadaa3ba2	Running	2.9.6 b3538	GWf9cff9_gw2b	CSULB	Success
☐	🟥	Plugloadaa5378	Running	2.9.6 b3538	GWf9cfeb_gw2a	CSULB	Success
☐	🟩	Plugloadaa53ab	Running	2.9.6 b3538	GWf9cfeb_gw2a	CSULB	Success
☐	🟩	Plugloadaa5388	Running	2.9.6 b3538	GWf9cfeb_gw2a	CSULB	Success
☐	🟥	Plugloadaa3c04	Running	2.9.6 b3538	GWf9cc58_gw3b	CSULB	Success
☐	🟩	Plugloadaa3c09	Running	2.9.6 b3538	GWf9cff7_gw3c	CSULB	Success

Source: California State University Long Beach

The floor plan subpanel provides access to the profile of the plug load controllers in each room. Figure 40 shows the information for a plug load controller installed on an overhead projector. The green box in Figure 40 shows the display that appears when the cursor hovers over the plug load controller. In this example, the plug load controller was working at full load status which consumed 223W.

Figure 41: Status of Plug Load Controller in Classroom 403



Full On
Managed Load
223.00 W

Unmanaged Load
0 W

Occupied
15 sec ago

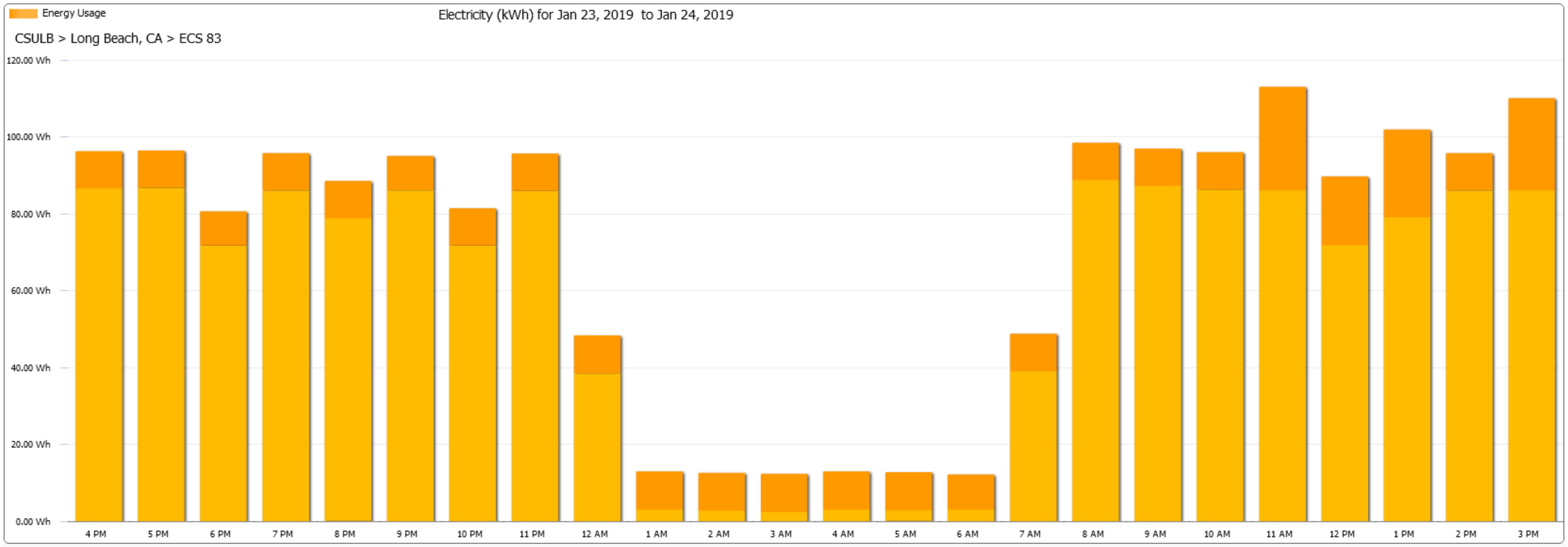
Plugloadaa6eea - CSULB - Auto

Source: California State University Long Beach

Collected Energy Consumption of Plug Load System

Figure 41 shows the reported energy consumption of all loads connected to the 30 installed Enlighted plug load controllers from 4 p.m. on January 23, 2019 to 3 p.m. on January 24, 2019. The two colors indicate the load of the unmanaged plug-in loads (with no control) and the managed plug-in loads (with control). The total energy used during that period was 285.04 W. Other detailed information available included current period load (96 W), period peak (116 W), and current baseline (96 W). Like lighting consumption, users can view plug load energy use in different zones and periods (days, weeks, months, and year).

Figure 42: Energy Consumption of Loads Connected to 30 Enlighted Plug Load Controllers from 1-23-2019 (4 p.m.) to 1-24-2019 (3 p.m.)



Source: California State University Long Beach

Deployment, Commissioning, and Testing of New Heating, Ventilation, and Air Conditioning System

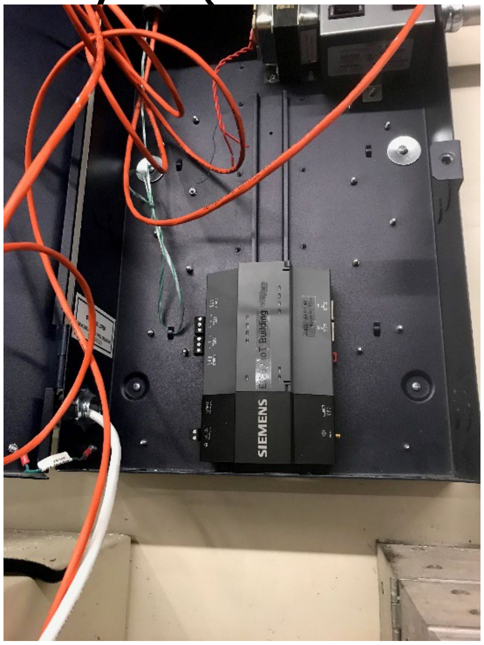
The new HVAC system implemented in the ECS building aimed at increasing the energy efficiency of the thereby providing cost savings. To achieve this, the existing BEMS was coalesced with the IoT network implemented by Enlighted Inc. to provide DR and intelligent control by leveraging applications such occupancy tracking, trending, scheduling, and remote control of the building's HVAC system.

The system combined the two networks of Enlighted and Siemens and used an interoperable control and communication platform with an open protocol called BACnet. The platform included microprocessor-based devices that communicated with sensors, actuators, routers, and workstations using the BACnet to exchange data and send command signals. Enlighted sensors interfaced with the Siemens network that provided occupancy data, which then triggered controllers and actuators to adjust temperature and pressure as needed, thereby preventing unnecessary operation of the HVAC system.

Type of Installed Equipment for New Heating, Ventilation, and Air Conditioning System

The installation of the HVAC control system including a global controller as seen in Figure 42, and a variable frequency driver as seen in Figure 43, and a software update.

Figure 43: Global Controller for Heating, Ventilation, and Air Conditioning Control System (Siemens TNM 8000)



Source: California State University Long Beach

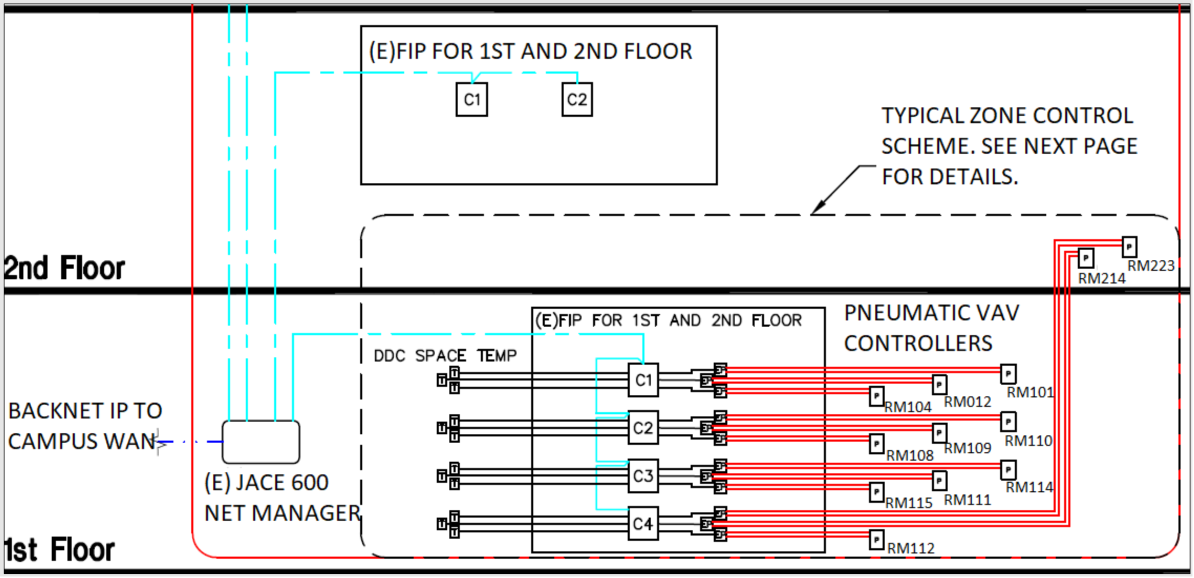
Figure 44: Variable Frequency Driver for Heating, Ventilation, and Air Conditioning Control System

Source: California State University Long Beach

Pneumatic Variable Air Volume Control Schedule

In the new network for the HVAC system, a typical control one had multizone controllers that monitored temperature and pressure. For example, in Figure 44, controller C2 monitored thermostat and pressure sensors for rooms 108, 109, and 110. Each multizone controller had an average of three rooms. Each floor of the ECS building had several zones based on the location of the air ducts. The first floor had four multizone controllers (C1, C2, C3 and C4) as shown in Figure 15.

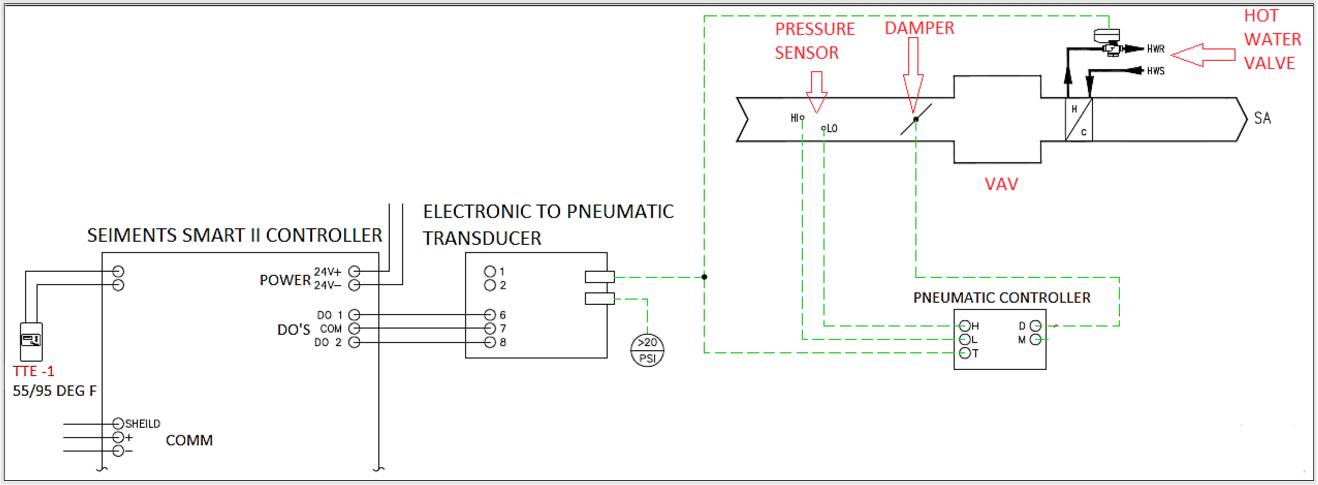
Figure 45: Multizone Controllers C1, C2, C3 and C4 on Left, Pneumatic Controller and Sensors on Right



Source: California State University Long Beach

A pneumatic transducer was used as a pressure control interface between the Siemen smart controller and the pneumatic controller of the VAV and hot water return (HWR) system can be seen in Figure 45. The controller modulated the air volume based on temperature and pounds per square inch (PSI). The multizone controller sent a signal to the transducer that modulated the VAV damper to minimum cubic feet per meter (CFM) to maintain a room "set-point" temperature of 72°F. If the temperature fell below the setpoint, the controller would send a signal for heating and the pneumatic control would open the hot water reheat valve. Once the temperature reaches 72°F, the hot water reheat valve would close and the VAV damper would modulate to maintain the temperature at the setpoint of 72°F.

Figure 46: Variable Air Volume

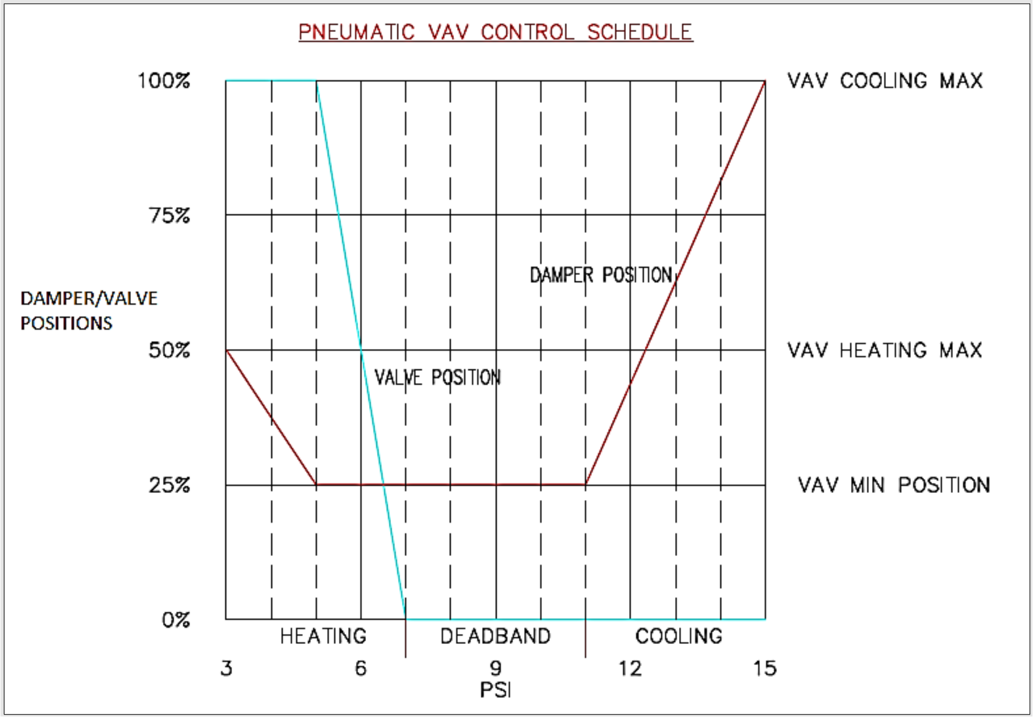


Source: California State University Long Beach

The damper and valve position were controlled based on a schedule as seen in Figure 46 and is used by the pneumatic VAV controller. The schedule had three main functions:

- Heating function.
- Dead band: Dead band range occurred from 7 to 11 PSI during which the damper would remain at 25 percent open and the hot water reheat valve would remain closed.
- Cooling.

Figure 47: Pneumatic Variable Air Volume Controller Schedule



Source: California State University Long Beach

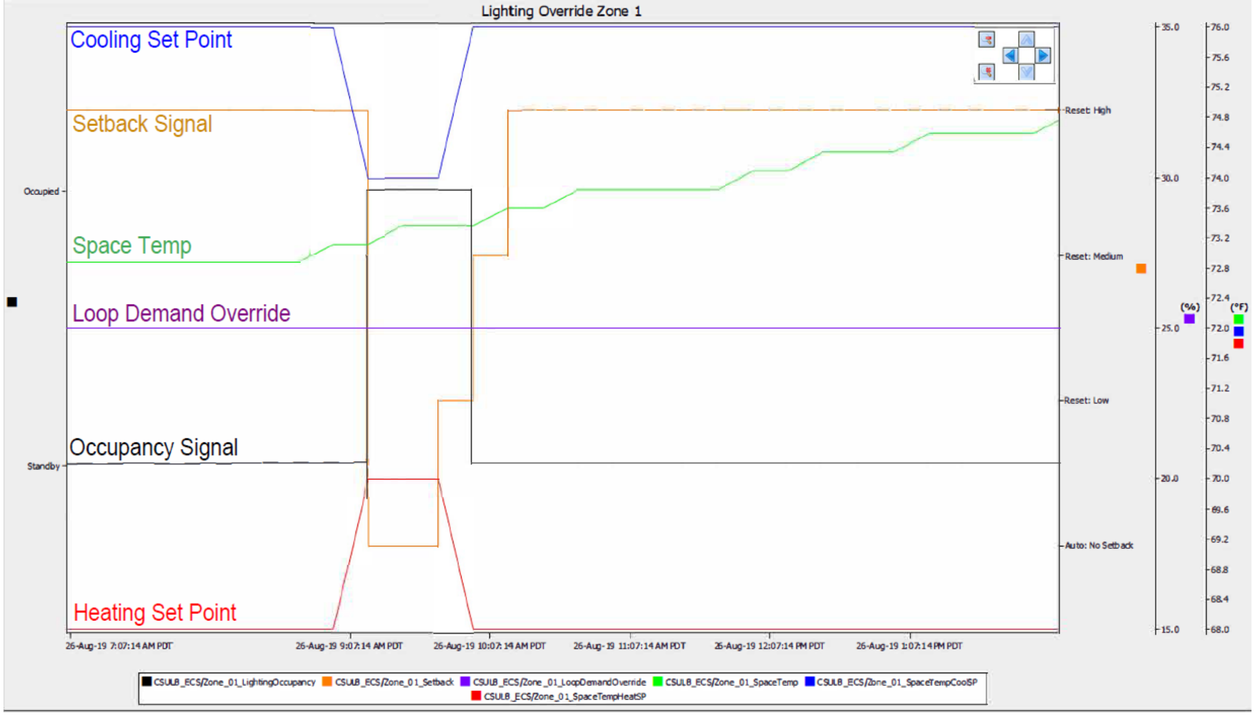
Sequence of Operations

The sequence of operations for the interoperability of the pneumatic VAV controller included:

- VAV box control without reheat.
- VAV box control with reheat.
- VAV box control with fan coil units.
- ON hour control.
- OFF hour.

The space temperature of the ECS building with new HVAC system would now control between 68°F to 76°F, rather than actively control to 72°F. Figure 47 shows an example of how the lighting system occupancy signal drove the setback logic of the new HVAC system. The data was captured from 7:07 a.m. on August 26, 2019 to 1:07 p.m. on August 26, 2019 for Zone 1. When the occupancy signal (the black line) showed "standby" (unoccupied), the cooling setpoint of the zone (the blue line) was 76°F. Then at about 9:20 a.m. that day, when the occupancy signal showed "occupied," the cooling set point was brought down to 72°F. The cooling setpoint was brought back to 76°F after the zone was unoccupied, at about 10:00 a.m. Figure 47 shows that the space temperature was controlled between 68°F to 76°F, rather than just 72°F.

Figure 48: Lighting System Occupancy Signal Drives Setback Logic of New Heating, Ventilation, and Air Conditioning System



Source: California State University Long Beach

Standard Fulfillment of New Systems

This section briefly discusses the standard fulfillment of the new systems, including the lighting and HVAC systems. By discussing the capability and validation of new installed equipment, summarizing the installation process, and evaluating the illumination, temperature, and ventilation across the ECS building, this report shows how the new systems met the requirement and guidelines set for educational facilities by the state regulation.

Compliance of New Lighting System

The method of compliance used was the “area category” method, which applies to any building permit including tenant improvements. Lighting power density values were assigned to each of the primary function areas of a building (offices, lobbies, corridors, etc., as defined in Title 24 building codes). The following lighting compliance documents, certificates of acceptance, and installation certificates were submitted for approval before the installation process:

- NRCC-LTI-01-E: Certificate of compliance. All pages required on plans for all submittals.
- NRCC-LTI-02-E: Lighting controls and certificate of compliance. All pages required on plans for all submittals.
- NRCC-LTI-03-E: Indoor lighting power allowance.
- NRCA-LTI-02-A: submitted for occupancy sensors and automatic time switch controls.
- NRCA-LTI-03-A: submitted for automatic daylight controls.
- NRCI-LTI-01-E: submitted for the ECS building.

- NRCI-LTI-02-E: submitted for an energy management lighting control system.

Table 12 shows the total allowed and adjusted installed lighting power for the ECS building. The table shows the compliance in the installed lighting power since total adjusted installed lighting power was less than the total allowed lighting power.

