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**FINAL PROJECT REPORT**

# Developing Flexible, Networked Lighting Control Systems to Save Energy in California Buildings

**Gavin Newsom, Governor**
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# PREFACE

The California Energy Commission's 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 California Energy Commission 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 Energy Commission 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.

*Developing Flexible, Networked Lighting Control Systems That Reliably Save Energy In California Buildings* is the final project report for Contract Number EPC-14-017 conducted by Lawrence Berkeley National Laboratory. The information from this project contributes to Energy Research and Development Division's EPIC Program.

For more information about the Energy Research and Development Division, please visit the [Energy Commission's research website](https://www.energy.ca.gov/research/) at www.energy.ca.gov/research/ or contact the Energy Commission at 916-327-1551.

# ABSTRACT

Innovative wireless communications, embedded sensors, data analytics, and controls can help meet California's ambitious energy efficiency goals by reducing lighting energy use in commercial buildings. This project developed a suite of networked lighting solutions including the PermaMote, a self-powered sensor and controller for lighting applications. The project also developed the Readings-At-Desk system that integrates sensors with data-driven daylighting control using an open communication interface. To reduce potential confusion for building occupants about operating traditional lighting control systems, the research team created content that could be the basis for a user interface standard for lighting controls. Finally, to help ensure that advanced lighting control systems deliver their promised energy savings, the project team developed a new method for evaluating and specifying lighting system performance.

In the laboratory, these technologies showed lighting energy savings of up to 73 percent for the PermaMote sensor system from occupancy control and daylight dimming features, compared to the same light source (LED replacement lamps) operated via simple on/off scheduling. The project team also developed a proposed standard lighting data model and user interface elements and provided them to the American National Standards Institute Lighting Systems Committee for standardization. To verify performance of lighting systems, the project team developed a more effective metric for capturing the actual energy effect of a lighting system over time—the energy use intensity (kilowatt-hours per square foot per year). The team tested three commercial lighting systems in FLEXLAB® using this new metric, with tests showing a wide range in the accuracy of the self-reported energy-use metric, from 0.5 percent to 28 percent error. The project team estimates that these advanced technologies can reduce California office lighting energy use by 20 percent above normal advanced lighting controls mandated by Title 24 standards, saving about 1,600 gigawatt-hours per year.

Keywords: wireless communications, networked lighting controls, embedded sensors, standard user interface, lighting system performance, task ambient lighting integration

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# EXECUTIVE SUMMARY

## Introduction

California Senate Bill 350 requires that the state's energy-efficiency savings double by 2030. One strategy toward meeting that goal is to use new technologies to greatly reduce electricity use while maintaining or improving building system and end-use performance. Commercial buildings account for more than one-third of the energy used in California, and lighting is the largest end-use in these buildings. Advances in information and communication technology over the last several decades created a wide range of innovative wireless communications, embedded sensors, data analytics and controls that offer opportunities to optimize building systems in real time to reduce energy use.

To take advantage of these technologies, lighting systems must evolve to:

1. Channel new entrants in the lighting market to address energy usage.
2. Harness innovation in the Internet of Things sector.
3. Respond to the needs of the utility grid to enable buildings as flexible loads.
4. Address entirely new lighting services, such as circadian lighting, that are making the lighting market more complex.

Several shortcomings keep lighting systems from realizing their energy saving potential. Traditional lighting systems lack "awareness," which leads to inefficiency and suboptimal performance. The increasing complexity of advanced lighting control systems leads to user confusion. Finally, dynamic and customized control capability in new lighting systems makes it hard to specify and verify energy performance.

## Project Purpose and Approach - A Suite of Networked Lighting Solutions

This project applied information and communication technology advances to address the shortcomings of traditional lighting control systems to increase energy efficiency and energy savings in support of reaching California's energy goals. The research was conducted in three main areas:

1. Sensor-rich networked lighting systems
2. Intuitive, standardized user interfaces for networked lighting systems
3. Verifiable performance for networked lighting systems

### Sensor-Rich Networked Lighting Systems

The project team developed a low-cost sensing, distributed intelligence, and communications platform, the PermaMote, which is a self-powered sensor and controller for lighting applications. As shown in Figure ES-1, the PermaMote includes multiple sensor types (for example, light level, light color, motion, temperature,

humidity) as well as energy harvesting capability, contained in a small and light form factor and using industry-standard networking protocols.