Table 13: Summary of Allowed Lighting Power

	Indoor Lighting Power for Conditioned Spaces	Watts	Indoor Lighting Power for Unconditioned Spaces	Watts
1	Installed Lighting NRCC-LTI-01-E, page 4	37,450	Installed Lighting NRCC-LTI-01-E, page 4	
2	PORTABLE ONLY FOR OFFICES NRCC-LTI-02-E, page 3	0		
3	Minus lighting Control Credits NRCC-LTI-02-E, page 2	0	Minus lighting Control Credits NRCC-LTI-02-E, page 2	
4	Adjusted Installed Lighting Power (row 1 plus row 2 minus row 3)	37,450	Adjusted Installed Lighting Power (row 1 plus row 2 minus row 3)	0
5	Complies ONLY if Installed ≤ Allowed		Complies ONLY if Installed ≤ Allowed	
6	Allowed Lighting Power Conditioned NRCC-LTI-03-E, page 1	76,867.15	Allowed Lighting Power Unconditioned NRCC-LTI-03-E, page 1	

Source: California State University Long Beach

Mandatory lighting control requirements (outlined in Title 24 building codes) were also fulfilled:

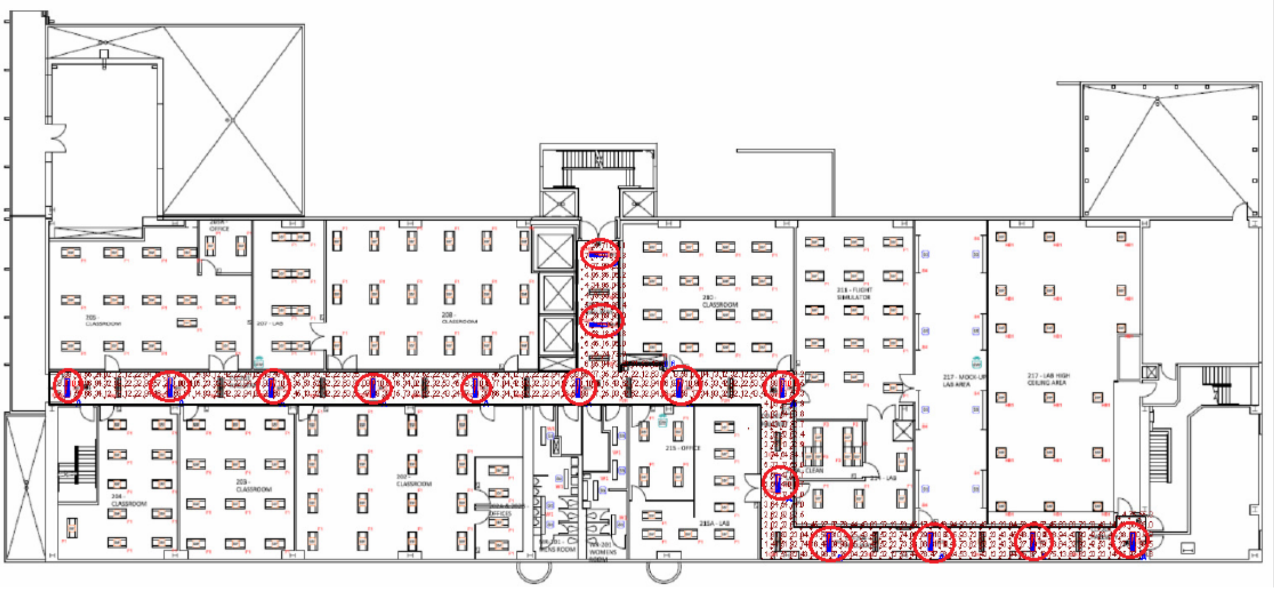
- Lighting was controlled by self-contained lighting control devices certified by the CEC according to the Title 20 Appliance Efficiency Regulations in accordance with section 110.9.
- Lighting was controlled by a lighting energy management control system in accordance with §110.9. An installation certificate was submitted in accordance with section 130.4(b).
- All lighting controls and equipment complied with the applicable requirements in §110.9 and were installed with the manufacturer’s instructions in accordance with section 130.1.
- All luminaires were functionally controlled with manually switched ON and OFF lighting controls in accordance with section 130.1(a).
- General lighting was separately controlled from all other lighting systems in the building. Floor and wall display, case display, ornamental, and special effects lighting were separately controlled on circuits that were 20 amps or less in accordance with section 130.1(a)4.
- The general lighting of the ECS building met the multilevel lighting control requirements in accordance with section 130.1(b).

- All installed indoor lighting was equipped with controls that met the applicable shut-off control requirements in section 130.1(c).
- Lighting in all daylit zones was controlled in accordance with the requirements in section 130.1(d).
- Lighting power in the ECS building could be automatically reduced in response to a demand response signal in accordance with section 130.1(e).

Overall, the energy features and performance specifications, materials, components, and manufactured devices for the ECS building design and system design conformed to the requirements of Title 24, Part 1 and Part 6 of the California Code of Regulations.

Although proposed in the original project proposal, emergency fixtures were installed in the hallway of each floor, with one emergency fixture per two lighting fixtures, to fulfill the requirement from the fire marshal since the lighting system had been renovated by more than 80 percent. Figure 48 shows the plan of emergency fixtures for the second floor, with the emergency fixtures circled in red.

Figure 49: Emergency Fixtures Plan for Engineering and Computer Science Second Floor



Source: California State University Long Beach

The retrofit kits were installed in a Lithonia GT8, white reference housing, white reflector, frosted plastic linear prismatic lens enclosure with 10W battery backup that can power on for 90 minutes. The kits allow emergency lighting to be turned on in the event of loss of normal utility power.

There are 45 emergency fixtures installed in the ECS building hallways.

Compliance of New Heating, Ventilation, and Air Conditioning System

Because the research team was only adding a new control approach to the ECS building's existing HVAC system, the most important code that applied to the new HVAC system was §120.2 (requirements for controls for space conditioning system) from Title 24 building codes. Table 13 provides the compliance of the ECS building's HVAC control system, based on Section 120.2 of Title 24 building codes.

Table 14: New Heating, Ventilation, and Air Conditioning System Compliance

Control Requirements	YES	NO
The supply of heating and cooling energy to each space-conditioning zone shall be controlled by an individual thermostatic control that responds to temperature within the zone and that meets the heating and cooling temperature ranges and dead zone requirements in accordance with Section 120.2(b).	✓	
Each space-conditioning system shall be installed with controls that are capable of automatically shutting off the system during periods of nonuse and shall have an occupancy sensor in accordance with Section 120.2(e).	✓	
The space-conditioning system shall be installed with controls that are capable of automatically setup the operating cooling temperature set point by 2°F or more and setback the operating heating temperature set point by 2˚F or more in accordance with Section 120.2(e).	✓	
Outdoor air supply and exhaust equipment shall be installed with dampers that automatically close upon fan shutdown in accordance with Section 120.2(f).	✓	
HVAC systems with DDC to the Zone level shall be programmed to allow centralized demand to shed for non-critical zones shutdown with controls that have the capability to remotely setup and set down the operating cooling and heating temperature set points by 4˚F or more in all non-critical zones in accordance with Section 120.2(h).	✓	
HVAC systems with DDC to the Zone level shall have controls that have the capability to remotely reset the temperatures in all non-critical zones to original operating levels and be programmed to provide an adjustable rate of change for the temperature in accordance with Section 120.2(h).	✓	
HVAC systems with DDC to the Zone level shall have disable, manual, and shed control capabilities in accordance with Section 120.2(h)5.	✓	
Direct Digital Controls to the zone shall be capable, in accordance with Section 120.2(j): Monitoring zone and system demand for fan pressure (§120.2(j)2).		✓
Monitoring zone and system demand for system pump pressure, heating and cooling (§120.2(j)2).	✓	
Transferring zone and system demand information from zones to air distribution system controllers and from air distribution systems to heating and cooling plant controllers (§120.2(j)3).	✓	
Automatically detecting the zones and systems that may be excessively driving the reset logic and generate an alarm or other indication to the system operator (§120.2(j)4).	✓	
Readily allow operator removal of zones(s) from the reset algorithm (§120.2(j)5).	✓	
Resetting heating and cooling set points in all non-critical zones upon receipt of a signal from a centralized contact or software point (§120.2(j)6).	✓	
Space conditioning systems with DDC to the zone level shall have optimum start/stop controls in accordance with Section 120.2(k).		✓

Source: California State University Long Beach

CHAPTER 4: Evaluate Performance Costs and Benefits Assessment

This chapter discusses the impact of the new EMS and DR on the ECS building's operation based on of lighting and plug load data, visual and occupant comfort, and power quality. The overall costs and benefits of this project are also discussed.

Impact of New Energy Management System on Engineering and Computer Science Building Operation

Analysis of Lighting Data

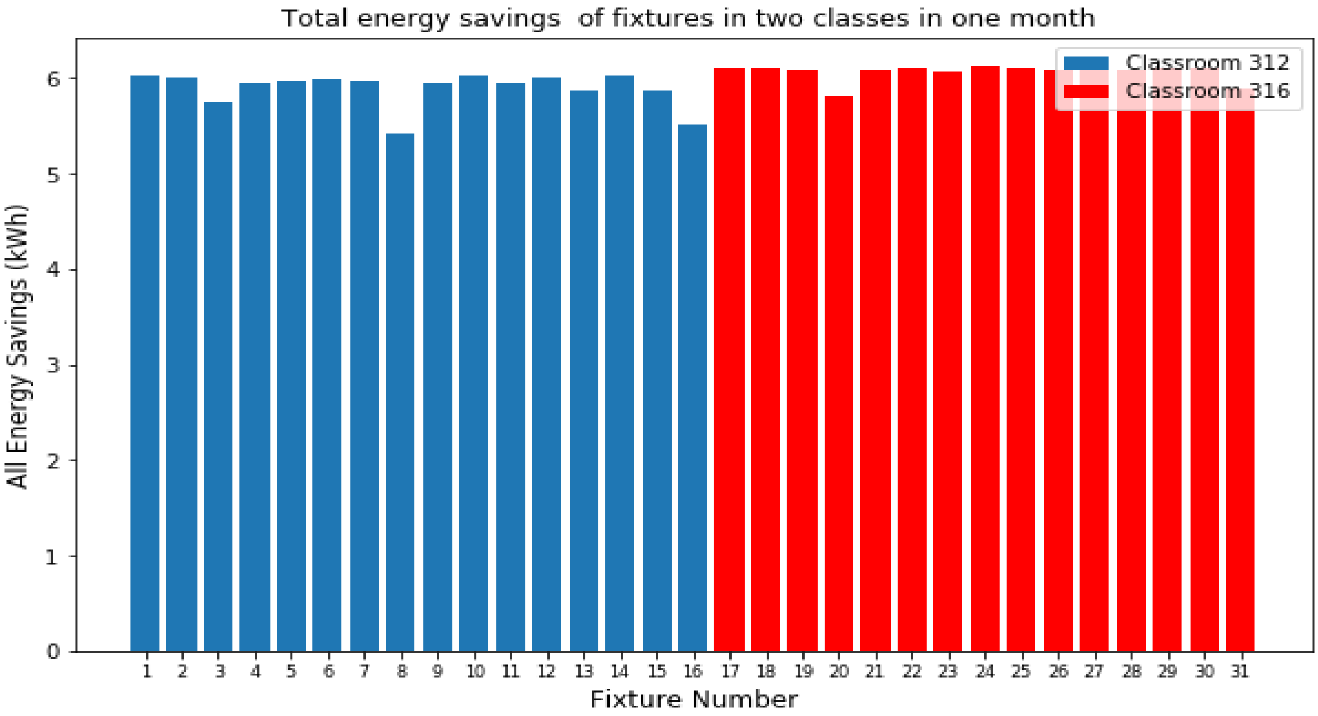
The data for the lighting load was substantial because of the number of fixtures and duration of data recording. Therefore, the team extracted the data for each fixture from the original data file separately, selected the data for fixtures during one month (May 18, 2019 to June 22, 2019), and analyzed the lighting fixtures of two classrooms, 312 and 316, first. The researchers then analyzed the entire building.

Each LED lighting fixture had a nominal power usage; for classrooms 312 and 316, this was 89 W. Note that this usage is below the nominal power of the type 1 florescent fixtures. However, the brightness of LED lights can be controlled, and the lights do not typically consume the nominal power. In both classrooms, the lights can perform three modes of operations, for example bright, dim, and off. In the bright mode, lights are set at 81 percent of the LED power/brightness. In the dim mode, lights are set at 24 percent of the brightness. Based on the occupancy of the room, the time of the day, and daylighting, the fixtures are automatically controlled to provide three types of energy savings:

- Energy savings from occupancy sensing (turning the fixture on and off based on occupancy).
- Energy savings from task-tuning (changing the dimming of the fixture).
- Energy saving from daylight harvesting.

The team examined the collection of these savings for both classrooms, as shown in Figure 49.

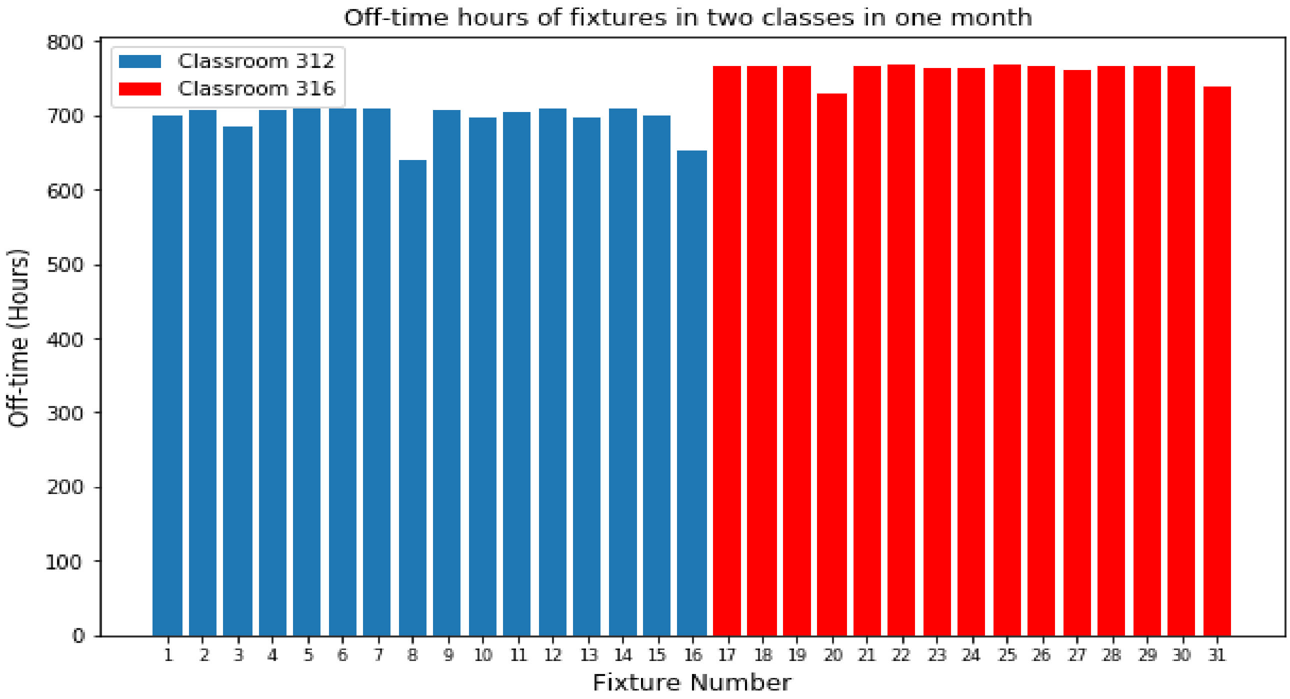
Figure 50: Total Energy Savings of Individual Fixtures in Classrooms 312 and 316



Source: California State University Long Beach

Considering the total wattage of the fixtures and the duration of the analysis, the energy savings were substantial (around 6 kWh) and are similar for both classrooms. Figure 50 illustrates the duration of the fixtures' off-time. Not surprisingly, lights were off for a large part of this period because it occurred during the summer break.

Figure 51: Off-Time Hours in Classrooms 312 and 316

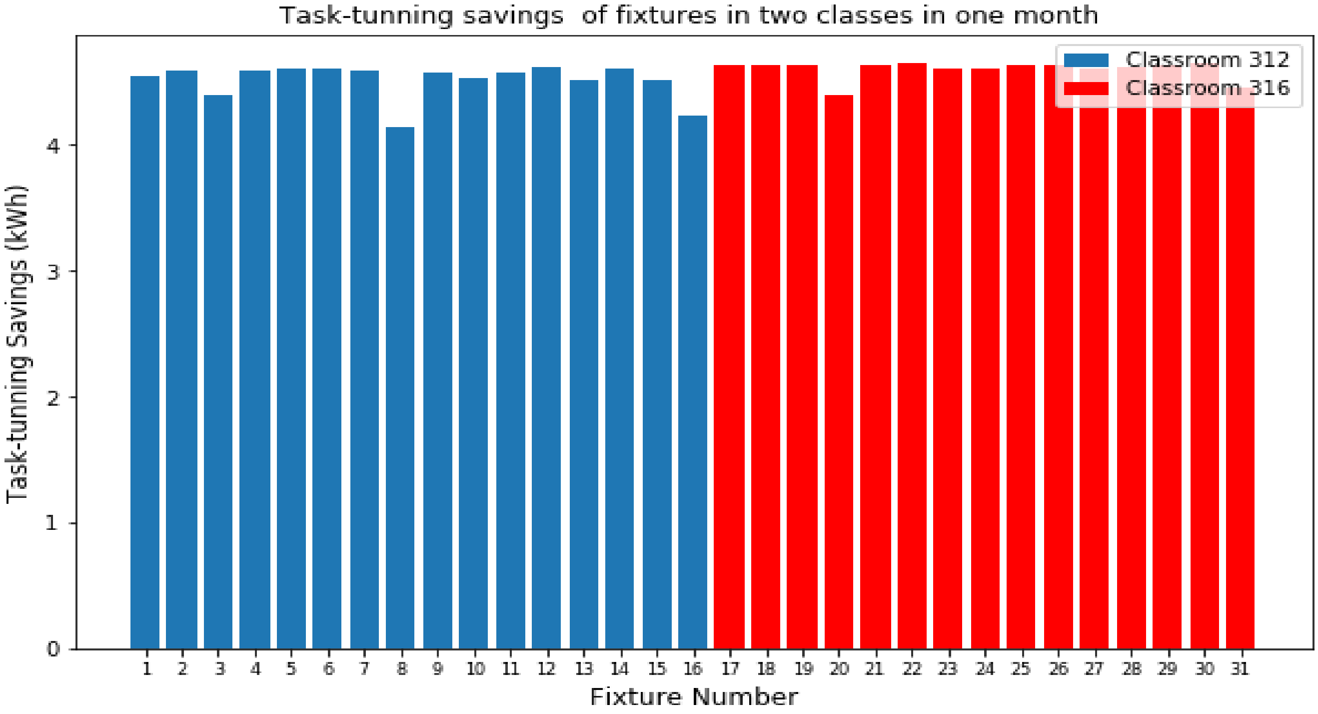


Source: California State University Long Beach

Next, the team examined the components of the energy savings (that is, task-tuning, occupancy-based control, and daylight harvesting).

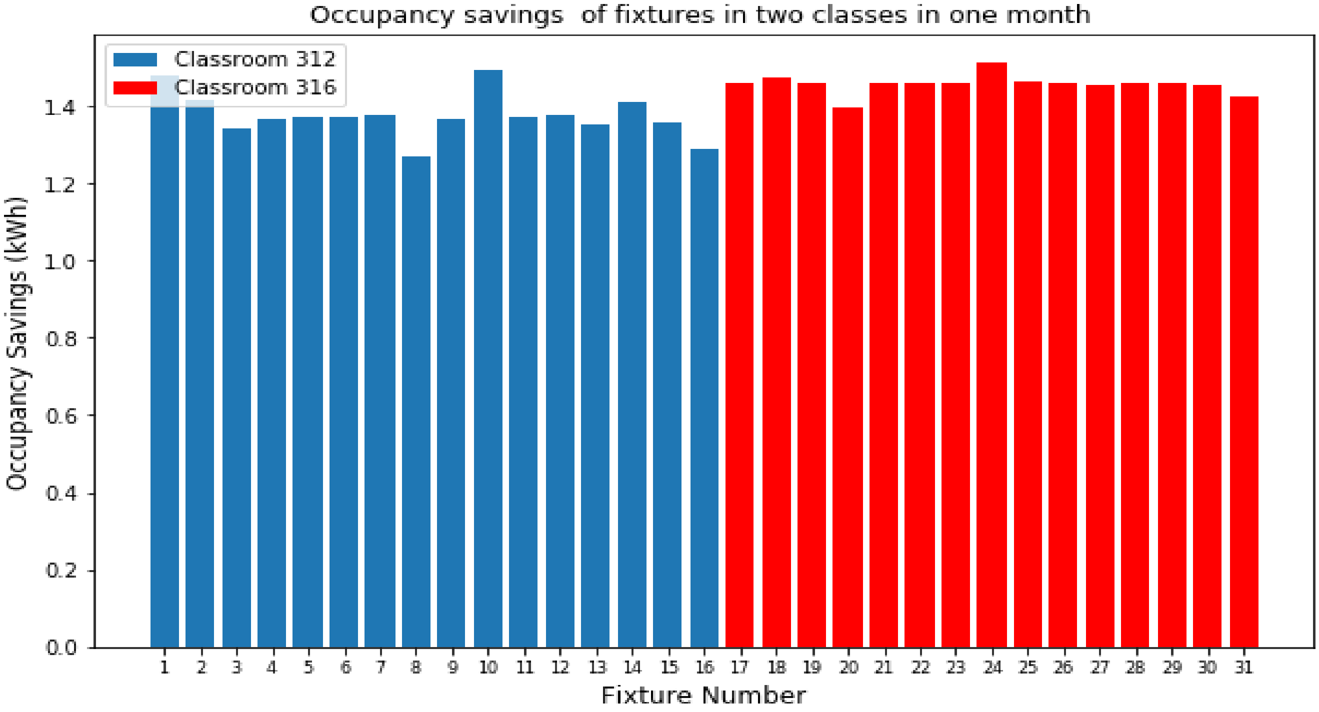
Figure 51 shows that the task-tuning savings represented a major component of the energy savings in the two classrooms. Note that in Figure 52, the savings calculated for occupancy were counted as an addition to the task-tuning, that is, it was assumed that the task-tuning savings could be achieved even if the lights were not controlled by the occupancy. The daylight savings are illustrated in Figure 53.