**Figure ES-1: PermaMote Design**
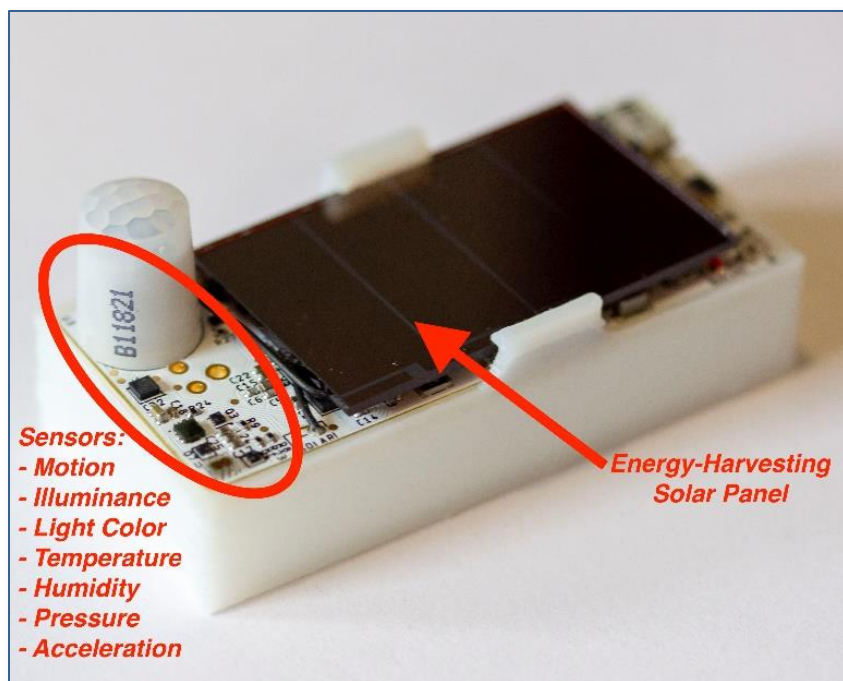


*Source: Lawrence Berkeley National Laboratory*

Sensors for environmental factors like temperature and RH provide the opportunity for optional future integration into heating, ventilation, and air conditioning control. Additionally, lighting color information can be processed into correlated color temperature for spectral tuning, which some solid-state lighting systems allow. The simple, low-cost, wireless multi-sensor platform allows dense distribution of sensors in the controlled space, providing rich spatial coverage for the measured attributes. The platform also implements a new reference lighting data model for improved interoperability with other lighting systems.

The project team also developed an effective task ambient daylighting system that integrates sensors with data-driven daylighting control using an open application programming interface—a set of definitions, communication protocols, and tools for programming and communication. This technology, the Readings-At-Desk system, uses illuminance measured at the desktop, with user-desired illuminance inputs, to control overhead lights. As shown in Figure ES-2, the Reading-At-Desk sensors located at the desktop easily integrate with commercially available Zigbee-controllable lamps and luminaires for a low-cost networked lighting control retrofit. Zigbee is an IEEE 802.15.4-based specification for wireless communication in personal area networks. It is intended for low-power operation in applications such as home automation, medical devices, and other low-power, low-bandwidth needs. Zigbee includes the entire network stack from physical to application layers.

**Figure ES-2: Task Light Version of Readings-at-Desk Controller**



*Source: Lawrence Berkeley National Laboratory*

**Intuitive, Standardized User Interfaces for Networked Lighting Systems**

Many modern lighting systems are confusing for and hard for building occupants to understand and operate. To address the problem, the research team created content to serve as the basis for a user interface standard for lighting controls. The content includes standard terms, symbols, and colors to help people more effectively control lighting systems. The user interface standard creates a consistent language for lighting control covering both basic and advanced capabilities and should influence the design of future lighting controls.

**Verifiable Performance for Networked Lighting Systems**

To address the difficulty of ensuring that advanced lighting control systems deliver their promised energy savings, the project team developed a new method for evaluating and specifying lighting system performance. This involved developing a set of evaluative metrics and reviewing current technologies for their ability to offer this information. The evaluation metric (lighting energy over time per unit area) allowed for comparison of measured lighting energy intensity to the lighting energy as reported by commercial technologies with energy reporting features to assess accuracy of reporting methods.