Figure 52: Energy Savings from Task-Tuning in Classrooms 312 and 316



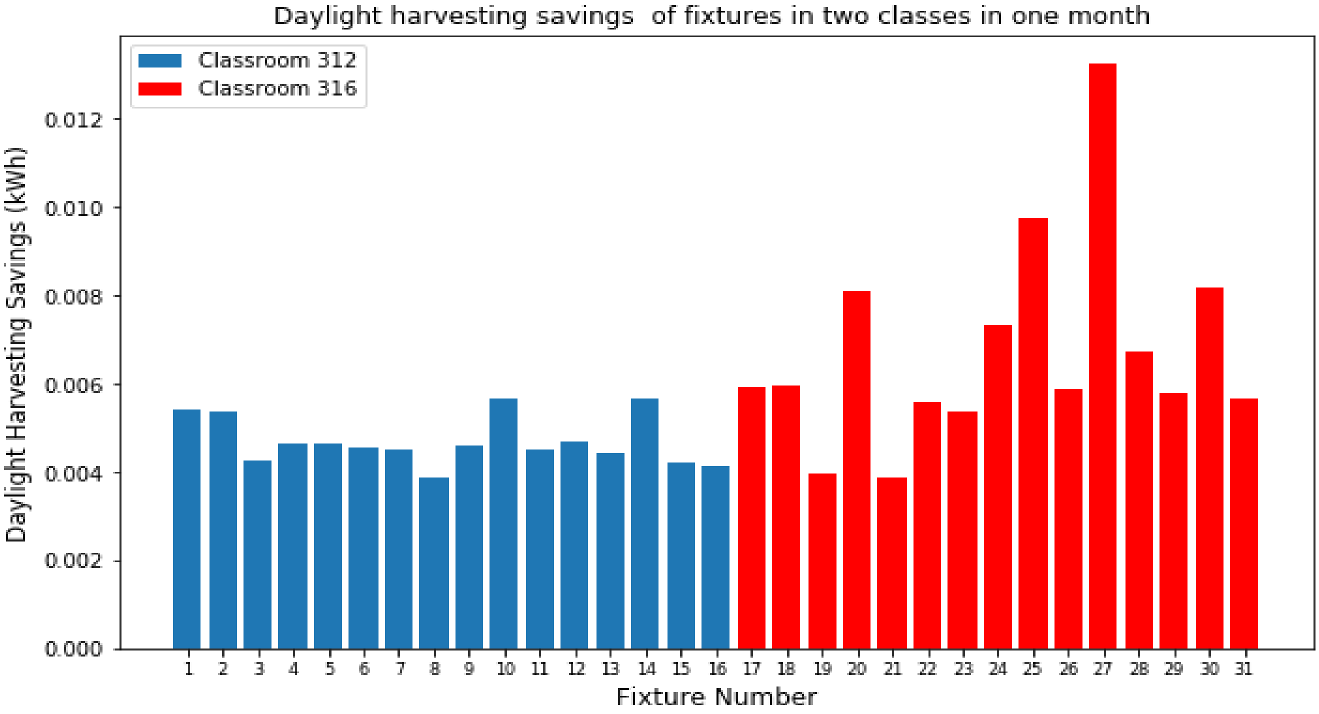
Source: California State University Long Beach

Figure 53: Energy Savings from Occupancy-Based Control in Classrooms 312 and 316



Source: California State University Long Beach

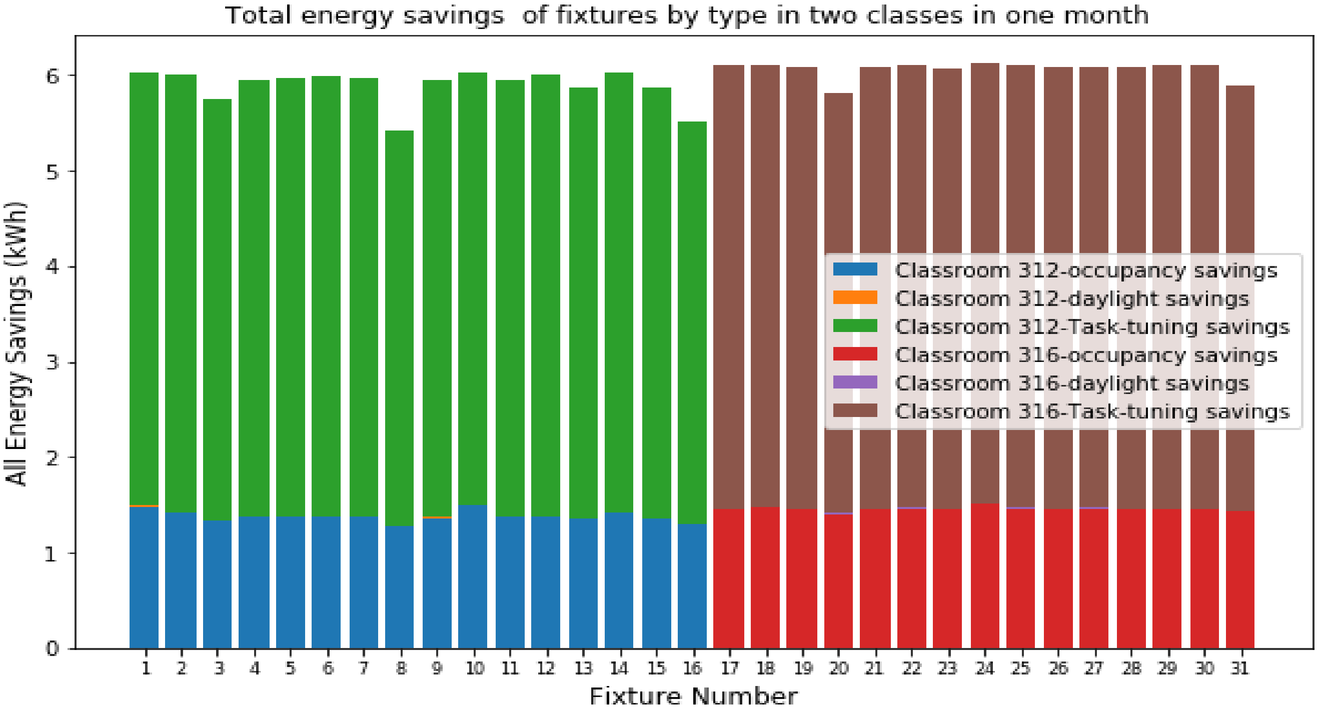
Figure 54: Energy Savings from Daylight Harvesting in Classrooms 312 and 316



Source: California State University Long Beach

Figure 54 shows the components of energy savings stacked that are compared between the two classrooms. From this figure, the question arises as to why the daylight savings in the two selected rooms were very minimal. This could be the result of the way the team calculated and counted the savings achieved by the daylight or could have been the result of the rooms not having outside windows or curtains.

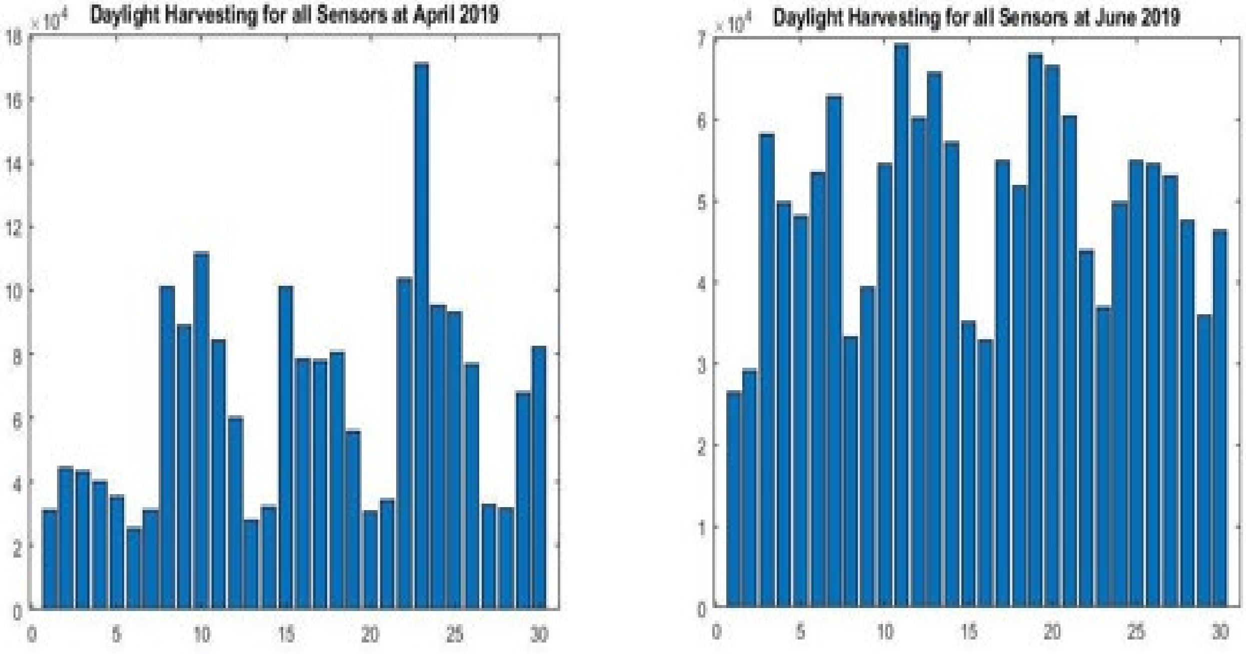
Figure 55: Total Energy Savings from Various Actions in Classrooms 312 and 316



Source: California State University Long Beach

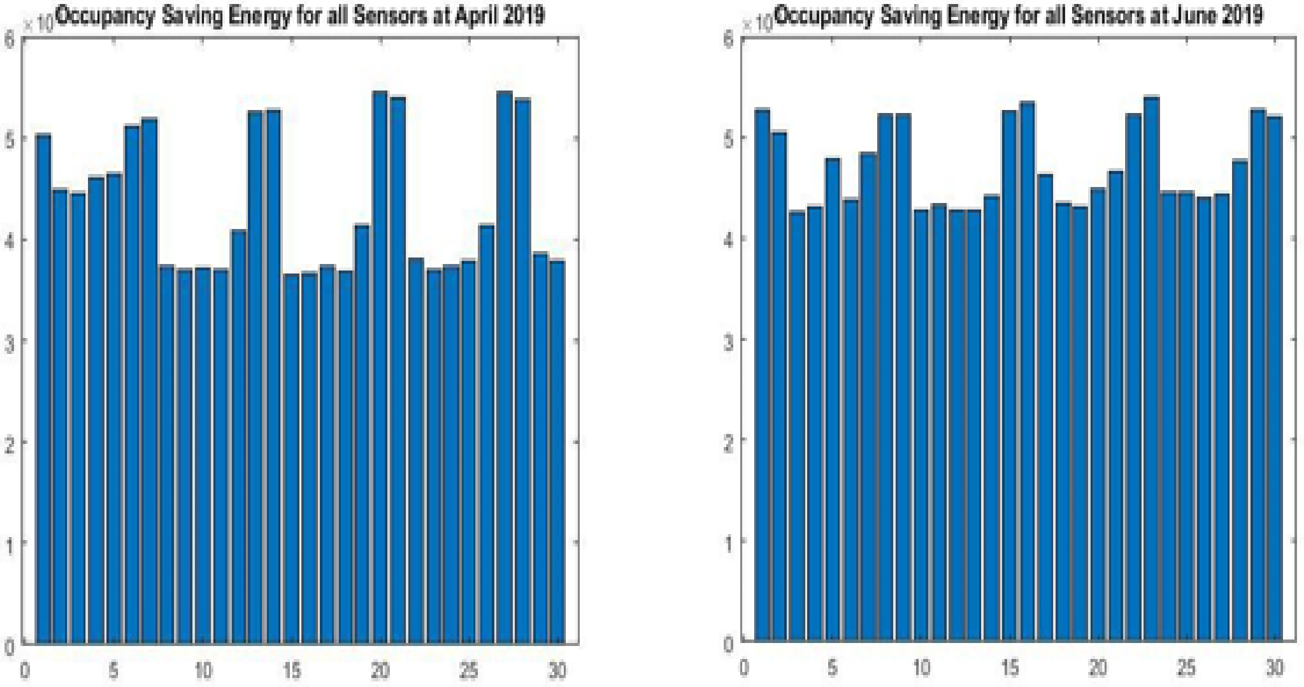
The team also investigated three types of energy saving for all sensors available in the ECS building for April and June 2019. Figures 55 shows the energy savings achieved with daylight harvesting, Figure 56 shows the energy savings achieved through occupancy based control and , and Figure 57 show the energy savings achieved through task tuning.

Figure 56: Energy Savings Through Daylight Harvesting for All Sensors for April (left) and June (right) 2019



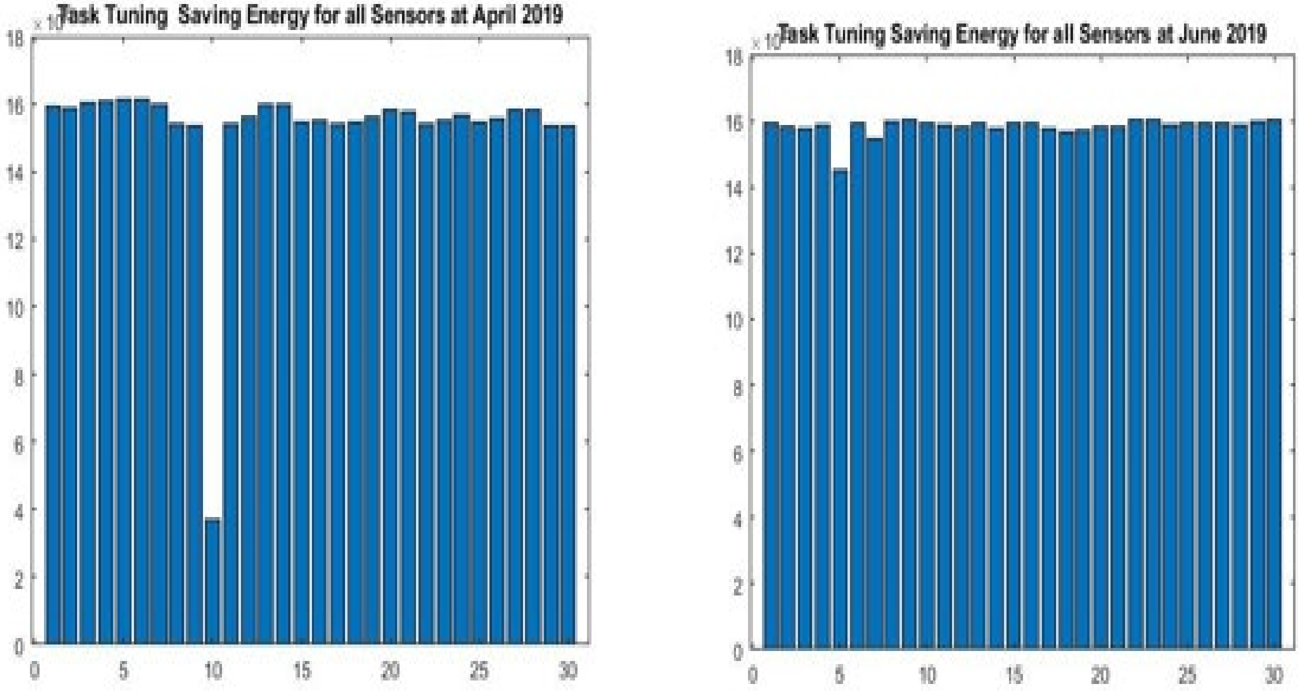
Source: California State University Long Beach

Figure 57: Energy Savings Through Occupancy-Based Control for All Sensors for April (left) and June (right) 2019



Source: California State University Long Beach

Figure 58: Energy Savings Through Task-Tuning for All Sensors for April (left) and June (right) 2019



Source: California State University Long Beach

Visual Comfort

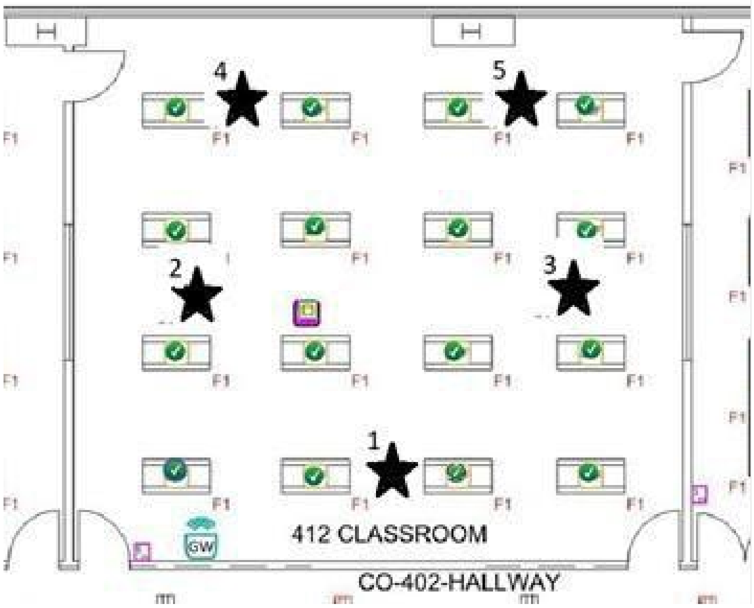
Visual comfort is a crucial parameter that affects the productivity and alertness of occupants in a building. For instance, in educational environments, improvements made in lighting level and quality enhance the learning ability of students. On the other hand, energy efficiency and cost are a concern for every building. So there is a trade-off between user comfort and energy cost with the optimal value influenced by various factors such as individual preferences for lighting, the importance of building functionality, and energy prices. As an educational environment, CSULB has the advantage of possessing an infrastructure to remotely control lighting fixtures. Moreover, the university has been involved in DR programs offered by Southern California Edison, which provides a unique capability to enhance occupant comfort level while saving energy and money.

Determining the optimal lighting level of classrooms, offices, research labs, and corridors, and controlling those levels through the installed lighting controllers, requires accurate measurement to determine the relationship between user comfort and preferred lighting level (or equally luminance level), and energy savings. Defining this relationship requires the measurement and acquisition of three types of data: (1) the lux level of the rooms, (2) the lighting energy consumption, and (3) the attitude of occupants toward different lighting conditions.

The lighting energy consumption was discussed in the previous section. To obtain the luminance data for the test spaces, the UC Riverside team performed several lux measurements tests on August 27, 2019, in classroom 412, one of the typical classrooms in the ECS building. Note that lux is the unit of measure used to describe the number of lumens falling on a square foot.

The team performed the tests at 7:00 am and 12:00 p.m. in the same classroom on the same day with cloudy weather at both times. Figure 58 shows the floorplan of classroom 412 and the tested spots in the room. The lux values in the measurements varied for each spot based on its distance from the windows.

Figure 59: Floor Plan and Test Spots in Classroom 412

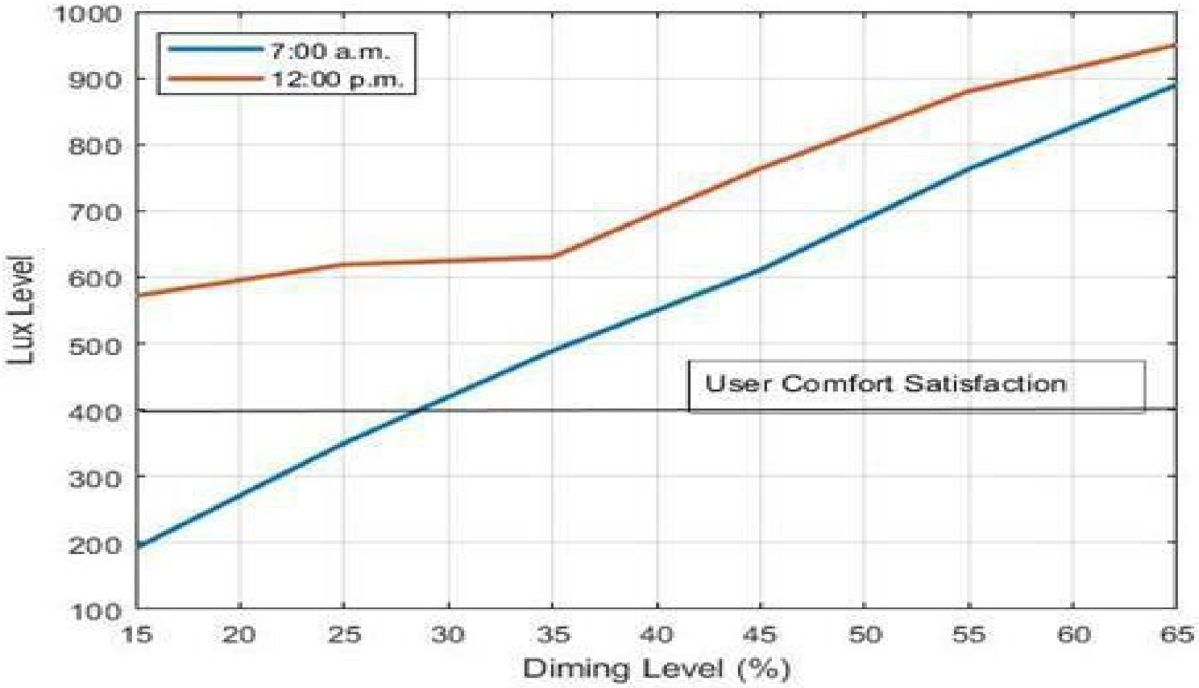


Source: California State University Long Beach

The average level at spots away from the windows at 7:00 a.m. was 589 lux, and for the spots next to windows was 900 lux. For the repeated test at 12:00 p.m., the lux level was an average 660 lux for spots away from the windows, and 970 lux for spots close to the windows. The team also measured the light level in corridors where there were few windows. On average, the level was 600 lux in corridors during the day, while the lighting standard recommends that required light level for corridors with dark surrounding should be 25-50 lux.

In addition, the team measured the lux level for the same classroom with different dimming levels at several spots. Figure 59 shows the lux levels vs dimming at the tested spots in the room.

Figure 60: Lux Level versus Dimming Level for Spot 5



Source: California State University Long Beach

While lighting energy usage and lux level can be assessed using physical measurements, the effect on building occupants cannot be physically measured. The team designed and distributed a questionnaire to collect ratings by users of the lighting level. In particular, the team performed a special test in classroom 412 on August 27, 2019 to assess occupant comfort while simultaneously measuring the lighting lux levels.

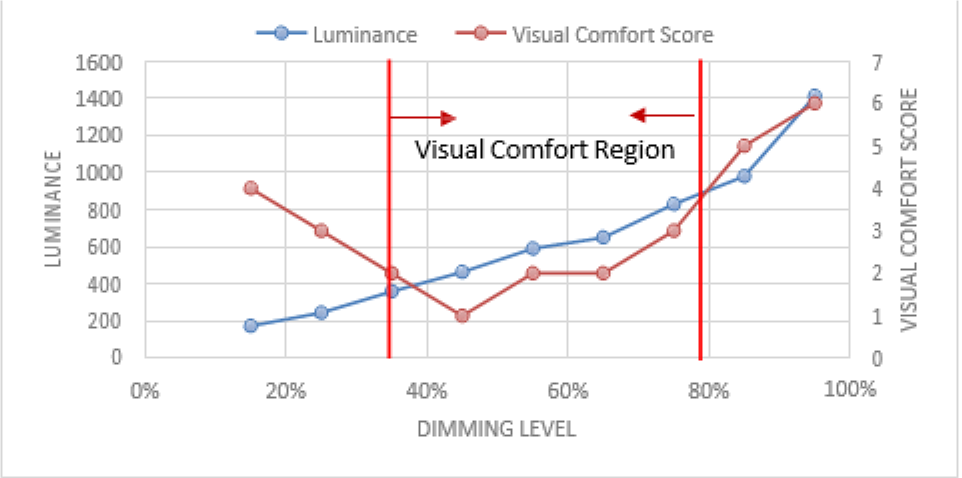
The questionnaire included questions that covered the attitudes toward the building as an educational environment, which considered lighting and other environmental factors such as thermal and acoustical conditions. However, the focus was on daylight and artificial light. The questionnaire included the following: how the classes are lit, if unshaded windows create problems, and the advantages and disadvantages of windows as a light source. Data concerning age and sex of respondents and length of time present in the classroom were also collected. Occupant identify was not revealed, but students were asked for a special code that enabled the researchers to compare the evaluation from one occasion to another and during different ambient light settings. To ensure that responses reflected student response to the lighting levels, the time of responses was determined then results were mapped to the lighting conditions achieved and the energy performance of the room.

Overall, nearly 60 questionnaires were distributed in the following locations of the ECS building: two classrooms on the west side (ECS-314 and ECS-412), a faculty office on the north side (ECS- 512), ECS-552 the department office on the south side (ECS-552), and a faculty office on the east side (ECS-662). According to the survey data, satisfaction of respondents about lighting levels improved as the dimming level was reduced to 35 percent. This indicates that meeting visual comfort does not necessarily require an increase in the artificial dimming level. When the light level was dimmed, only 3 percent of respondents felt the light was insufficient, while the rest were satisfied.

The typical standard recommendation for visual comfort is that the ideal light luminance level for normal office work, class activity, research lab, or study library is within 250-500 lux. Actual comfort, though, depends on the desires of individuals using the room. The standard recommends that required light level for corridors with dark surrounding should be 25- 50 lux.

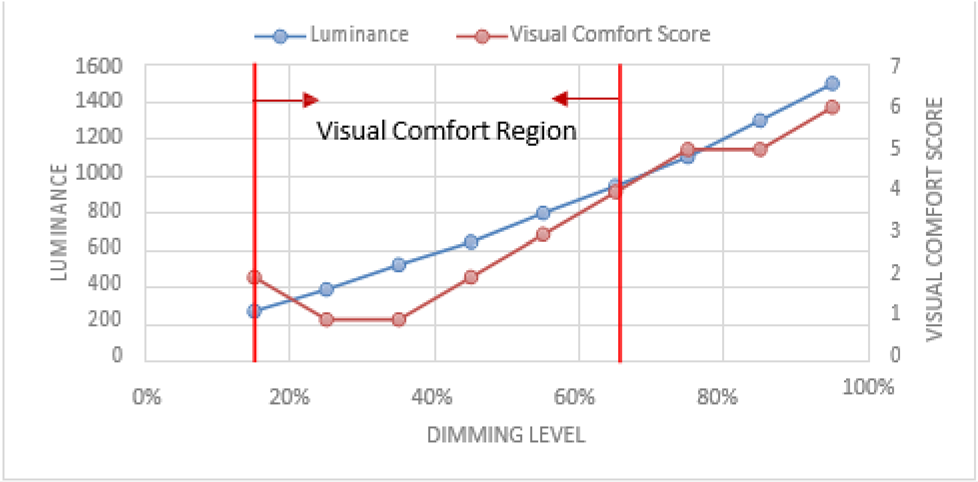
Based on the measurements at room 412, the lux measurements in the room were between 589 lux and 970 lux depending on the time of the day and position towards the windows. Under the standard setting, the resulting light level was far above the standard. Also, the average level measured in the corridors was 600 lux during the day, which exceeded standard recommended luminance. This lux level was achieved when all lighting fixtures were set to 65 percent of their nominal power when they were turned on. In general, a 5 percent decrement in the dimming level of LED lights saves 4 W of energy. A typical classroom at CSULB has 16 lighting fixtures. Figures 60 and 61 show the luminance and visual comfort scores versus the dimming level at the middle zone in room ECS 412 in early morning and early afternoon.

Figure 61: Luminance and Visual Comfort Score versus Dimming Level for Engineering and Computer Science 412 at Middle Zone in Early Morning



Source: California State University Long Beach

Figure 62: Luminance and Visual Comfort Score versus Dimming Level for Engineering and Computer Science 412 at Middle Zone in Early Afternoon



Source: California State University Long Beach

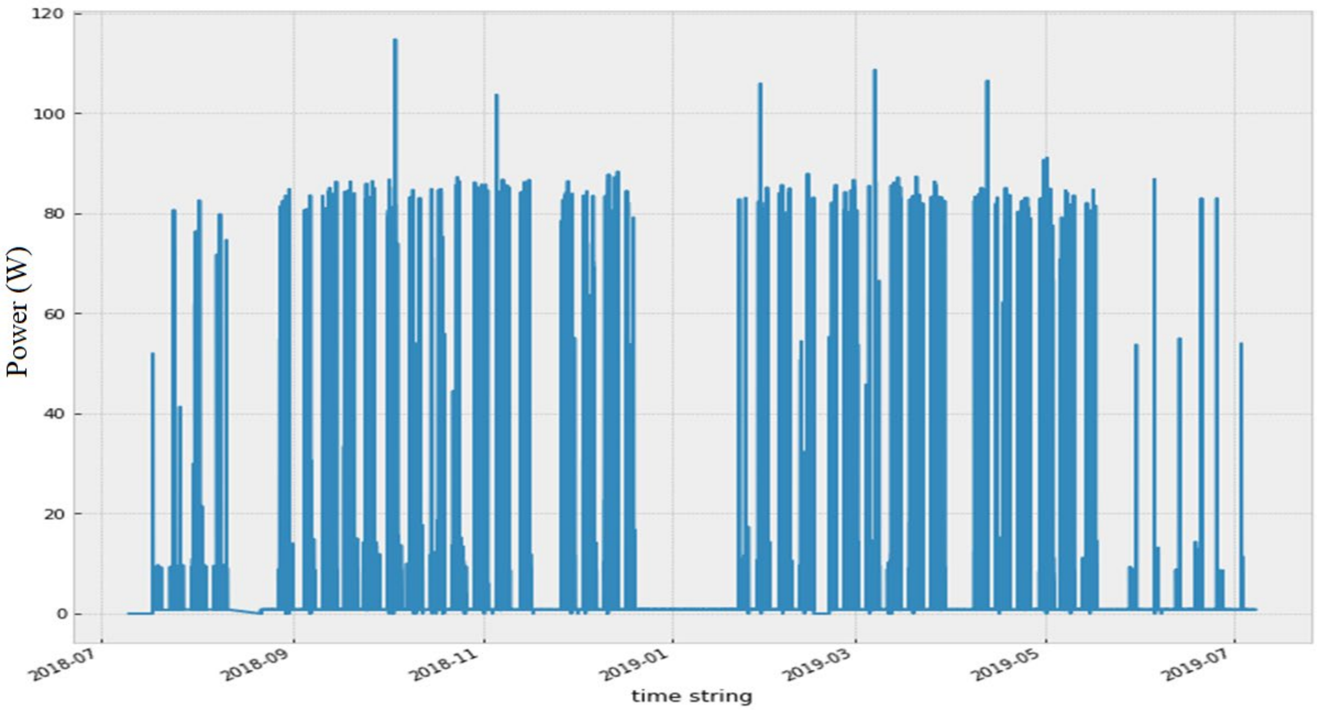
For areas away from the windows, a 45 percent dimming level resulted in an average 480 lux level that was ideal for visual comfort. For areas close to the windows, a 35 percent dimming level provided the same lux level. Therefore, on average one could save up to 0.4 kWh energy in each classroom while maintaining user comfort. The amount of saved energy in the hallways was about 0.6 kWh, indicating a huge potential for energy savings without sacrificing the user visual comfort. Moreover, all lighting fixtures were turned on and off as a group in each classroom, so granular control over the lighting can further improve energy savings since different spots require different light levels.

Analysis of Smart Plug Controller Data

Each installed Enlighted smart plug controller (that is, each power outlet) included two plugs: one conventional and the other managed based on occupancy. Analysis of the plug loads in this section focuses on their operation. Given that the building occupants had sole control over the choice to use the managed socket, there was no reason to investigate user comfort with respect to plug loads. Similarly, because the plug-in devices themselves had no impact on power quality, this aspect did not require additional investigation.

Thirty-eight smart plug controllers were installed. The locations, names, and power consumption of these smart plug controllers are available in a database on the Enlighted energy manager GUI webpage. Figure 62 presents the managed power of a single smart plug controller in room 308.

Figure 63: Manage Power of Smart Plug Controller in Room 308



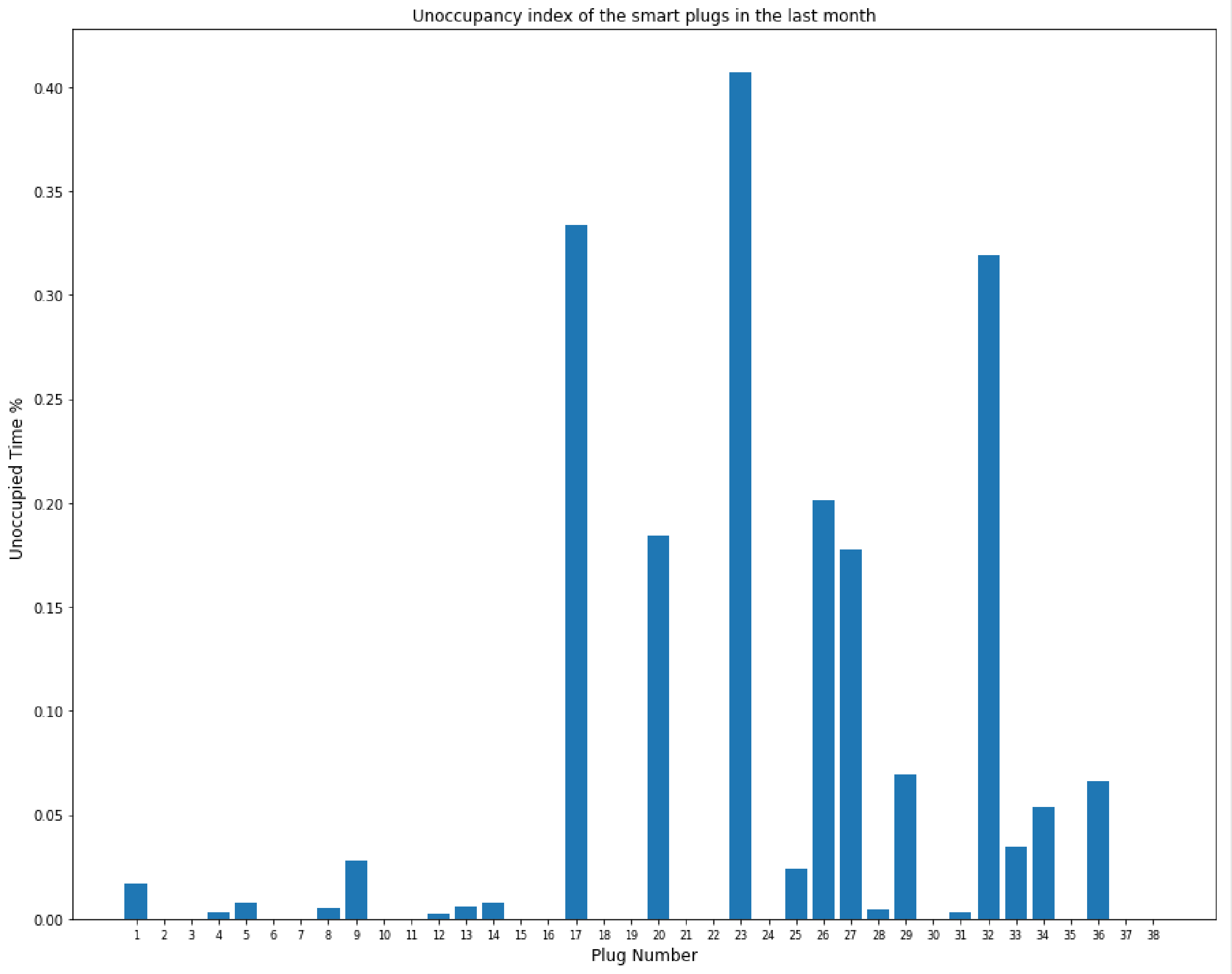
Source: California State University Long Beach

The first consideration when analyzing smart plug controller data is how much data and viable data (that is, the actual reading) is available for each plug. One can visualize this by using a step curve. For time intervals for which there is any data, if the data is the actual reading the researchers show a "1 or on" value and if the time period includes non-viable data (the device is connected, but it is not functioning properly and produces no reading) a "0 or off" value is shown.

Most of the smart plug controllers were active in the last 2 months of the year examined. Therefore, the project team focused its analysis on the final month of data (from 06/06/19 to 07/06/19). The result showed that during this period, only 16 smart plug controllers provided fully available data. This analysis also helped identify the reliability of each smart plug controller (the ratio of the actual readings to the total reported values during a month).

The second consideration was to identify how much time a room was reported as unoccupied at the times during which the smart plug controllers were actually reporting. Doing so provides the ratio of unoccupied to reading time (unoccupied time divided by total reading time) of each smart plug controller during the analysis period. Figure 64 shows the ratio of unoccupied time to available data, and shows that several of the low-availability smart plug controllers had a high index.

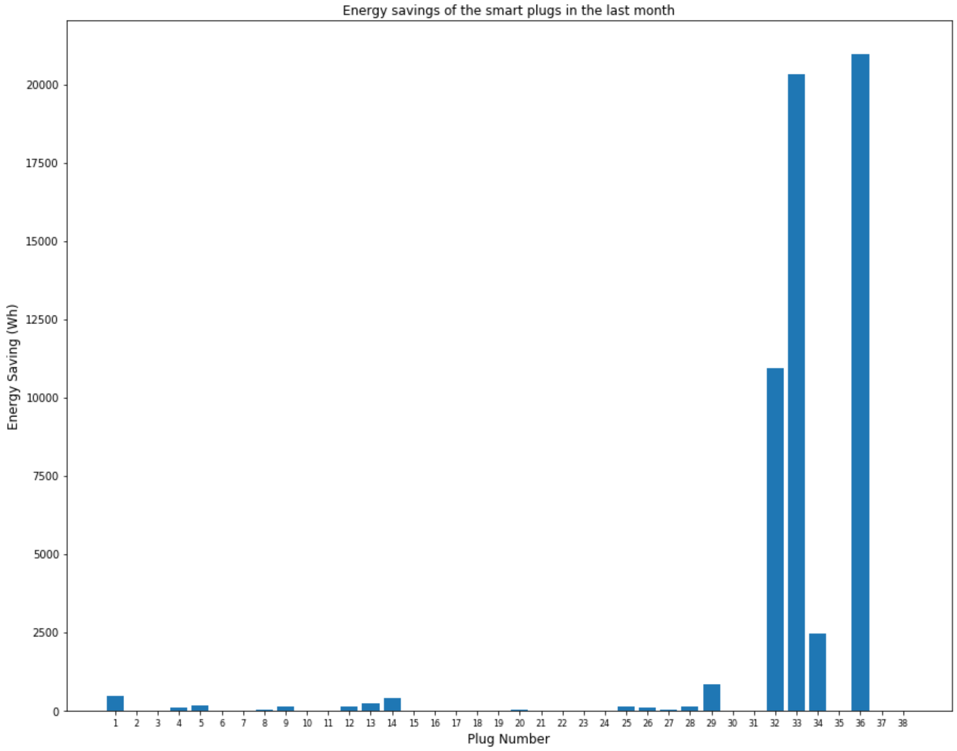
Figure 64: Occupancy Ratio for All Smart Plug Controllers



Source: California State University Long Beach

The last consideration was the amount of energy savings achieved by the smart plug controllers in 1 month (from 06/06/19 to 07/06/19). The total energy savings for all smart plug controllers during this period was 46.69 kWh (Figure 65).

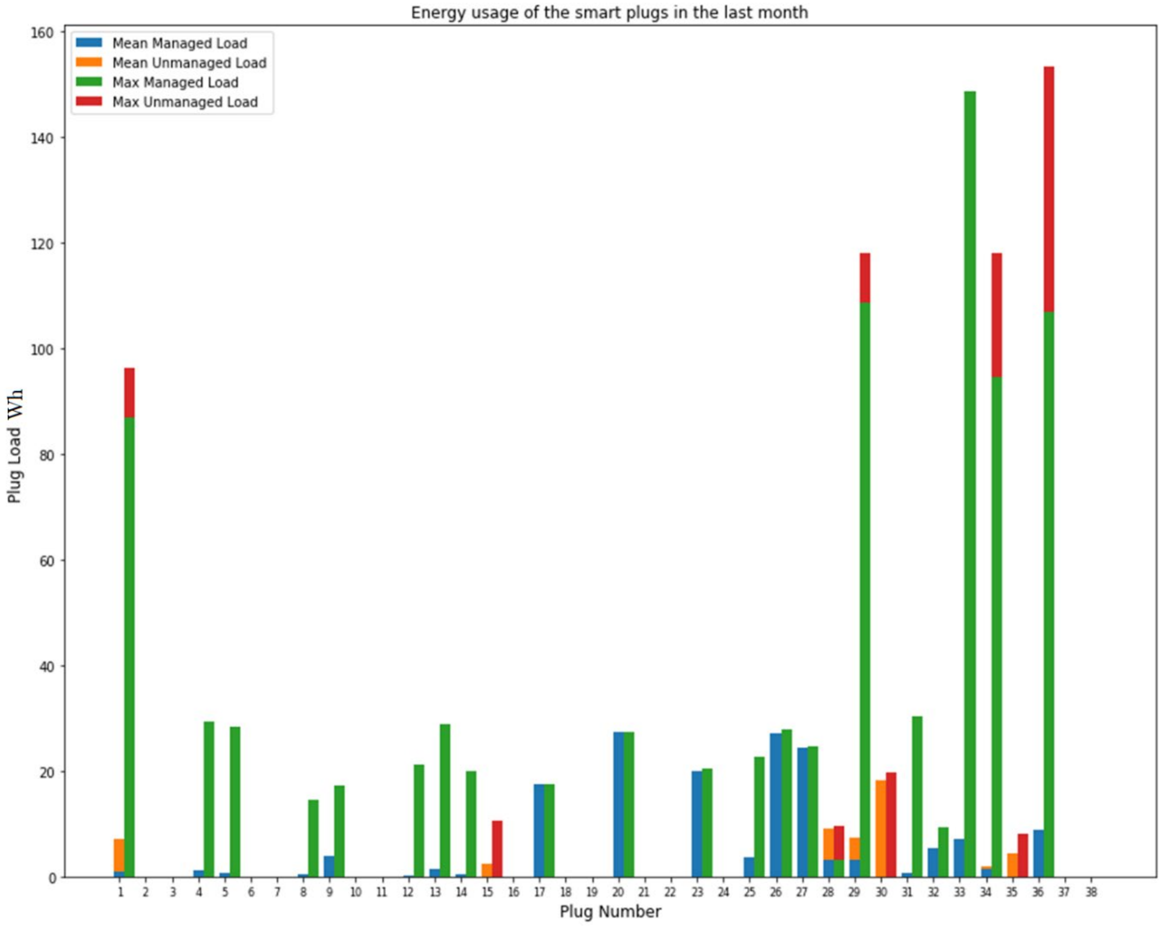
Figure 65: Energy Savings for All Smart Plug Controllers from 06/06/19 to 07/06/19



Source: California State University Long Beach

The energy savings of some smart plug controllers can be explained with respect to the reliability indices of the smart plug controllers. For example, smart plug controller number 1 had a high index but relatively low savings (Figure 66). This situation can be partially explained by noting the occupancy ratio. However, even for plug number 29 with high occupancy, the amount of the savings was not comparable. Thus, the UC Riverside team investigated the information on the connected load of the plugs for all smart plug controllers in 1 month. The result showed that for the smart plug controllers with the most savings, the managed load was utilized more.

Figure 66: Mean and Max Energy Usage of Smart Plug Controllers from 06/06/19 to 07/06/19



Source: California State University Long Beach

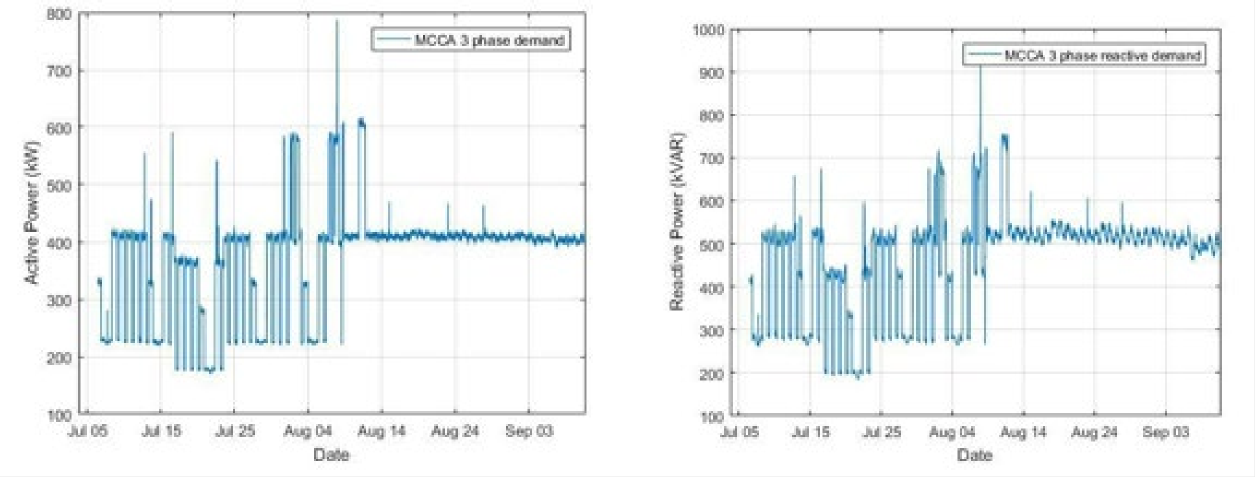
Analysis of Heating, Ventilation, and Air Conditioning System Data

Analyzing the data from the HVAC system, which integrated the new IoT-based EMS and the existing building systems and designs, was not straightforward. The electric demand of the ECS building related to the HVAC system was the load of the motors, pumps, and fans that are distributed across the building for AHU and VAV systems. Most of the chilled or heated water was supplied to the building from a central plant. Accordingly, the energy savings related to cooling was the combination of the savings of chilled/heated water and electric pumps/motors. Hence, measuring all HVAC loads accurately was not feasible for this building due to restrictions with the cost for metering.