## Key Innovations

This project took advantage of advances in low-cost sensors, wireless communication, computation, and data storage to deliver these innovations:

- Energy harvesting sensors and open communication that enable autonomous placement of sensors throughout space in dense yet cost-effective networks, reliable operation over time, and seamless communication via open protocol with controlled endpoints

- Desktop-based daylight sensing and control that more accurately characterize the light levels that matter for users and wireless sensor architecture that allows situation and movement of the sensor.

- Intuitive, standardized interface elements for lighting that provide a consistent language for lighting control capabilities, enabling interoperability and competition in the marketplace.
- Verification of performance and metrics through Lawrence Berkeley National Laboratory FLEXLAB® testing, which enables comparison of systems' energy reporting accuracy and an energy intensity metric that provides the basis for outcome-based lighting code that focuses on real-world performance rather than installed capacity.

## Project Results

FLEXLAB® testing for the PermaMote showed significant energy saving through occupancy and daylight control, as shown in Figure ES-3. With the occupancy control and daylight dimming features, the experimental offices saved around 73 percent energy on average during the week-long test.

As part of the research to develop an open application programming interface to allow facility managers and owners to extend the reach of wired lighting systems, the research team developed a reference data model to communicate between existing lighting systems and the PermaMote sensors. The intent of standardizing the data model is to enable vendor interoperability.

**Figure ES-3: Comparison of Average Hourly Energy Consumption Across Test Offices**
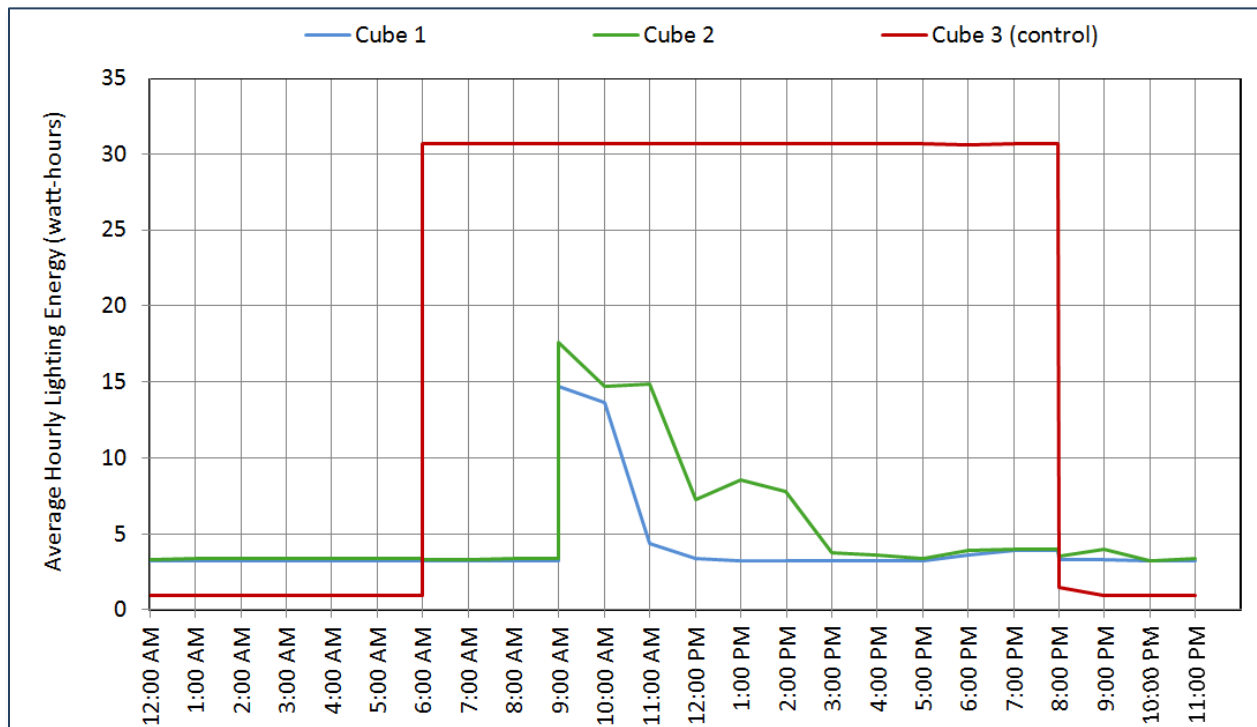