The electric load measurements of the motors for each unit deployed at VAVs or AHUs was not available. However, the electric load of the HVAC system could be obtained indirectly because the load of all motors was sourced from certain circuits/switchboards. There were two switchboards specifically, MCCA and MCCC, that supplied the motor loads in the ECS building.

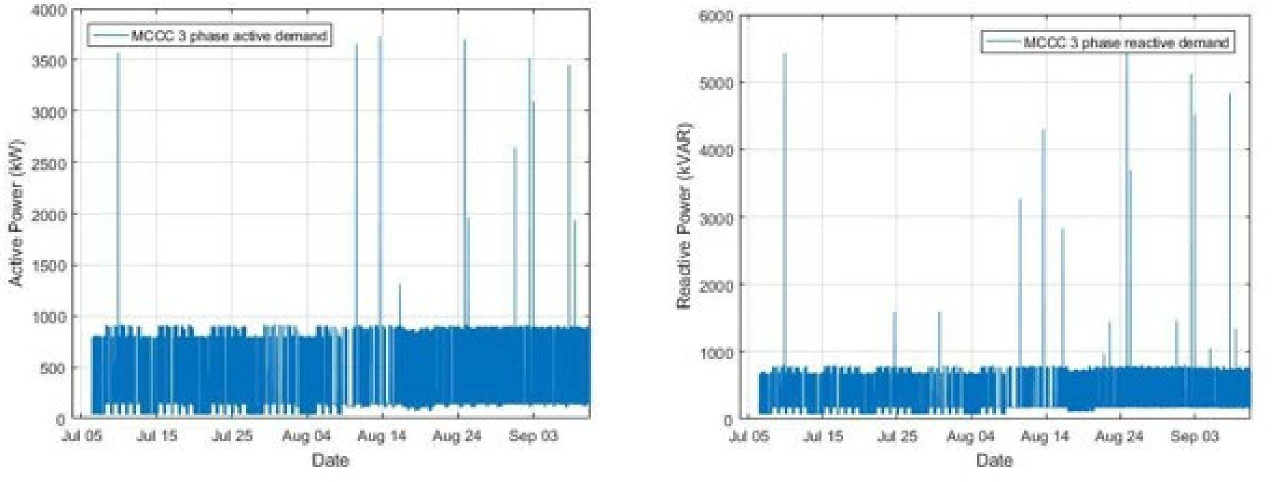
Energy information and measurements at the zone level of the HVAC system were not available except for the occupancy data presented earlier. Based on information from the VAVs deployed in the building including their types and characteristics, the measurements on MCCA and MCCC circuits were performed using high-resolution shark meters[1] and include per-phase voltage, current, active power, reactive power, apparent power, power factor, frequency, and so forth. From the measured variables, the active and reactive power demands of the circuits on the three-phase basis was of primary interest. Figures 67 and 68 show the active and reactive power across the motor loads of the HVAC system fans and pumps from July 2019 to September 2019 for the MCCA and MCCC circuits, respectively. The effect of frequent switching in the motors as a result of occupancy signals can be seen in the month of July in both figures.

Figure 67: Active (left) and Reactive (right) Power Measurement of Heating, Ventilation, and Air Conditioning Motor Loads on MCCA Circuit



Source: California State University Long Beach

Figure 68: Active (left) and Reactive (right) Power Measurement of Heating, Ventilation, and Air Conditioning Motor Loads on MCCC Circuit



Source: California State University Long Beach

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[1] Shark meter is an energy meter which provides high resolution data about the energy consumption of buildings.

One of the notable observations in the measurements was the high difference in power demand in the switching events. These switching events also appeared to affect the power quality, discussed in the next section. Finally, the occasionally high peaks in active and reactive power could be an indication of faults across the HVAC system. However, from the current measurements there was insufficient evidence to identify the source of these events.

Analysis of Power Quality

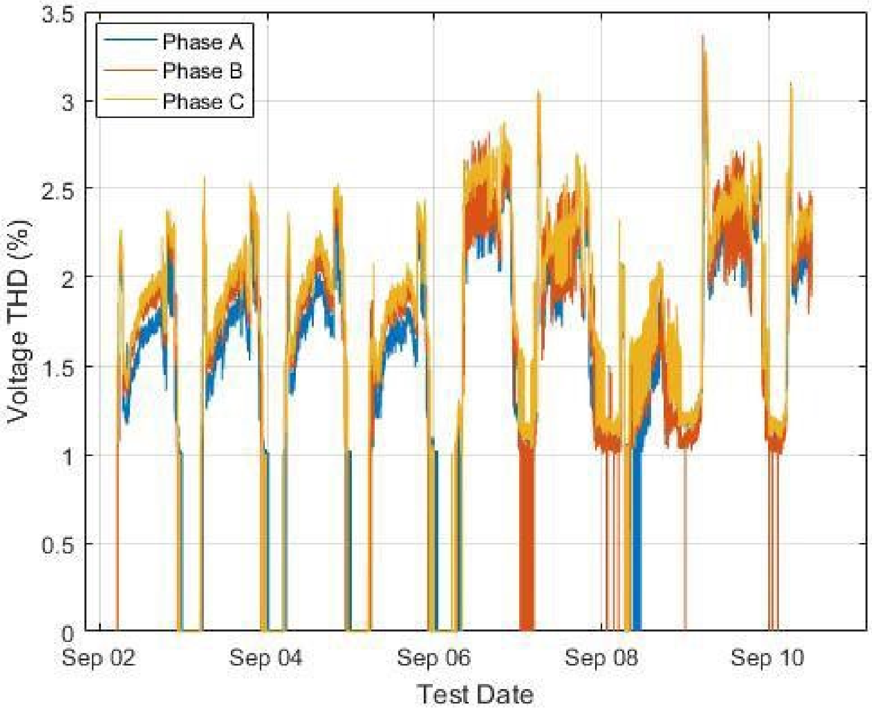
There are different parameters for evaluating power quality and each requires a specific type of meter. The typical parameters for power quality assessment include, voltage, voltage sags and swells, voltage total harmonic distortion (THD), voltage flicker, current, current THD, power factor, crest factor, and frequency.

Smart meters were connected to four distinct circuits of the ECS building including 10A, 10B, MCCA, and MCCC. Circuits 10A and 10B were for the whole building, while MCCA and MCCC corresponded to building motor loads. The high-resolution smart meters provided per minute readings on phase-to-neutral and phase-to-phase voltages, current, active power, and reactive power of the 3 phases. The meters also provided THD readings of each phase voltage in percent of nominal voltage.

Based on the time resolution of data (which was at least every 5-minutes), a power quality assessment based on voltage sags or flicker was not possible. Therefore, the UC Riverside Team’s analysis of the power quality relied mainly on the aspect of voltage and current THD.

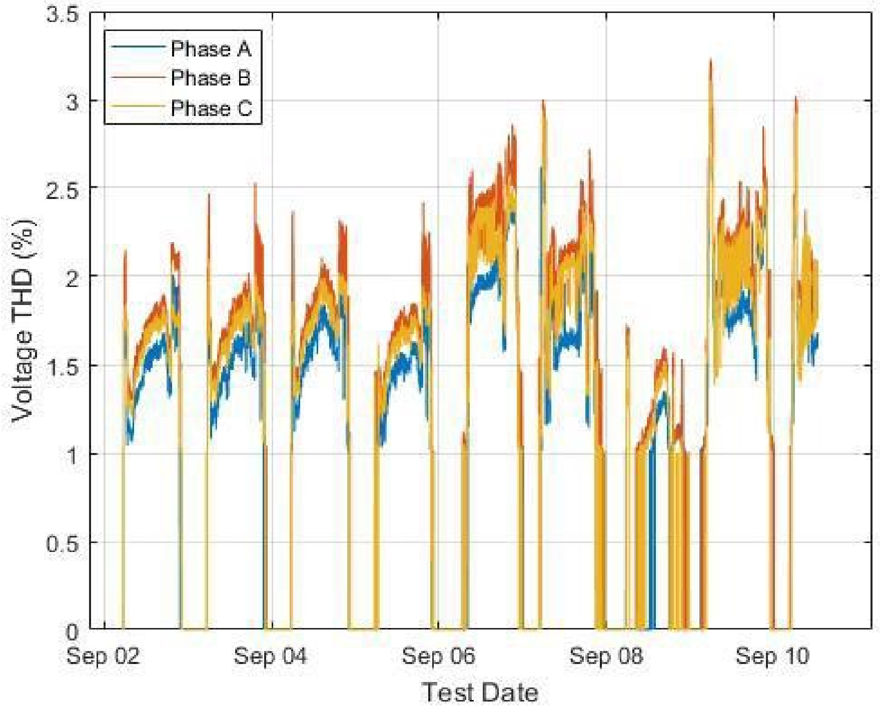
The team used IEEE power quality standards and NFPA 70B in its decision regarding the power quality of ECS building after installing the new systems. These standards suggest that for distribution networks, voltage THD should be less than 5 percent to avoid power quality issues. Figures 69 and 70 show examples of the voltage THD recordings for voltage on each phase from September 2, 2019 to September 10, 2019. As shown in the figures, voltage THD for these circuits was below 5 percent, which meant that power quality was satisfactory from the standpoint of voltage THD.

Figure 69: Example of Per-Phase Voltage Total Harmonic Distortion Measurement Readings on Circuit 10A



Source: California State University Long Beach

Figure 70: Example of Per-Phase Voltage Total Harmonic Distortion Measurement Readings on Circuit 10B



Source: California State University Long Beach

The average voltage THD for all 4 circuits (10A, 10B, MCCA, MCCB) is reported in Table 14. All values were below 5 percent, as suggested by the IEEE standard 519 for power quality, proving that the power quality of the ECS building after installing new systems was.

Table 15: Average voltage Total Harmonic Distortion for all 4 circuits

Circuit		Average Voltage THD
10A	Phase a	1.4088%
	Phase b	1.5657%
	Phase c	1.5068%
10B	Phase a	1.4827%
	Phase b	1.6068%
	Phase c	1.6501%
MCCA	Phase a	1.5021%
	Phase b	1.6709%
MCCC	Phase a	1.4299%
	Phase b	1.5930%

Source: California State University Long Beach

The correlation between lighting loads and voltage THD was 0.403, demonstrating a direct relationship among them; that is, increasing load caused an increase in voltage THD. Also, the correlation between lighting loads and current THD was 0.512, showing that increasing the load caused more distortion in current waveform. Thus, in cases where the current THD is not within the threshold suggested by the standard, better control over the lighting load might lead to an improvement in the current THD (power quality).

Additionally, the team investigated whether the occupancy sensor installation for the HVAC controller affected the power quality. The team compared the voltage THD before and after September 2019. The power quality data was only available for 10 days in September, and because by September classes have started at CSULB this comparison may not have been accurate. For September, the average voltage THD was 1.33 percent, while for August it was 1.35 percent, indicating a slight improvement in voltage THD.

Impact of Demand Response on Engineering and Computer Science Building Operation

Lighting System and Heating, Ventilation, and Air Conditioning System Demand Response Assessment

This section provides a detailed DR assessment of the lighting and HVAC systems done by the UC Riverside team. Since the analysis of DR assessment for the lighting system was discussed previously in this report, this section focuses on the analysis of the performance and capability of the HVAC system during DR. Because there were few smart plug controllers installed in the ECS building, the plug load system of ECS building was not included in any DR program due to the system's low contribution in reducing power consumption.

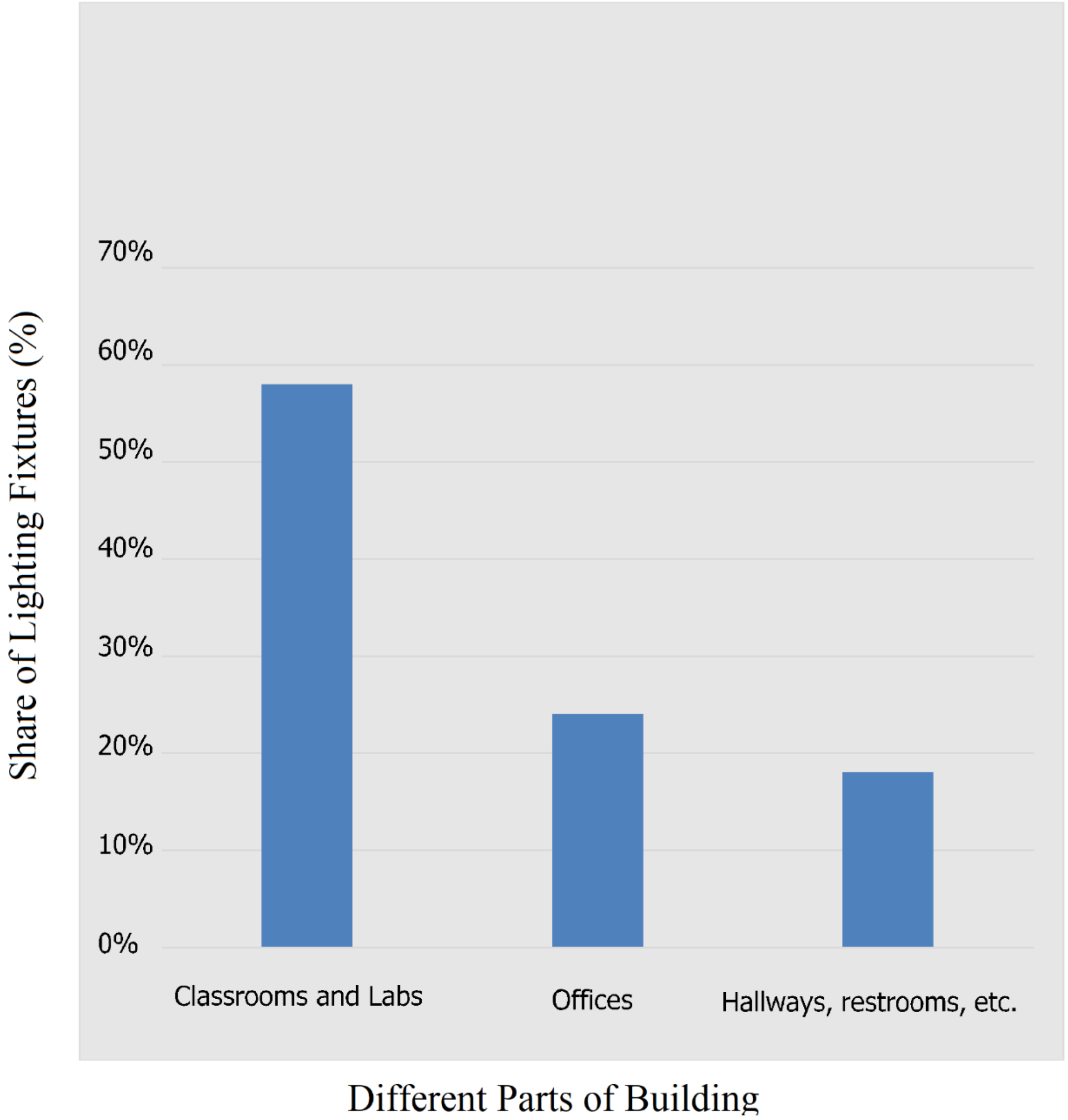
Integrating DR capabilities into the energy management strategy assured that building energy was fully optimized and monetized and integrated the HVAC and the lighting system under a single management system. This integration allowed the system to respond more quickly to energy demand. The lighting system was able to deliver a faster load reduction compared to the HVAC system, which by itself tends to be sluggish and exhibit an extensive time lag between changes made to the HVAC setting and the desired result. Attempting to aggressively respond to a load shedding or demand event using only HVAC may result in an uncomfortable building environment and could possibly incur peak charges. Thus, the new BMS, integrated with the Enlighted's BACnet network, sensor devices, and existing BMS, allowed the HVAC system to achieve any major load adjustment and the lighting network to deliver fine tuning to accomplish optimal demand response.

The new IoT-based building energy management system (including the new lighting and HVAC systems) significantly increased the flexible capacity of the ECS building that can be used in DR programs. According to the field measurements of the DR tests and the results that we presented earlier, the lighting and HVAC systems can provide roughly between 80 kW to 150 kW flexibility during DR events depending on occupancy conditions and outside temperature.

Energy Curtailment to Support Demand Response

Three critical factors determine how much energy is consumed in the lighting sector: the type of the lamp and control, the luminance, and the architecture of the room. In the ECS building, the nominal power of the lighting fixtures for default dimming level (65 percent) was 30W to 35W. When the dimming level was reduced to 35 percent, the power consumption of lighting fixtures was lowered to 15W 20W. So, with every 5 percent decrement in dimming level for each lighting fixture, one can save approximately 3W of power. The share of different parts of the building from the lighting fixtures is plotted in Figure 72. The researchers assumed the sky condition was either sunny or overcast. Based on the previous research, the team assumed that for the overcast condition, the luminance would be decreased by 10-20 percent compared to the sunny sky condition. Based on the tests that were taken in summer and winter, the research team assumed that luminance during fall and winter was 15 percent to 25 percent less than during the spring and summer seasons for a sunny sky condition under the same electric light dimming level. Since the majority of ADRM programs are planned to be run during afternoon and evening, this report does not further discuss the early morning condition.

Figure 71: Share of Each Part of Building from Lighting Fixtures



Source: California State University Long Beach

Different control strategies for the lighting system provide different possible energy reductions. The researchers considered four control strategies including:

- Strategy 1: Uniformly control lighting fixtures for all rooms and hallways. This strategy used uniform control over all lighting fixtures in the building. Although luminance was different in various rooms and even various spots in a room, the researchers used average luminance level (250-350 lux) for the whole building.

- Strategy 2: Categorize lighting fixtures into two types (fixtures in rooms and fixtures in hallways and restrooms). Lighting fixtures were separated into these categories and control strategy was defined for each category. For fixtures in rooms, the same threshold for visual comfort level was used as in strategy 1. For fixtures in hallways and restrooms, a lower average luminance level of 50-150 lux was used.
- Strategy 3: Group rooms at each side of the buildings and control lighting fixtures for each zone. Rooms of the ECS building were separated into different groups according to the side of the building, and uniform controls over dimming level for each group were defined. Lighting fixtures in hallways and restrooms had the same control strategy. Rooms that located on the side that received higher sunshine would have a lower average luminance level for the control strategy, and those located on the side with less sunshine would have a higher average luminance level.
- Strategy 4: Fully personalized control over the lighting fixtures in every room. A fully decentralized control for lighting fixtures for every room was defined and the ambient light based on the preference of occupants was personalized. The complexity of control for this strategy was much higher than for the other strategies. The assessment of energy reduction of this control strategy required a thorough analysis on the preferences of all occupants on the light setting, which was impossible due to the limitations of the project, so the result was based on the prediction that this control strategy would provide a 20-25 percent lower reduction compared to strategy 3.

Table 16 summarizes results for the four types of light level control strategy. In terms of energy reduction, strategy 2 yielded the highest reduction. Although strategy 4 was the lowest in energy ranking, it had the best performance in terms of visual comfort score level and had the highest complexity level among the discussed strategies.

Table 16: Comparison of Control Strategy Performance (Whole Building)

Control Strategy	Yearly possible reduction in energy during Weekdays (MWh)	Average Visual Comfort Score	Complexity Level
1	18.28	2.85	Low
2	21.51	2.85	Moderate
3	19.35	1.86	High
4	Nearly 15	Nearly 1	Extremely high

Source: California State University Long Beach

Potential Demand Response Program Evaluation

Southern California Edison offers a range of DR programs with different incentives. The benefits for businesses participating in these programs include receiving discounted rates, incentives, or bill credits as well as advanced notification of a DR event which helps to mitigate the impact of the event on building operation. There are two types of suitable DR programs: critical peak pricing (CPP) and real-time pricing (RTP).

In CPP, a participant would receive monthly bill credits from June through September when energy usage is reduced during a DR event. The reduced rate of energy from June through September is significantly lower than the 12-month total. CPP is a 12-month program in which commitment and events may be called year-round on any nonholiday weekday from 4 p.m. to 9 p.m. and are limited to 12 events per year. There is no penalty in this program, but energy rates are significantly higher during CPP events. CPP is an optional rate that offers a discount on summer electricity rates in exchange for higher prices during 12 CPP event days per year. CPP events are sent one day ahead, so that participant can plan accordingly.

For precise evaluation of participating in a CPP program, one needs to know the details of the incentive. Based on the analysis in the previous section, the amount of possible energy reduction in the lighting sector during a summer season weekday from 4 p.m. to 9 p.m. was about 90 kWh while the visual comfort level of occupants was maintained. However, the energy price during a CPP event is about 4 times higher than normal condition, which means that the energy consumption for HVAC, reduced lighting, and other types of load in the building that cannot be shut down during the CPP event would cost four times more. Therefore, an exact evaluation must be performed to determine whether the total of credited bills and savings in the lighting load during the CPP event is still higher than the cost of energy for the rest of the loads. Such assessment requires knowledge about the details of the CPP program, how the building is credited, and the details for the other types of load in the building. Due to the high energy rates during the CPP events, one could end up either paying more for energy or curtailing the visual comfort of occupants. Therefore, another DR program which gives higher flexibility over the load scheduling would be more suitable.

In RTP, a participant can lower its energy costs by reducing energy usage during hours with higher temperature-driven prices or shift usage to lower-priced hours. In this program, a participant has the flexibility to manage the load because of the hourly energy rates and no minimum reduction in energy is needed. Like the CPP, there is a 12-month program commitment and there is no penalty. The pricing mechanism in this program is based on the time of day, season, and temperature.

There are seven different pricing schedules for RTP: three different pricing schedules during the summer season (hot summer weekdays > 91˚F, medium summer weekday 81˚F – 90˚F, and mild summer weekday < 80˚F), two during the winter season (high-cost winter weekday > 90˚F and low-cost winter < 90˚F), and two which apply on all weekends throughout the year (high-cost weekend > 78˚F and low-cost weekend < 78˚F). RTP varies 24 hours a day, seven days a week with hourly rates based on the time of day, season, and temperature. Participating RTP customers have an opportunity to benefit from lower energy costs every day throughout the year.

The cost per kWh of energy varies based on time of day, time of year, weekday or weekend, and daily maximum temperature. Again, exact evaluation of cost-benefit for this DR program requires information about the RTP rates during the year to make a fair comparison. However, based on the four discussed controlling strategies, which gives the flexibility to reduce the energy consumption in lighting sector, it can be concluded that RTP is a more suitable DR program for the building to participate in compared to the CPP.