Source: Lawrence Berkeley National Laboratory

**Figure ES-4: Proposed Data Model**

## Data Elements for Standardization

### General Elements

- General Identification
  - Manufacturer name
  - Brand name
  - Model name/number
- Unique Identification
  - UUID
  - Local identity
- Timestamp
- Power Consumption
  - Current power use
  - Current energy use
  - Power source

### Lighting-specific Elements

- Current Status (on/off)
- Brightness level/ dimming level
- Occupancy
- Color control
  - Current hue
  - Current saturation
- Color temperature
- Scenes
  - Available scenes
  - Current scene
- Schedule
- Daylight sense

*Source: Lawrence Berkeley National Laboratory*

In addition to the project team's research, Lawrence Berkeley National Laboratory (LBNL) engaged with the American National Standards Institute (ANSI) Committee C137, which is in the process of creating an ANSI standard for lighting control systems. As part of the committee's work, LBNL participated in the development of a standard data model that will be a part of the eventual standard.

For the Readings-At-Desk controller, FLEXLAB® testing showed significant energy saving through daylight harvesting and more precise desktop illuminance, as shown in Figure ES-5.

**Figure ES-5: Performance of One Readings-At-Desk Controller During One Week of Testing**
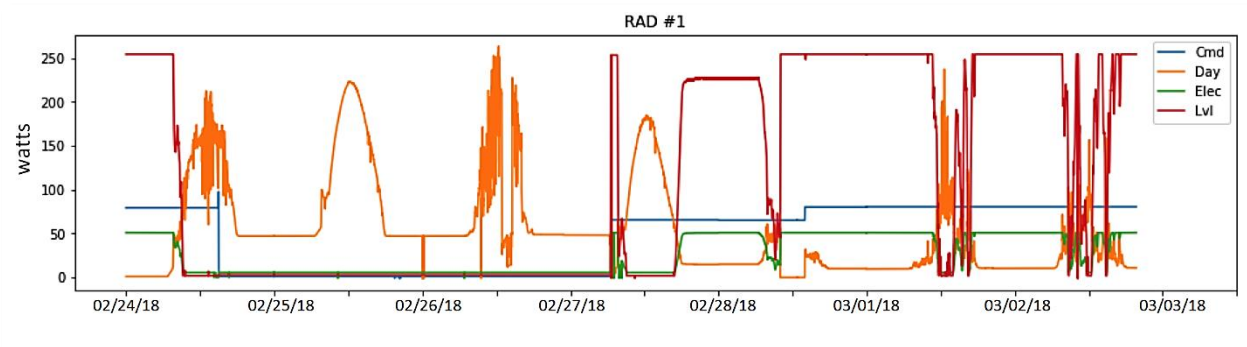


*Source: Lawrence Berkeley National Laboratory*

For the standard user interfaces portion of the task, the project team extensively surveyed the content of user interfaces on products currently for sale. The team then crafted the content for a potential standard (Figure ES-6), and presented it to a suitable

standards development organization, the National Electrical Manufacturers Association, which sponsors the ANSI Committee C137. LBNL met with the ANSI committee several times throughout 2017 and 2018 and presented the proposed content to the committee. As of the publication date of this report, the ANSI committee is still considering the proposed standard.

**Figure ES-6: Lighting User Interface Elements**

| Lighting in General | Basic Switching | Bright-ness | Dynamic Control | Color | Other (Shades, etc.) |
|---|---|---|---|---|---|
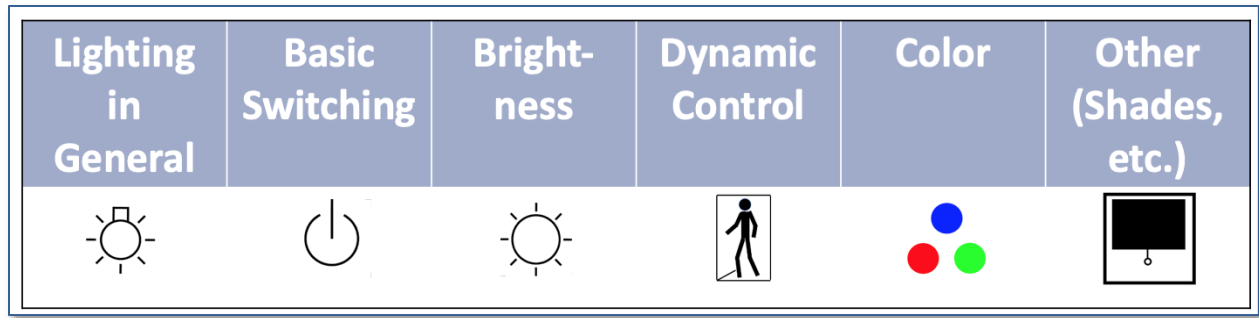


*Source: Lawrence Berkeley National Laboratory*

For the task on verifiable performance of lighting systems, the project team developed a more effective metric for capturing the actual energy effect of a lighting system over time, which is the energy usage intensity (lighting energy per unit area over time); the typical lighting system metric in building code is simply installed capacity (lighting energy per unit area), which says nothing about system energy performance over time for systems that are highly controllable and dynamic. The team then developed software to validate the ability of lighting systems to monitor their energy use, for purposes of calculating an energy use intensity (defined as the measured building's annual energy consumption, either in British thermal units or kilowatt-hours, relative to its gross area in square footage). Three commercially available lighting systems were then tested in FLEXLAB® to compare their energy reporting capabilities (some systems measure energy, with different degrees of accuracy; whereas, others calculate energy based on assumptions and lookup tables) to the values measured by FLEXLAB®. Results of this testing are shown in Table ES-1. One observation from this testing is that lighting systems that directly measure their energy use tend to report more accurate data, compared to those that estimate energy use using a model.

**Table ES-1: Networked Lighting Control System Energy Reporting Data Compared to Reference Measurements**

| | Reference Energy Data (Wh/ft$^2$) | Reported Energy Data (Wh/ft$^2$) | Daily Error: Reported − Reference (Wh/ft$^2$) | Daily Error/ Daily Total (%) |
|---|---|---|---|---|
| System 1 (calculated) | 4.66 | 5.95 | 1.29 | 27.7% |

| | Reference Energy Data (Wh/ft$^2$) | Reported Energy Data (Wh/ft$^2$) | Daily Error: Reported − Reference (Wh/ft$^2$) | Daily Error/ Daily Total (%) |
|---|---|---|---|---|
| System 2 (measured) | 6.10 | 6.13 | 0.03 | 0.5% |
| System 3 (measured) | 9.86 | 9.07 | −0.78 | −7.9% |

*Source: Lawrence Berkeley National Laboratory*

## Benefits to California

By capturing detailed environmental and device level sensory information, networked lighting controls systems can implement strategies to reduce energy consumption and manage building lighting load without negatively affecting lighting characteristics, such as dim level or color, so that user comfort is unaffected. Overall benefits related to project outcomes include:

- Helping California achieve its policy goal of 60 – 80 percent reduction in lighting energy use with an estimated 1,600 gigawatt-hours per year statewide savings potential from these solutions (20 percent incremental savings added to average savings from Title 24-mandated advanced controls of 38 percent).
- Reducing cost to install and commission advanced lighting controls, targeting existing buildings (Assembly Bill 758).
- Pervasive sensing and control that improve occupant satisfaction and productivity.
- Standard user interfaces that make lighting systems easier to use and avoid energy waste.
- New performance metrics that allow outcome-based codes.

## Conclusions and Recommendations

Through this project, promising new networked lighting controls solutions were developed with easily implemented sensor packages for more accurate representation of conditions in the built environment, thereby providing better lighting control. These systems include the low-cost sensing, distributed intelligence and communications platform, the PermaMote, and the Readings-At-Desk system, which uses illuminance measured at the desktop to control overhead lights. Functional testing of these systems yielded generally positive results; the technologies controlled lights as intended through sensor inputs, programming, and wireless protocols. Field evaluations of both systems also proved their viability in actual occupied office environments. These technologies are expected to continue to develop through further research efforts and eventually transition into commercial viability. The project team also developed a reference data model for lighting and engaged with the ANSI Committee C137 for adoption as an

industry standard. More work is needed with this committee to adopt the standard data model.

For lighting user interfaces, this project developed standard content and proposed it to the appropriate body for adoption. The content was derived from extensive analysis of existing user interface standards as well as examination of the controls found on many diverse products in the market. More work is needed to turn this content into a final standard.