Overall Costs and Benefits Analysis

This section assesses the cost and benefits of the project for building operations occupants and equipment. The goal is to assess: 1) the energy efficiency of the project; 2) the economic benefits of control systems for lighting, HVAC, and plug-in loads; 3) the cost of control systems for lighting, HVAC, and plug-in loads; and 4) the project benefits to the investor-owned utilities.

Energy Efficiency Assessment

Electric energy efficiency and savings are assessed with respect to two main aspects at the ECS building: 1) improvements in the load profile (that is load leveling, peak reduction); and 2) reduction in electrical energy consumption at the building level. Also, the thermal heating energy savings are estimated by analyzing the hot water data delivered from the campus central plant.

Lighting, plug-in loads, and HVAC loads are the three main building systems that were analyzed. To analyze the efficiency of the Enlighted EMS in reducing overall electric energy consumption at the ECS building, data covering a full academic year was used. Considering data availability based on the installation and implementation of the Enlighted EMS, as well as the closure of the entire campus and the ECS building due to the COVID-19 pandemic, the analysis and energy efficiency assessment was performed by using full-year data from January 1, 2019 to December 31, 2019. Also, for the HVAC system analysis, the shark meter data from March 10, 2019 to August 8, 2019 was used as the preinstallation period, while data from August 9, 2019 to October 11, 2019 was used for the post-implementation period.

Load Profile Analysis

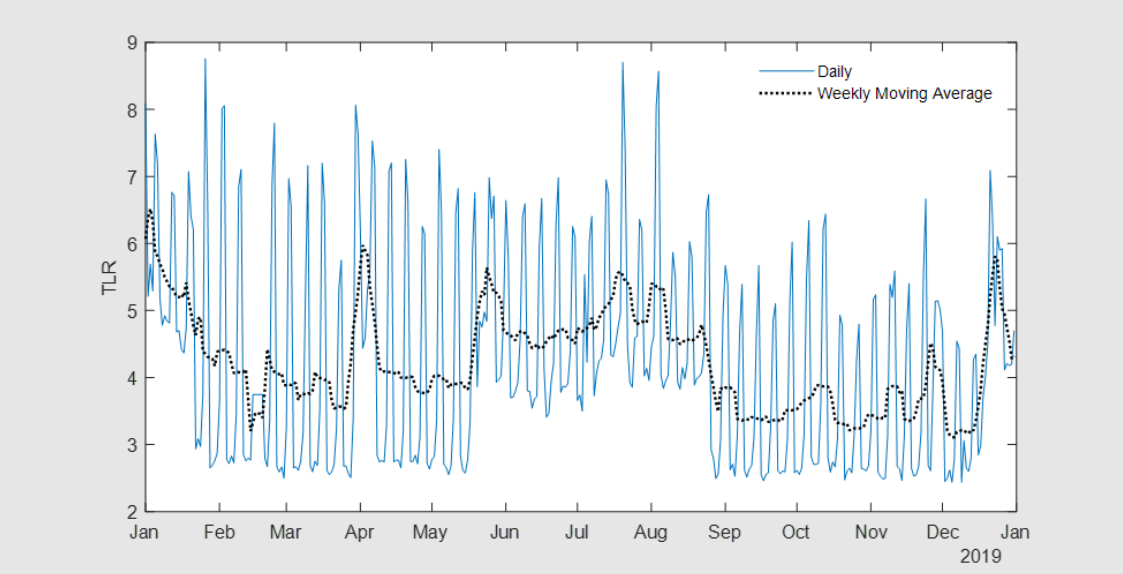
Two indices were defined for the load profile analysis: total load ratio (TLR) and peak load ratio (PLR). These indices represent the load profile comparison for the pre- and post-implementation of the EMS and are described as follows:

$$\begin{aligned} TLR &= \frac{Total\ Daily\ Load\ of\ Building\ Before\ EMS\ Implementation}{Total\ Daily\ Load\ of\ the\ Building\ After\ EMS\ Implementation} \\ PLR &= \frac{Peak\ Daily\ Load\ of\ Building\ Before\ EMS\ Implementation}{Peak\ Daily\ Load\ of\ the\ Building\ After\ EMS\ Implementation} \end{aligned} \tag{6}$$

The load ratios were used to identify possible seasonal effects, as well as to compare weekdays versus weekends and holidays. If the load profile had a *TLR* or *PLR* greater than one, then the EMS was achieving energy savings.

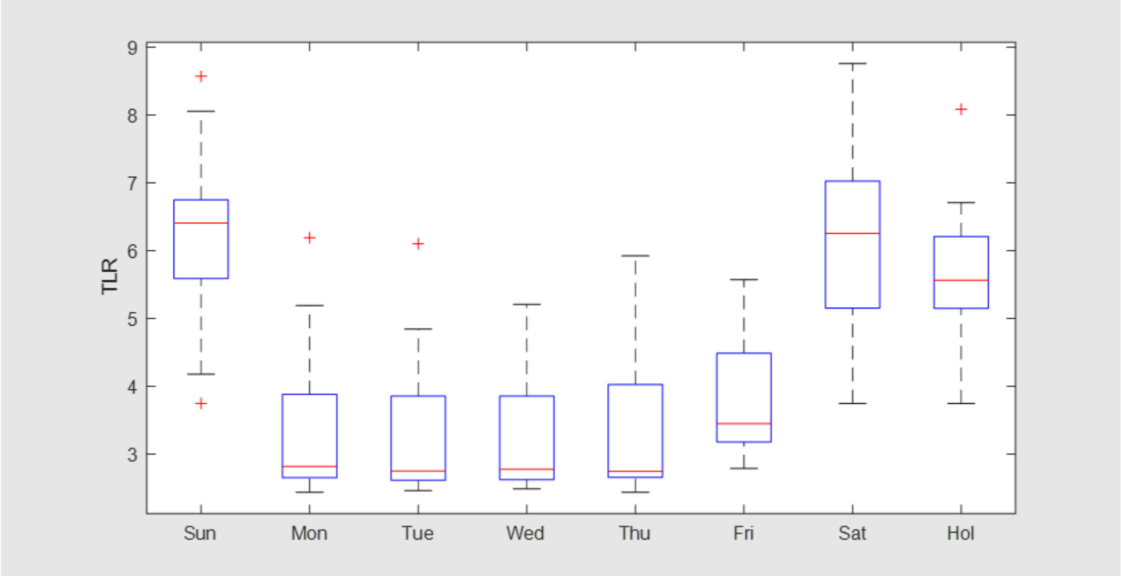
Using the TLR and PLR indices for the combined lighting and plug-in load components (respectively) allows comparison with EMS pre- and post-implementation data measured and recorded by the Enlighted system. Seasonal and daily patterns are shown in Figures 73 and 74, respectively. Due to the occupancy and activity sensors in the ECS building, most smart lighting and plug-in loads were turned off during breaks. As shown in Figure 73, a higher *TLR* was observed during academic breaks, including from January 10-21, April 1-7, May 25-August 16, and December 25–31. Figure 74 is a box plot showing weekdays versus weekends and holidays.

Figure 72: Total Load Ratio Seasonal Pattern



Source: California State University Long Beach

Figure 73: Total Load Ratio Weekdays versus Weekends and Holidays Pattern



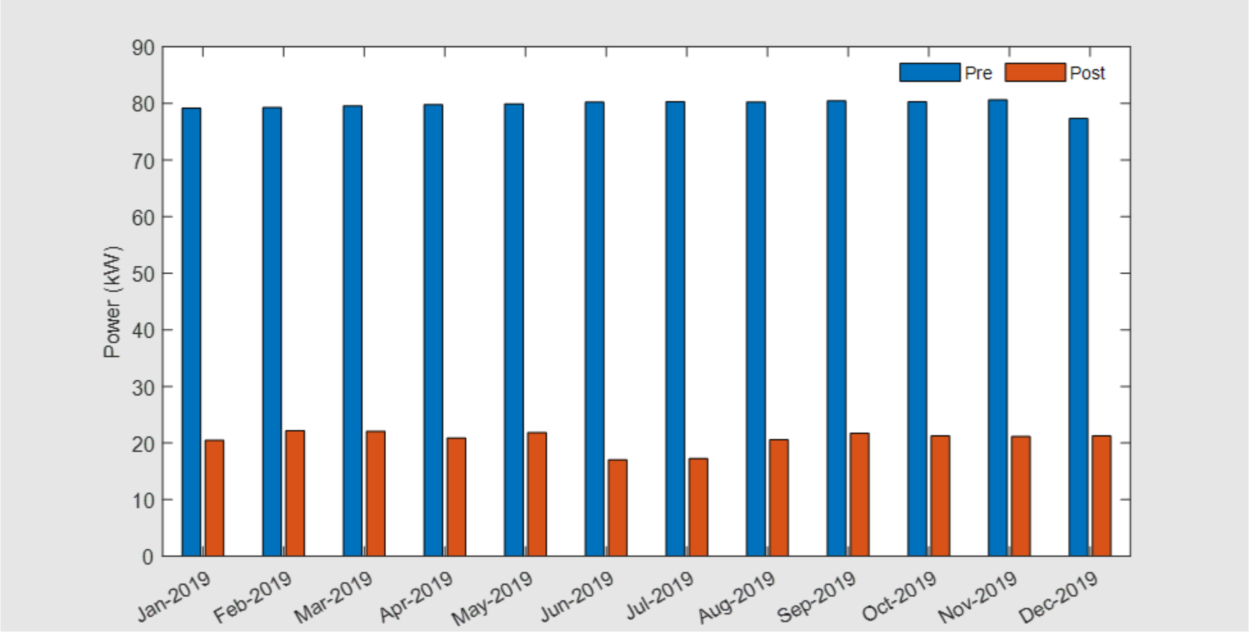
Source: California State University Long Beach

In Figure 74, the lines within the boxes indicate the median data value for each day group. The bottom and top edges of the box, known as the interquartile range, indicate the 25th and 75th percentiles, respectively. The black "whiskers" extend to the most extreme data points not considered outliers, while outliers are plotted individually using a '+' symbol. Outliers are defined as values that were more than 1.5 times away from the interquartile range. A similar pattern is observed in Figure 74, where on weekends and holidays the *TLR* was normally higher than weekdays, attributed to a reduced activity level at the ECS building during this type of days. For weekdays, the median of the *TLR* was similar from Monday to Thursday, but slightly higher on Fridays, attributed to fewer classes being held on Fridays, and consequently fewer students being in the ECS building.

Similar patterns for PLR as observed for TLR were also obtained.

Figure 75 shows the 15-minute interval data for the monthly peak demand of the combined lighting and plug-in loads pre- (baseline loads) and post-implementation (actual loads) of the EMS. The measured monthly average peak reduction was 59.11 kW/month. A maximum peak reduction of 63.18 kW was observed in June, with a minimal reduction of 56.06 kW in December.

Figure 74: Monthly Peak Load Comparison for Lighting and Plug-In Loads



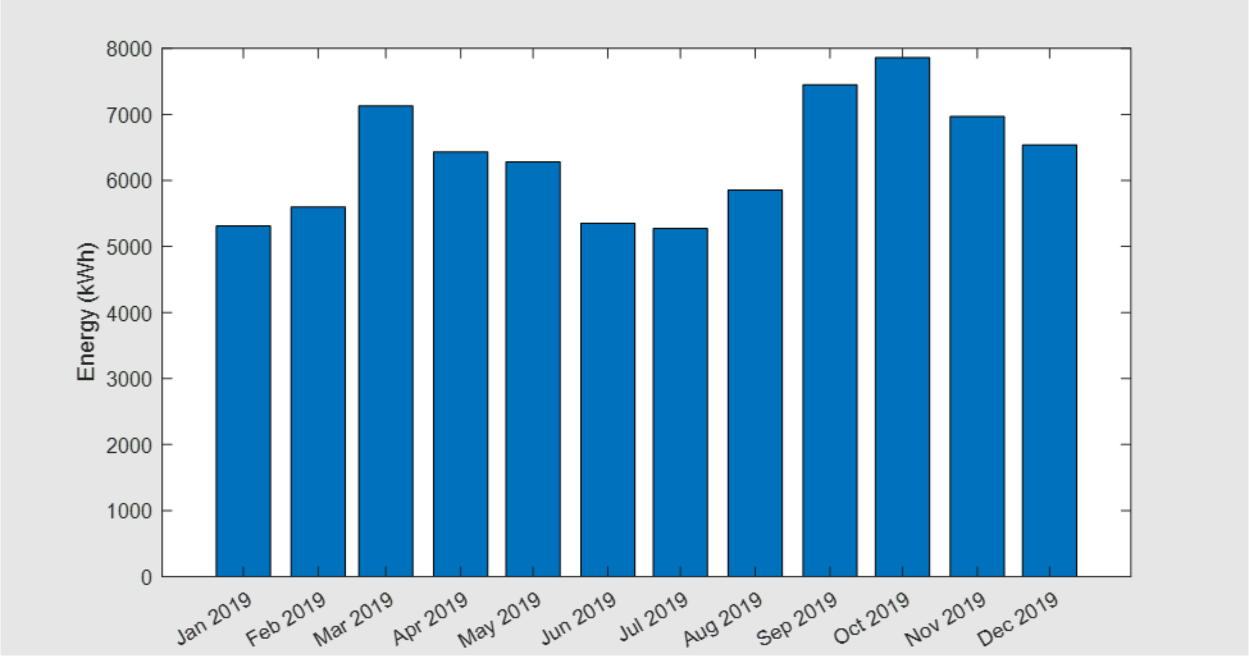
Source: California State University Long Beach

In addition, the ECS building's HVAC system was served by a total of 7 air handlers. The air-handling units were served by chilled water from the central plant, while a local refrigeration compressor/ice storage system provided chilled water when the central plant could not meet the load. Based on 15-minute interval data, the HVAC load cycles swung between 5 kWh and 17 kWh. This cycling shows that the HVAC system could to reduce load by 48 kW on a monthly basis.

Electricity Consumption and Thermal Energy Saving Analysis

In the Enlighted EMS lighting system, energy savings can be achieved via three energy conservation schemes: occupancy savings, task-tuning savings, and daylight harvesting savings. Figure 76 shows the monthly energy usage for the lighting system in the ECS building. The yearly lighting electricity usage was 76,047 kWh.

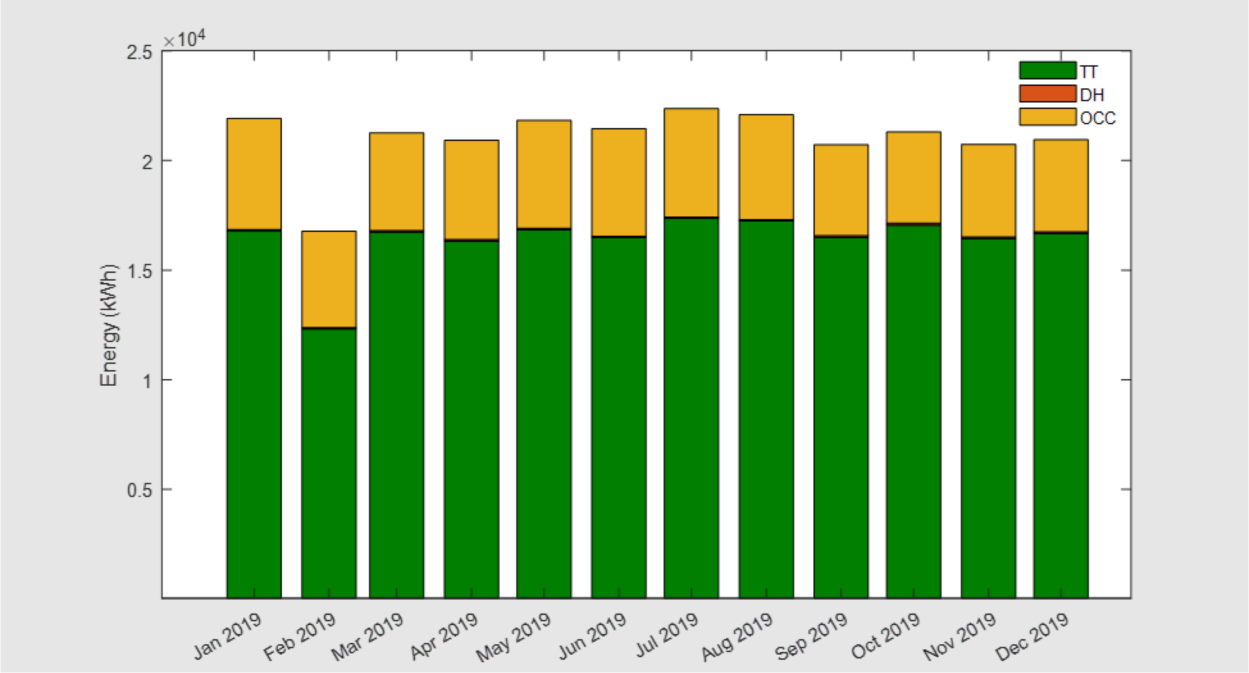
Figure 75: Monthly Lighting Loads Energy Consumption



Source: California State University Long Beach

Figure 77 shows the breakdown of the energy savings achieved through the three savings schemes for lighting loads implemented via the Enlighted system. The yearly savings for occupancy, task-tuning, and daylight harvesting were 54,817 kWh, 196,761 kWh, and 812 kWh, respectively. The total electricity savings for the lighting system was 252,390 kWh. Comparing the pre- versus the post-implementation of the Enlighted EMS system, the energy consumption by the controlled lighting devices was reduced by 76.85 percent.

Figure 76: Breakdown of Monthly Energy Savings Based on Lighting Control Schemes

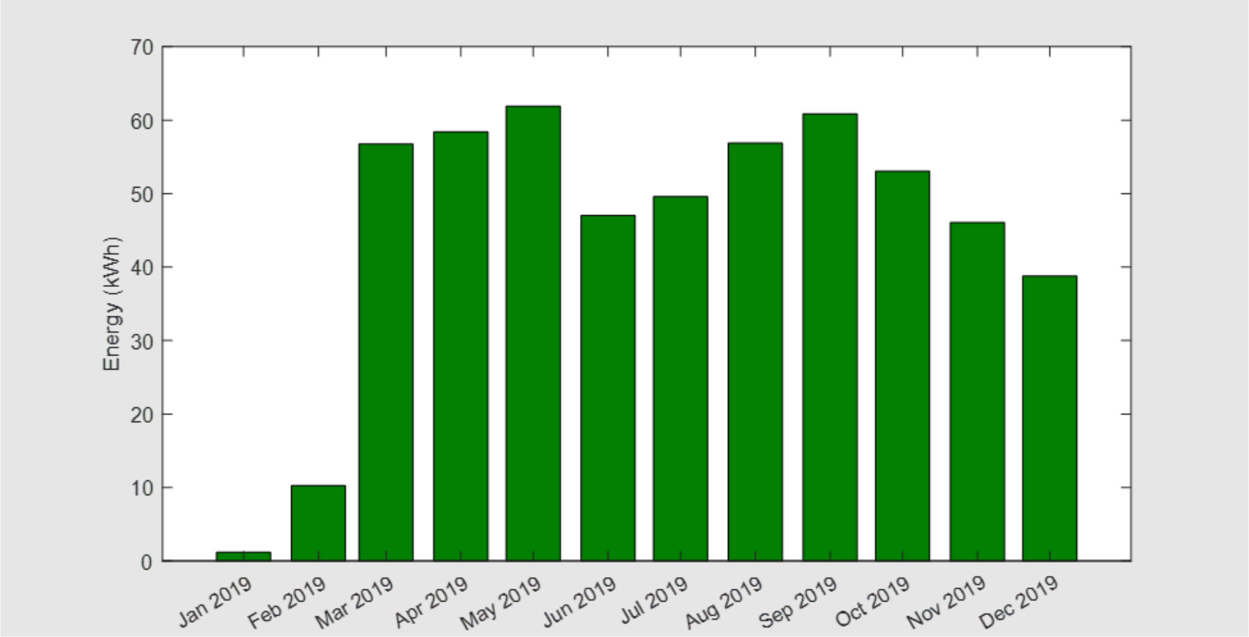


Source: California State University Long Beach

About 30 Enlighted plug load controllers were installed to control noncritical loads in the ECS building like overhead projectors and printers in classrooms and laboratories. The controlled plug-in load electricity consumption for 2019 was 3,108 kWh.

Figure 78 shows the monthly savings achieved by using occupancy data through the Enlighted EMS. The total yearly energy savings was 541 kWh. Comparing these savings to the system without smart controllers for the controlled plug-in loads, an energy consumption reduction of 14.83 percent was achieved.

Figure 77: Monthly Energy Savings of Plug-In Load Controllers



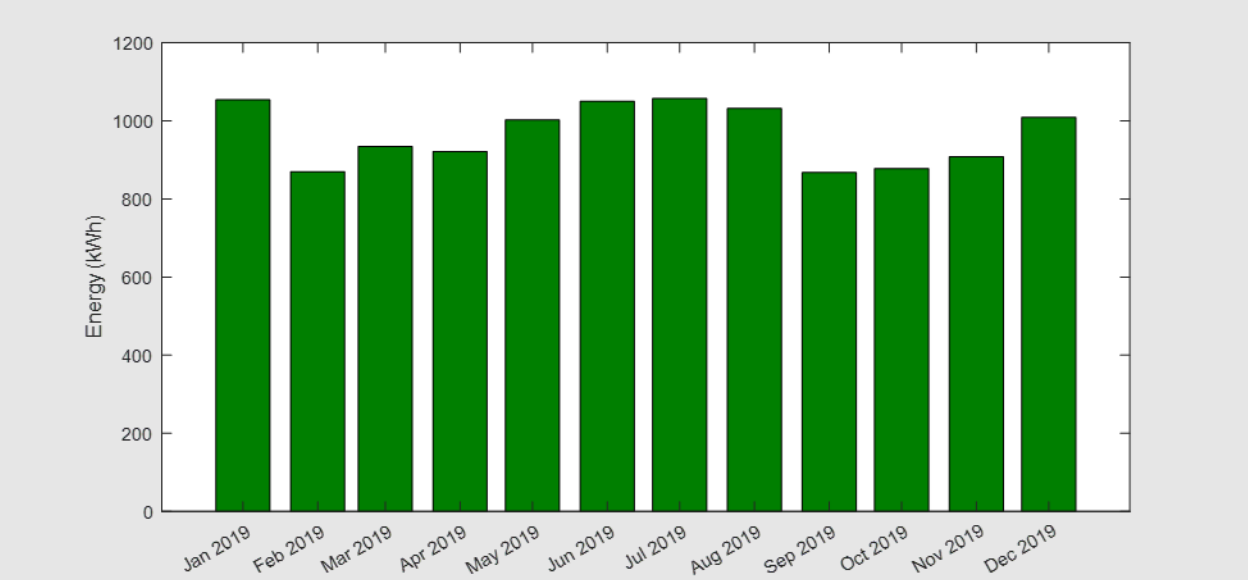
Source: California State University Long Beach

The ECS building's new HVAC system, by relaxing the cooling and heating setpoint of the unoccupied HVAC zones by 2˚F, reduced daily average HVAC energy consumption by 37.8 kWh (from 183.1 kWh to 145.3 kWh for the whole building). The monthly consumption reduction (MCR) potential was be calculated as:

$$MCR_{month} = 37.8 \times (1 - AverageOccpancy_{month}) \times Days_{month} \quad (7)$$

Figure 79 shows the monthly energy savings potential for the HVAC system. A yearly HVAC energy savings potential of 11,585 kWh was calculated. Comparing these savings to the preinstallation HVAC estimated energy consumption of 290,000 kWh, the calculated energy savings post-implementation of the Enlighted EMS represents an energy consumption reduction of 3.99 percent.

Figure 78: Heating, Ventilation, and Air Conditioning System Monthly Energy Savings Potential



Source: California State University Long Beach

Thermal energy savings was another main aspect of the project that was analyzed. Heating energy to the ECS building was provided by hot water delivered from the campus central plant. The thermal energy dissipated to the ECS building was measured by taking the temperature difference of incoming hot water versus returning hot water, multiplied by the water flow rate.

As show in Table 17, pre-implementation energy use data was recorded for May, June, and July in 2019, while post-implementation data was captured for October, November, and December of 2019 and January and February of 2020. To account for the seasonal fluctuation of natural gas consumption for heating during the spring/summer months and the fall/winter months, the total natural gas consumption data at the central plant was used to normalize post-implementation energy use data at the ECS building. This was accomplished by using the ratio of pre-implementation to post-implementation period natural gas use at the central plant and applying it to the post-implementation period thermal energy use data at the ECS building. Based on this methodology the pre- and post-implementation thermal energy use for heating were calculated to be 3,502,808 kBTU (35,036 therms; 1,026,572 kWh) and 3,060,754 kBTU (30,615 therms; 897,018 kWh), respectively.

Table 17: Thermal Energy Savings for Engineering and Computer Science Building

Period	Month	Total kBTU	Number of Days	Adjusted kBTU	CSULB NG Use (CF)	Normalized Adjusted kBTU	Savings %
Pre	May-19	233,108	31	233,108	3,929,940	233,108	
Pre	Jun-19	189,982	30	189,982	2,312,000	189,982	
Pre	Jul-19	165,933	31	165,933	1,900,050	165,933	
Post	Oct-19	193,530	28	214,265	1,193,900	245,211	12.62
Post	Nov-19	269,111	30	269,111	4,717,860	307,978	12.62
Post	Dec-19	281,175	26	335,247	5,739,290	383,666	12.62
Post	Jan-20	300,318	30	310,329	6,263,790	355,149	12.62
Post	Feb-20	213,518	20	298,925	4,673,120	342,098	12.62

Source: California State University Long Beach

The heating thermal energy savings due to the implemented HVAC operational changes were estimated at 12.62 percent, translating to 442,054 kBTU annually, or 4,422 therms. Note that the project also resulted in thermal energy savings for cooling, but due to the lack of data the researchers could not estimate these thermal savings.

The total yearly calculated reduction in electrical energy consumption of the whole building was 23.41 percent. Table 18 shows the actual calculated electrical energy savings for each component type. This result validated that the ECS building achieved the target of reducing energy consumption by more than 20 percent.

Table 18: Measured Energy Management System Pre- and Post-Implementation Energy Consumption and Savings

Building Loads	Pre-EMS Energy Consumption (kWh)	Post-EMS Energy Consumption (kWh)	Achieved Energy Savings Percent	Individual Saving Contribution Percent
Lights	350,000	97,610	72.11%	95.42%
Plug-in Loads	490,000	489,459	0.11%	0.20%
HVAC Units	290,000	278,415	3.99%	4.38%

Source: California State University Long Beach

The total annual electricity energy savings were 252,390 kWh, 541 kWh and 11,585 kWh from lighting, plug-in loads, and HVAC respectively, while the monthly demand average peak reduction was 107.11 kW. According to the TOU-8-D-CPP electric tariff, the weighted average energy cost was $0.0836/kWh, resulting in an annual benefit of $22,114 in energy savings.

Furthermore, according to the same tariff, monthly facility demand charges were set at $14.66/kW, while the weighted average time-of-use demand charges were estimated at $16.83/kW. Thus, the peak demand reduction associated with the project generated $40,475 in demand savings per year. Participation in a DR program, such as CPP, assuming a demand peak reduction of 98 kW and 12 DR events per year, can generate an additional annual benefit of $10,012.

As mentioned previously, annual thermal heat energy savings was 442,054 kBTU due to the implementation of new HVAC system. Based on the average commercial price of natural gas in California for 2020 of $9.71/thousand cubic feet, the estimated annual thermal savings translated to $4,208 in savings.

Thus, the combined financial project benefits amount to $76,809. Considering a useful life span of the installed system of 15 years and a conservative energy cost escalation rate of 1 percent per year, the estimated project benefit over 15 years would be $1,236,386.

Cost and Benefit Analysis

Cost Analysis

The project cost was assessed for three aspects: equipment and software cost, equipment installation cost, and maintenance and operation cost.

The cost of the equipment and software account for developmental costs involved in the (1) design and engineering, (2) procurement of components, (3) fabrication, (4) research and development, (5) marketing, and (6) profit. The cost for the WiFi network communication was based on the procurement of standard off-the-shelf network solutions. The equipment costs are listed in Table 19.

Table 19: Equipment and Software Costs

Hardware and Software Component	Cost
Lights, temp/occupancy/light sensors, plug load controllers and actuators	$245,098
Gate way	$40,290
Control panel and EMS	$33,575
Software License	$16,788
Communication hardware and software	$10,975
Meters to measure HVAC energy usage	$8,149
HVAC equipment for controlling exhaust fan speed	$3,080
Subtotal =	$357,954

Source: California State University Long Beach

The equipment costs represent an upfront cost to customers. The server and platform are fixed costs, while the cost for the elements and network communication depends on the number of sensors that are connected to a single element and the total number of elements deployed as part of the CSULB solution.

Table 20 shows a breakdown of the installation costs associated with the deployment and setup of the equipment and Table 21 shows the maintenance and operational costs associated with the operation and support of the system.

Table 20: System Installation Costs

Installation Cost Component	Description	Cost
Electrical Subcontractor	Preparation of set of plans, physical installation of hardware, electrical connections	$47,629
On-site Facility Personnel	Facilitation, supervision, and access	$78,107
Balance of Systems	Hardware, supplies, materials & miscellaneous	$20,413
System Implementation	System wide implementation of Enlighted and Control Works solutions	$292,143
Subtotal		$438,292

Source: California State University Long Beach

Table 21: Maintenance and Operational Costs

M&O Cost	Description	Cost
Yearly Support	Service plan and tech support for troubleshooting, maintaining, replacing and fixing any issues with the Enlighted solution	$34,000/year

Source: California State University Long Beach

In addition to separating costs by upfront (one-time) cost versus recurring costs, a key step in determining the project lifetime costs was to convert costs into annual and present value forms. The total cost of the CSULB smart building project was calculated as follows:

$$C = P * (1 + i)^n + \frac{A}{i} * \ [(1 + i)^n - 1] \qquad (8)$$

where P: initial cost ($796,246 which includes equipment and software cost, and installation costs)

- A: recurring annual cost ($34,000)
- i: inflation rate (2 percent over the period of 15 years)
- n: number of years (15 years)

Using this equation, the total future cost over the period of 15 years was $1,659,618.

Benefit Analysis

Expected Impacts to Investor-Owned Utilities from Energy Efficiency Improvements

Improved energy efficiency could reduce the need to buy new central station generation capacity and/or "rent" generation capacity in the wholesale electricity marketplace [10]. The resulting cost reduction (or avoided cost) is the benefit associated with energy efficiency for the electric supply capacity application. For many regions, the most likely type of new generation plant "on the margin" is a clean, efficient natural-gas-fired combustion turbine-based power plant (state-of-the-art combined cycle or advanced simple cycle configuration) that operates for 2,000 hours to 6,000 hours per year. The generic installed cost assumed is $1,000/kW. A typical annual fixed operation and maintenance cost for such plant is assumed to be $10/kW-year. Applying the standard value of 0.11 for the utility fixed charge rate yields an annual cost of ownership of $1,000/kW × 0.11 = $110/kW-year. After adding the $10/kW-year fixed operation and maintenance cost, $120/kW-year represents the maximum value for cases involving combustion-turbine based generation, on the margin.

Transmission capacity additions are not keeping pace with the growth in peak electric demand. Consequently, transmission systems are becoming congested during periods of peak demand, driving the need and cost for more transmission capacity and increased transmission access charges. Additionally, transmission congestion may lead to increased use of congestion charges or locational marginal pricing for electric energy.

Transmission congestion charges are becoming more common. In the parts of California's transmission system where it occurs, congestion is present for 10 percent to 17 percent of all hours during the year. Average value of transmission congestion relief a lifecycle benefit averaging about $86/kW.

Transmission and distribution (T&D) upgrade deferral involve delaying utility investments in transmission and/or distribution system upgrades. For a T&D system whose peak electric load is approaching the system's load carrying capacity, in some cases energy efficiency improvements downstream from the nearly overloaded T&D node could defer the need for a T&D upgrade. In California, for 50 percent of all locations requiring an upgrade in any given year, the marginal cost is $420/kW or more. The upgrade factor is the ratio of the capacity added to the existing capacity. Typical values for upgrade factor range from 0.25 to 0.50. An upgrade factor of 0.33 is assumed for this guide.

Financial Benefits to Investor-Owned Utilities from Energy Efficiency Improvements

Table 22 summarizes previous benefit analyses, such as electric supply capacity service, transmission congestion relief service, transmission and distribution upgrade service. The yearly potential benefits to IOUs will be $36,906, based on demand reduction of 107.1 kW. Over 15 years the total benefit to IOUs is estimated at $600,453.

Table 22: Benefit Evaluation Summary

Term	Benefit Value
Electric Supply Capacity Service	$120/kW
Transmission Congestion Relief Service	$86/kW
Transmission and Distribution Upgrade Service	$138.6/kW

Source: California State University Long Beach

Societal Project Benefits

The project reduced grid energy use by 264,516 kWh per year. Using an emissions factor of 0.228 kg CO_2e/kWh, the annual GHG emissions reduction was 60.31 metric tons CO_2e per year, resulting in 904.65 metric tons CO_2 reduced over 15 years.

Benefits to Cost Ratio

The benefit to cost ratio is defined by the fraction of total benefit and total cost. The total project benefit is the sum of financial benefits to CSULB ($1,236,386) and benefits to California IOUs ($600,453). Note that this benefit does not include the thermal cooling energy savings due to the IoT-based HVAC technology. The total project cost was estimated at $1,659,618. Thus, the resulting benefit to cost ratio is 1.1, which implies that the benefits of the project will overweigh the costs and the project can recover its costs over its lifetime.

CHAPTER 5:
Technology/Knowledge/Market Transfer Activities

Below is the list of conferences, workshops, or symposia at which the project team has published technical papers or presented posters:

- North American Power Symposium (NAPS) 2017: the 49th North American Power Symposium, was hosted by West Virginia University and was held at Waterfront Place in Morgantown, West Virginia, from September 17-19, 2017. NAPS has been a very active symposium since its inception in 1969 as the Midwest Power Symposium and later renamed as North American Power Symposium in 1986. NAPS is held every year at a different university in North America and provides an open forum for participants from academia and industry to exchange innovative ideas and solutions. NAPS will continue the long-held tradition of encouraging student-presented papers and recognizing student best efforts by awards to be presented at the end of the symposium. NAPS welcomes papers on analytical, computational, experimental studies aimed at solving problems related to optimized operation, real time and near real time control, monitoring and data collection, protection with and without distributed generations, reliability as well as economics of power and energy systems along with recent trends in connected and smart cities, DC grids and microgrids with its components. The research team published a paper in this conference:
    - E. Sanchez, and M. H. Nazari, "Model Predictive Energy Scheduling for Building Microgrid," 2017 North American Power Symposium (NAPS), Morgantown, WV, 2017, pp. 1-6.
- North American Power Symposium (NAPS) 2019: 51st North American Power Symposium was held at Wichita State University, Wichita, Kansas from October 13-15, 2019. NAPS, a student-centric conference has been bringing together students, faculty, and researchers in the power and energy systems area since its inception in 1969. The purpose of this symposium was to provide a forum for students, faculty, and industrial representatives to discuss research ideas for next generation power grid and present their research outcomes. The researchers published a paper in this conference:
    - D. H. Tran, E. Sanchez and M. H. Nazari, "Model Predictive Energy Management for Building Microgrids with IoT-based Controllable Loads," *2019 North American Power Symposium (NAPS)*, Wichita, KS, USA, 2019, pp. 1-6.
- Innovative Smart Grid Technologies (2019): The 10th Conference on Innovative Smart Grid Technologies (ISGT 2019), sponsored by the IEEE Power & Energy Society (PES), was held February 17-20, 2019 in Washington D.C. The conference featured plenary sessions, panel sessions, technical papers, and tutorials by experts representing the electric utilities, regulators, technology providers, academia, the national laboratories, and both federal and state governments. The 2019 theme was "10 years of ISGT – Innovation for a Flexible and Resilient Grid". The research team published a paper in this conference:

    - D. H. Tran, M. H. Nazari, A. Sadeghi-Mobarakeh, and H. Mohsenian-Rad, "Smart building Design: a Framework for Optimal Placement of Smart Sensors and Actuators," 2019 IEEE PES Innovative Smart Grid Technologies (ISGT), Washington, DC, 2019.
- Innovative Smart Grid Technologies (2020): The Eleventh Conference on Innovative Smart Grid Technologies (ISGT 2020), sponsored by the IEEE Power & Energy Society (PES), was held February 17-20, 2020 at the Grand Hyatt Washington, Washington D.C. The researchers published a paper in this conference:
    - E. Samani *et al.*, "Anomaly Detection in IoT-Based PIR Occupancy Sensors to Improve Building Energy Efficiency," *2020 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT)*, Washington, DC, USA, 2020, pp. 1-5.
- IEEE Transaction on Smart Grids (2021): The IEEE Transactions on Smart Grid is a cross disciplinary journal aimed at disseminating results of research on and development of the smart grid, which encompasses energy networks where prosumers, electric transportation, distributed energy resources, and communications are integral and interactive components, as in the case of microgrids and active distribution networks interfaced with transmission systems. The journal publishes original research on theories and principles of smart grid technologies and systems, used in demand response, advance metering infrastructure, cyber-physical systems, multi-energy systems, transactive energy, data analytics, and EV integration. Surveys of existing work on the smart grid may also be considered for publication when they propose a new viewpoint on history and a challenging perspective on the future of intelligent and active grids.
    - M. H. Nazari, S. Xie, L. Y. Wang, G. Yin and W. Chen, "Impact of Communication Packet Delivery Ratio on Reliability of Optimal Load Tracking and Allocation in DC Microgrids," in *IEEE Transactions on Smart Grid*, doi: 10.1109/TSG.2021.3062024
    - M. H. Nazari, S. Xie, L. Y. Wang, "Communication-Delay-Tolerant MIMO Architecture for Distributed Frequency Regulation in Multi-Agent Smart Grids," in *IEEE Transactions on Smart Grid*, under review.
- Winston Chung Energy Storage Conference 2019: The conference provided a forum for faculty, researchers, practitioners, regulators, technology developers, community leaders and utility companies to share the latest advances and future opportunities for energy. Participants took part in invited and contributed presentations, panel discussions, industry showcases, and a networking reception to enhance the opportunities and collaborations among various stakeholders. The conference theme focused on two pillars of energy storage technologies as well as system integration, operation, and business models for energy storage across a variety of applications.
    - The researchers presented a poster at this conference entitled: "Designing a Smart Building Microgrid with Model Predictive Energy Management.**"**
- EPIC Forum: Reimagining Buildings for a Carbon Neutral Future (2020). This forum highlighted innovative new clean energy technologies that can help reimagine new and existing building development to achieve carbon neutrality in the electricity sector by

2045. This technical forum was part of the CEC's administration of the Electric Program Investment Charge (EPIC).

    - The researchers presented a poster at this EPIC Symposium entitled:" Internet of Things and Ubiquitous Sensing in University Building Energy Management: Design Optimization and Technology Demonstration."
- The researchers also presented a poster at CEC annual workshop at Sacramento in 2019. The title of the poster was: "Enhancing Energy Efficiency and Demand Response Capability in University Building."
- IEEE Green Energy and Smart Systems Conference (IGESSC): This conference covers wide range of topic areas in Green Energy, Power, and Smart Systems.
    - Dr. Nazari presented the results and progress of this project to the public in IGESSC 2017, 2018, and 2019.

The research team's partner in this project, Enlighted Inc. (a commercial manufacturer) has been installing their products for many other customers (both academia and industry) since the beginning of the project. Their academia customers include Stanford University, University of South Florida, University of California Irvine, and California State University Dominguez Hills. Their industry customers include: Veeco Services, AT&T, Interface Inc., Agilent Technologies, and Menlo Business Park.

Access to the project's data, analysis methods, performance, and results are available upon request. All technology development, integration, and operational strategies will be made available to appropriate decision-makers and commercialization teams for commercial deployment. CSULB hosted site visits and workshops as outreach activities during the project.

For market adoption, California energy efficiency companies will pioneer new markets. Energy savings in academic institutions has most direct/influential benefits to ratepayers and also a direct and wide exposure of the public to demonstration of energy savings approaches.

CHAPTER 6:
Conclusions

This report discussed in detail the development of a customized and cost-effective energy efficiency and demand side management system implemented at the CSULB-ECS building. The deployment and demonstration of the IoT-based BEMS were presented, as well as the compliance of this new BEMS system. Finally, its performance costs evaluation and benefits assessment were provided in this report.

The research team evaluated the lighting, plug-in, and HVAC loads in the ECS building to validate the performance and energy savings achieved by the deployed smart IoT-based EMS. Originally, there were 1,288 lights, 841 plug-in loads, and 75 HVAC zones in the ECS building. The estimated energy consumption pre-implementation of the EMS was 350,000 kWh for lighting, 490,000 kWh for plug-in loads, and 290,000 kWh for HVAC. In this project, 1,048 lights representing 81.37 percent of the total number of building lights were converted and integrated into the smart lighting system. This resulted in the reduction of 252,390 kWh, representing a decrease in lighting energy consumption of 72.11 percent. Among the 841 plug-in loads at the ECS building, 30 non-critical plug-in loads, equating to 3.57 percent of the total plug-in loads, were incorporated into the smart plug-in loads system. The energy decrease achieved by the 30 loads was 541 kWh, achieving a plug-in energy consumption reduction of 0.11 percent. The ECS building was divided into 75 zones by the HVAC units, where 55 zones were controlled by the deployed smart IoT-based EMS. The calculated energy reduction through the HVAC units was 11,585 kWh, leading to a reduction in HVAC energy consumption of 3.99 percent. The total reduction in electrical energy consumption of the ECS building was 23.41 percent, which meets the initial project target of reducing energy consumption by more than 20 percent.

In addition, the thermal energy savings for heating due to the implemented IoT-based HVAC operational changes were estimated at 12.62 percent, translating to 442,054 kBTU annually, or 4,422 therms. Considering other benefits such as reduced peak demand charges, increased demand response capacity, deferral of transmission and distribution upgrades, and improved electric service quality and reliability, the total economic benefit over 15 years was estimated at $1,836,839. The estimated benefit to cost ratio was 1.1 indicating that the benefits of the project will overweigh the costs and the project can recover its costs over its lifetime.

LIST OF ACRONYMS

Term	Definition
CEC	California Energy Commission’s
ADR	Automatic Demand Response
AHU	Air Handling Unit
APIs	Application Programming Interface
BACnet	Building Automation and Control network
BAS	Building Automation System
BEMS	Building Energy Management System
CFM	Cubic Feet per Meter
CHW	Chilled Water
CPP	Critical Peak Pricing
CSULB	California State University, Long Beach
DDC	Direct Digital Control
DR	Demand Response
ECS	Engineering and Computer Science
EPIC	Electric Program Investment Charge
GUI	Graphical User Interface
HID	High Intensity Diffusion
HVAC	Heating, Ventilation and Air Conditioning
HWR	Hot Water Return
HWR	Hot Water Reheat
IoT	Internet of Things
IOU	investor-owned utility
IP	Internet Protocol
JACE	Java Application Control Engine
M&V	Measurement and Verification
MS/TP	Master Slave/Token Passing
MTHW	Medium Temperature Hot Water
OS	Operating System

Term	Definition
RTP	Real-time Pricing
SVG	Scalable Vector Graphics
TES	Thermal Energy Storage
THD	Total Harmonic Distortion
VAV	Variable Air Volume
VFD	Variable Frequency Driver

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[3] D. H. Tran, M. H. Nazari, A. Sadeghi-Mobarakeh, and H. Mohsenian-Rad, “Smart building Design: a Framework for Optimal Placement of Smart Sensors and Actuators,” 2019 IEEE PES Innovative Smart Grid Technologies (ISGT), Washington, DC, 2019.

[4] E. Samani *et al.*, "Anomaly Detection in IoT-Based PIR Occupancy Sensors to Improve Building Energy Efficiency," *2020 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT)*, Washington, DC, USA, 2020, pp. 1-5.

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APPENDIX A:
Published Technical Papers

Paper 1: Model Predictive Energy Scheduling for Building Microgrid

Model Predictive Energy Scheduling for Building Microgrid

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***Abstract*—This paper presents a model predictive control (MPC) approach to economic scheduling for a building microgrid at California State University, Long Beach. We first propose a peak demand cost model to extend MPC-based microgrid energy scheduling. The corresponding objective function is then formulated as a mixed-integer linear programming (MILP) problem. The MPC framework is implemented into MILP optimization to construct MPC-MILP, which is formulated to compensate for uncertainties in day-ahead demand and photovoltaic (PV) power forecasts. Next, we provide the forecast modeling for demand and PV power to improve the accuracy of MPC-MILP. The simulation results show that the MPC-MILP optimization approach provides superior cost minimization over strategies such as MILP, which controls the microgrid subject to one calculation using day-ahead forecasts.**

***Index Terms*—energy management, microgrids, mixed integer linear programming (MILP), model predictive control (MPC), power management.**

NOMENCLATURE

x^b	Energy in storage device
x^{sb}	Energy degradation of storage device
x^b_{min}, x^b_{max}	Min/max energy for storage device
P^b	Power from storage device
η^{ch}, η^{dis}	Charge/discharge efficiency of storage
x^{DG}	Unit commitment of DG unit
x^{SU}, x^{SD}	Startup/shutdown state of the DG
P^g	Power from the utility grid
c^{peak}	Peak demand cost coefficient
c^{OM}	Operation and maintenance cost coefficient for the DG unit
c^{SU}, c^{SD}	Startup/shutdown cost coefficient for DG
P^{PV}	PV power output
c^P	Cost rate for buying power from utility grid
P^{DG}	Power output from the DG unit
P^{DG}_{min}, P^{DG}_{max}	Min/max power output from DG unit
C^{min}	Cost of fuel use for DG at P^{DG}_{min}
T^{up}, T^{down}	Minimum uptime/downtime for DG unit
a_1, a_2, a_3	Coefficients for quadratic cost curve
s_m, l_m	Slope/power length of segment m
δ^b	Storage charge/discharge decision variables
H_c	Correction time horizon
$\hat{P}^{PV}$, $\hat{D}$	PV power, demand forecast prediction
N	Number of equipartition segments
T	Initial prediction horizon length
Z^g	Auxiliary peak demand variable

I. INTRODUCTION

The advent of modern microgrid technology has opened quality possibilities for electricity market users. For instance, microgrids increase reliability in power supplied to end users [1]. Moreover, the self-reliance brought on from the utilization of renewable energy sources (RESs) and distributed generators (DGs) makes this technology attractive for environments where satisfying power demand is critical, such as hospitals [2]. In [3], Katiraei *et al.* showed that an energy management strategy is necessary to successfully operate the multiple facets of the microgrid, such as DGs, RESs, utility grid energy purchasing, energy storage control, and load control. In [4], [5], and [6], it is shown that optimal scheduling and utilization of on-site resources is crucial for cost minimization and efficiency improvement of microgrids and DG units. In [7] and [8] respectively, Marzband *et al.* and Parisio *et al.* offered mixed-integer program algorithms to minimize the day-ahead operational cost of the microgrid. However, in the case of [7], the mixed integer nonlinear program (MINLP) led to large computation times and resulted in non-optimal solutions [9].

The mixed-integer linear programming (MILP) performance depends largely on the accuracy of the next-day forecasts for RES, electric demand, and utility grid's spot price. But forecasts are not always accurate, particularly when the prediction horizon increases [10]. To minimize the effects of uncertainties, we propose updating the forecasts with new data from the microgrid, recalculating the optimal schedule to correct for errors, implementing the control decisions, and repeating the process at fixed time intervals throughout the day. The basis of this technique comes from model predictive control (MPC) optimization. In [11], MPC is implemented as a high-level microgrid economic scheduling strategy to account for the system modeling uncertainties via feedback and to make control decisions based on prediction of futures states.

In [12], Yafeng *et al.* utilized neural networks as an approach to non-linear forecasting. In [13] and [14] respectively, Yue *et al.* and Sharma *et al.* applied support vector machines (SVMs) to predict user demand and solar generation. However, since our emphasis is on scheduling strategies, we

Paper 2: Model Predictive Energy Management for Building Microgrid with IoT-based Controllable Loads

Model Predictive Energy Management for Building Microgrids with IoT-based Controllable Loads

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Abstract—**This paper develops an economic scheduling framework for a building microgrid with internet of things (IoT) based flexible loads to synchronize the buildings' controllable components, with occupant behavior and environmental conditions. We employ model predictive control (MPC) methods to minimize building operating costs, while maximizing the utilization of the on-site resources. The main research thrusts are 1) Developing the building microgrid model; 2) Defining different building operation strategies; 3) Minimizing the building's daily operating costs. Simulation results show that the proposed approach provides superior energy cost savings and peak load reduction in comparison with other operation controls, such as offline Mixed Integer Linear Programming (MILP), All from Utility (AFU), and MPC-MILP with non-controllable loads.**

Index Terms—**Building Microgrid; Demand Response; Energy Efficiency; Internet of Things Flexible Loads; Model Predictive Protocol; System Uncertainty.**

NOMENCLATURE

β^l, β^p	Curtailment of the lighting and plug loads
δ^b	Storage charge/discharge decision variable
η^{ch}, η^{dis}	Charge/discharge efficiency of storage
ρ^b	Curtailment penalty coefficient
C^g	Cost rate for buying power from utility grid
C^{min}	Cost of fuel use for DG at P_{min}^{DG}
C^{OM}	Operation and maintenance cost coefficient for the DG unit
c^{peak}, Z^g	Peak load cost penalty, peak load variable
c^P, c^S	Purchasing and selling electricity rates for utility grid
c^{SU}, c^{SD}	Startup/shutdown cost coefficient for DG
D^l, D^p	Controllable lighting and plug load demand
N	Number of equipartition segments
N_{lights}, N_{plugs}	Number of controllable loads
P^b	Power to/from storage device
P^g, P^{PV}, P^{DG}	utility power, PV power, DG unit power output
$P_{min}^{DG}, P_{max}^{DG}$	Min/max power output from DG unit
s_m, l_m	Slope/power length of segment m
T	Initial prediction horizon length
x^b, x^{sb}	Energy in storage, energy degradation of storage
x^{DG}	Unit commitment of DG unit
x^{SU}, x^{SD}	Startup/shutdown state of the DG
x_{min}^b, x_{max}^b	Min/max energy for storage device

I. INTRODUCTION

A building microgrid, which can represent a commercial, residential, or an industrial building, is a small prosumer (producer-consumer) with local controllers, local consumers, flexible loads, renewable energy resources (RESs), distributed generators (DGs) and/or energy storage devices. The advent of building microgrid technology has opened quality possibilities for electricity market users. For instance, building microgrids increase reliability in power supplied to end users [1]. Moreover, the self-reliance brought on from the utilization of distributed energy resources (DERs) makes this technology attractive for environments where satisfying power demand is critical, such as hospitals, police stations, and emergency operating centers.

Applying advanced energy efficiency technologies across loads in building microgrids is important for energy reduction and increasing demand response capability. For instance, energy efficiency technologies, such as grid-friendly appliances [2], can be applied across lighting fixtures, plug-in loads, and HVAC systems. Energy efficiency technologies can also use smart sensors, actuators, and microchips [3] to collect and manage data according to buildings functions and services. These advanced sensors and actuators can be connected through an Internet of Things (IoT) platform that enables data collection and data transmission to the Building Energy Management System (BEMS) [4]. The IoT-based BEMS system processes the data and extracts useful information for optimal energy scheduling and facility management, as well as synchronizing the building's energy consumption with environmental conditions, occupant behavior, and power grid operation.

Another aspect of building microgrid management is the optimal scheduling and utilization of on-site resources for cost minimization and energy efficiency improvement [5]–[8]. Researchers have been studying microgrid configurations, planning, control, and operation strategies because of their benefits to the grid such as increased efficiency, reliability, and resilience. Many algorithms have been proposed for the optimal scheduling of microgrids [9]–[12]. However, the uncertainties of RESs and demand profile have been treated as deterministic data in these studies, which is not always accurate and realistic. Authors in [13] and [14] presented a mixed integer linear programming (MILP) control strategy, which consider uncertainties of RESs and demand profile as stochastic data, to minimize the operating cost of residential microgrids. The MILP performance, however, could lead to sub-optimal results since decision variables are chosen based

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Paper 3: Smart Building Design: a Framework for Optimal Placement of Smart Sensors and Actuators

Smart Building Design: a Framework for Optimal Placement of Smart Sensors and Actuators

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***Abstract*—This paper introduces a framework for transforming buildings into smart infrastructures with high energy efficiency objectives and demand response capability. The proposed smart building design will significantly drive down energy costs, while improving occupant comfort and system reliability. The design process is done for the Engineering and Computer Science (ECS) building at California State University, Long Beach (CSULB). A comprehensive inventory is provided to identify and characterize the lighting and plug-in load control potential across classrooms, research labs, teaching labs, offices, and other areas of the building. This is done by also developing the three-dimensional (3-D) model of the CSULB-ECS building. Next, we develop a model-based optimization method to identify the optimal number and location of the smart sensors and actuators in the building. Accordingly, an analysis is conducted to explore energy cost savings opportunities due to the implementation of the energy efficiency and demand response measures; thus, providing the road map for implementation.**

***Index Terms*—Demand Response; Energy Cost Savings; Energy Efficiency; Smart Building; System Optimization.**

I. INTRODUCTION

The combination of residential and commercial buildings account for approximately 40% of the annual energy consumption in the United States [1], and similar statistics apply worldwide [2]. Thus, improving energy efficiency and reducing peak load in buildings open a door for significant energy savings and cost reduction. There are several opportunities in this area. For instance, up to 40% of energy used by heating, ventilation, and air conditioning (HVAC) systems in commercial buildings is wasted due to faulty operation [3].

Both consumers and utilities can benefit from implementing buildings energy efficient measures. For instance, consumers benefit from reducing energy bills as well as having a more reliable electricity supply. Meanwhile, the deployment of energy efficiency technologies can directly reduce overall and peak-hour energy consumption (kWh) and energy demand (kW) from the grid [4].

Advanced energy efficiency technologies can be applied across lighting fixtures, plug loads, and the HVAC system such as service oriented architecture [8] [9], grid-friendly appliances [12], techniques for enhancing energy efficiency [13], and optimal operation of existing building stocks [14]. It also includes security measures and using smart sensors, actuators, and microchips [10] [11] to collect and manage data according to buildings functions and services. These advanced sensors and actuators are connected through an Internet of Things (IoT) platform [5] [6] that enables data collection over an internet-like network and data transmission to the energy management system (EMS) of the building. EMS processes the data and extracts useful information for optimal energy scheduling and facility management [7].

Typical existing buildings monitoring, communication, and control are limited to components and subsystems and lacking holistic system integration. For instance, the HVAC control systems are commonly rule-based, reactive, and separated from lighting control, resulting in low energy efficiency and high energy costs. To address these challenges, it is proposed to design smart buildings with advanced EMS system based on IoT to synchronize building's energy consumption with environmental conditions, occupant behavior and power grid operation.

This paper aims to address one aspect of the smart building design, namely optimal placement of smart sensors and actuators. We develop a design process for implementing IoT sensors and controls across lighting, plug-in loads and HVAC in a 101,670 sqft conditioned space Engineering and Computer Science (ECS) building, at California State University, Long Beach (CSULB). The ECS building will be integrated with the IoT-based EMS system to increase overall energy efficiency and demand response capability, and optimize energy use relative to building power demand and activity level while improving occupant comfort and system reliability. We focus on analyzing the opportunities of energy reduction in a general academic building and developing a framework for identifying potential energy savings. To such aim, we define and perform the following four steps:

- Specifying load characteristics and operation requirements.

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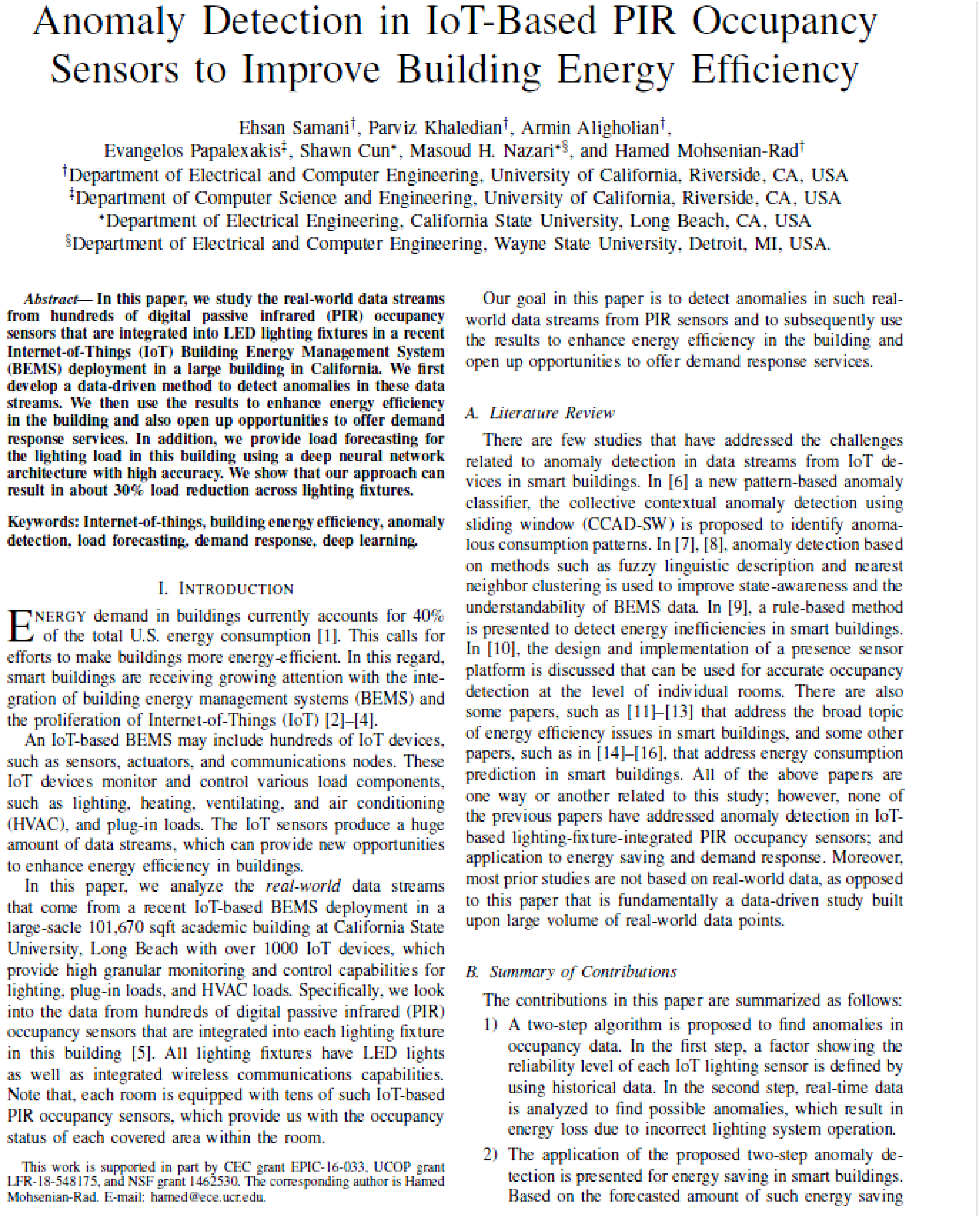
Paper 4: Anomaly Detection in IoT-based PIR Occupancy Sensors to Improve Building Energy Efficiency



Anomaly Detection in IoT-Based PIR Occupancy Sensors to Improve Building Energy Efficiency

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***Abstract*— In this paper, we study the real-world data streams from hundreds of digital passive infrared (PIR) occupancy sensors that are integrated into LED lighting fixtures in a recent Internet-of-Things (IoT) Building Energy Management System (BEMS) deployment in a large building in California. We first develop a data-driven method to detect anomalies in these data streams. We then use the results to enhance energy efficiency in the building and also open up opportunities to offer demand response services. In addition, we provide load forecasting for the lighting load in this building using a deep neural network architecture with high accuracy. We show that our approach can result in about 30% load reduction across lighting fixtures.**

Keywords: Internet-of-things, building energy efficiency, anomaly detection, load forecasting, demand response, deep learning.

I. INTRODUCTION

ENERGY demand in buildings currently accounts for 40% of the total U.S. energy consumption [1]. This calls for efforts to make buildings more energy-efficient. In this regard, smart buildings are receiving growing attention with the integration of building energy management systems (BEMS) and the proliferation of Internet-of-Things (IoT) [2]–[4].

An IoT-based BEMS may include hundreds of IoT devices, such as sensors, actuators, and communications nodes. These IoT devices monitor and control various load components, such as lighting, heating, ventilating, and air conditioning (HVAC), and plug-in loads. The IoT sensors produce a huge amount of data streams, which can provide new opportunities to enhance energy efficiency in buildings.

In this paper, we analyze the *real-world* data streams that come from a recent IoT-based BEMS deployment in a large-sacle 101,670 sqft academic building at California State University, Long Beach with over 1000 IoT devices, which provide high granular monitoring and control capabilities for lighting, plug-in loads, and HVAC loads. Specifically, we look into the data from hundreds of digital passive infrared (PIR) occupancy sensors that are integrated into each lighting fixture in this building [5]. All lighting fixtures have LED lights as well as integrated wireless communications capabilities. Note that, each room is equipped with tens of such IoT-based PIR occupancy sensors, which provide us with the occupancy status of each covered area within the room.

Our goal in this paper is to detect anomalies in such real-world data streams from PIR sensors and to subsequently use the results to enhance energy efficiency in the building and open up opportunities to offer demand response services.

A. *Literature Review*

There are few studies that have addressed the challenges related to anomaly detection in data streams from IoT devices in smart buildings. In [6] a new pattern-based anomaly classifier, the collective contextual anomaly detection using sliding window (CCAD-SW) is proposed to identify anomalous consumption patterns. In [7], [8], anomaly detection based on methods such as fuzzy linguistic description and nearest neighbor clustering is used to improve state-awareness and the understandability of BEMS data. In [9], a rule-based method is presented to detect energy inefficiencies in smart buildings. In [10], the design and implementation of a presence sensor platform is discussed that can be used for accurate occupancy detection at the level of individual rooms. There are also some papers, such as [11]–[13] that address the broad topic of energy efficiency issues in smart buildings, and some other papers, such as in [14]–[16], that address energy consumption prediction in smart buildings. All of the above papers are one way or another related to this study; however, none of the previous papers have addressed anomaly detection in IoT-based lighting-fixture-integrated PIR occupancy sensors; and application to energy saving and demand response. Moreover, most prior studies are not based on real-world data, as opposed to this paper that is fundamentally a data-driven study built upon large volume of real-world data points.

B. *Summary of Contributions*

The contributions in this paper are summarized as follows:

1) A two-step algorithm is proposed to find anomalies in occupancy data. In the first step, a factor showing the reliability level of each IoT lighting sensor is defined by using historical data. In the second step, real-time data is analyzed to find possible anomalies, which result in energy loss due to incorrect lighting system operation.
2) The application of the proposed two-step anomaly detection is presented for energy saving in smart buildings. Based on the forecasted amount of such energy saving

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Paper 5: Impact of Communication Packet Delivery Ratio on Reliability of Optimal Load Tracking and Allocation in DC Microgrids

Impact of Communication Packet Delivery Ratio on Reliability of Optimal Load Tracking and Allocation in DC Microgrids

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***Abstract*—Communication systems introduce uncertainties that directly impact power system management. Quantitative analysis of such impact is essential for power system reliability and resilience. This paper establishes rigorous relationships between communication packet delivery ratio and errors on optimal load tracking and allocation (OLTA) in DC microgrids (MGs). By modeling channel uncertainties using packet delivery ratio and communication network topologies, impact of communication packet loss on the distributed OLTA algorithm for DC MGs is studied. It is shown that communication packet loss directly affects the convergence rate of the distributed OLTA algorithm under intermittent renewable generations. The results of this paper quantitatively characterize a practical criterion for securing reliability of OLTA solutions under communication uncertainty. Simulation studies using a real-world DC MG are conducted to validate the theoretical findings.**

Keywords. DC microgrids, optimal load tracking and allocation, reliability, packet delivery ratio, randomly switching network.

I. INTRODUCTION

CYBER-physical power systems naturally integrate communication and control for system coordination and resilience enhancement. For instance, microgrids (MGs) rely ubiquitously on communication systems for data exchange [1]. New power system architectures employ communication systems to exchange data, including Wi-Fi and Wi-MAX (IEEE 802.16), cellular (GPRS/UMTS/LTE), WLAN [2]. Customer premise communications include ZigBee, WiFi (802.11), IEEE 1901/ G.hn/ Home-plug/PRIME PLC, BPL, and wireless.

Reliability of communication systems is essential for power systems and has drawn increased attention [3]–[5]. In particular, wireless communications inherently encounter random uncertainties such as channel interruption, packet loss, and delays [6], creating random link interruption and consequently randomly switching communication networks. Such communication uncertainties directly impact many time-sensitive power system management tasks. This paper focuses on analysis of such impact on optimal load tracking and allocation (OLTA) problems under intermittent renewable generations.[1]

To ensure power system reliability, sensing, management, and control must be sufficiently fast so that optimal solutions can be quickly attained after perturbations. Fast convergence of the power system algorithms, particularly time sensitive algorithms, is essential for the reliability of the power system. This paper proves that communication packet loss significantly slows down the convergence of the distributed OLTA algorithm. In particular, the paper establishes the quantitative relationship between communication uncertainties and errors in distributed OLTA for DC MGs.

DC MGs are common and efficient in distribution-level smart grids. They support renewable generation and electric vehicle integration and can simplify control design by avoiding unnecessary ac/dc conversions. Many advanced control methods have been designed for high-performance DC MGs. Various optimization methods have been employed for DC MG power management, including primal-dual distributed optimal control algorithms [7], optimal power sharing strategy with line resistance [8], distributed optimal control architecture for multiple dc-dc converters [9], cooperative and distributed secondary/primary control framework [10]. Reference [11] proposed a decentralized current-sharing control strategy for fast transient response. Reference [12] proposed a trust-based cooperative controller to mitigate adverse effects of attacks on communication links and controller hijacking, [13] studied the impact of communication delay on the small-signal stability of MGs with distributed secondary frequency and voltage control, and [14] considered the asynchronous distributed power control problem of hybrid MGs. The previous results did not investigate stochastic communication uncertainties. In our early work, distributed optimization methods were introduced with rigorous convergence analysis [15]–[17].

Impact of communications on networked control systems has been investigated from different perspectives such as noisy communication channels [18], added constant delays [19], [20], and event-trigger-based strategies [21]–[23]. Reference

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[1] Although stochastic communication uncertainties will significantly affect frequency and voltage regulation, time for contingency clearance, among many other power efficiency and reliability issues, for concreteness this paper will treat only OLTA issues.