With the advent of energy reporting features from many networked lighting control systems, and from the FLEXLAB® study of several systems, the project team found it is possible to track lighting energy outcomes from a new lighting system. If self-reported demand and energy use from lighting systems is reliably accurate (within an acceptable tolerance), building codes for lighting systems could move from the prescribed lighting-power-density approach to an outcome-based energy use approach. In general, the measurement-based approach was more reliable and able to address baseline issues, and therefore, preferred for validation purposes.

# CHAPTER 1:
# Introduction

## Background

The California Lighting Action Plan (LAP) calls for a 60 percent to 80 percent reduction in lighting energy use by 2020. Additionally, the Lighting Efficiency and Toxics Reduction Act (Assembly Bill 1109) requires significant reduction in the average statewide electrical energy consumption from 2007 levels—a 50 percent reduction in indoor residential lighting and a 25 percent reduction in indoor commercial and outdoor lighting. These laws and policy directives from the State of California are driving the urgency to reduce lighting energy consumption.

## Project Description

This project advances lighting control system innovation to help realize California's energy goals. Research, driven by the convergence of four major trends in commercial buildings, is opening a portal to new opportunities to pursue dramatic energy savings through advanced, automated, and intelligent control systems:

- Increased control granularity: An increasing number of building systems are now controllable with a level of discretion that has not been possible before, particularly in LED systems that are fully dimmable and individually addressable.

- Increased sensor availability and use: Environmental sensors such as light sensors, occupancy sensors, carbon dioxide ($CO_2$) sensors, and power meters are becoming less expensive to install in buildings.

- Pervasive communication through wireless networks: Wireless networks are almost ubiquitous in buildings today. Wi-Fi, Bluetooth, ZigBee and others are increasingly used for building control purposes.

- Low-cost computation: Bundling digital intelligence at sensors and lights adds virtually no incremental cost. Coupled with communications, this enables interactive, optimized, rule-based control and fault detection systems at very low cost.

This project, "Developing Flexible, Networked Lighting Control Systems That Reliably Save Energy," is a comprehensive strategy to make the energy use of all plug loads observable, thereby enabling users to more easily control those loads to save energy, with four technical tasks as follows.

### Objectives

- Develop and promote low-cost sensing, distributed intelligence, and communications.

- Create an effective task ambient daylighting system integrating sensors with data-driven daylighting control using open application programming interface (API).
- Develop standard user interface elements for lighting control systems.
- Develop industry-accepted, outcome-based lighting system methods, metrics, and controls testing.
- Target California's Title 24 Building Energy Efficiency Standards revisions in 2022 to incorporate next generation lighting control systems.
- Identify next generation lighting control systems technology solutions to realize energy savings.
- Work with standards organizations to add capabilities to their protocols.

## Project Tasks

- Develop and test ubiquitous, low-cost sensing, distributed intelligence, and communications.
- Develop and test task ambient daylighting—data-driven daylighting control.
- Develop standard user interface elements.
- Validate outcome-based lighting systems: methods, metrics, and controls testing.

## Anticipated Benefits

- Overall estimated energy savings potential of advanced, networked lighting controls is estimated to be more than 20 percent; equivalent to 1.6 TWh per year for California after technologies have been implemented in commercial building stock.
- The result will be that ratepayers benefit from greater electricity reliability and lower costs by enabling building owners and occupants to better understand, interact with, and control lighting system energy use.

## Smart Lighting Controls Literature Review

Substantial research and development has been conducted to improve lighting controls and controls algorithms. The onset of Internet of Things (IoT) technologies and networked sensors capabilities has provided controllers with more points to analyze and on which to make decisions. Singhvi (2005) runs an optimization problem that maximizes the user comfort with respect to the lighting system while using the least energy, demonstrating this using both open-loop and closed-loop control strategies in a small set up with 10 60-watt lamps and 12 sensor nodes. Rather than built-in occupancy sensors, these used an occupant's RFID tag and similar methods (additional hardware) to detect occupant location. Karapetyan (2018) uses mobile applications and sensors on wearable devices like Google Glasses and smart watches to obtain environment data and control lights in the space. This work tries to minimize energy consumption from fixtures while meeting user-specified requirements, demonstrated by

controlling LIFX smart bulbs (https://www.lifx.com/) bulbs using sensor measurements from smart phones in a residential environment. The system represents "… a practical application of IoT-based sensing and actuation … for smart lighting control with oblivious mobile sensors, which seeks to induce adaptive continuous control in real time without complete knowledge of the dynamic uncertain environment."

In a different approach, occupancy and location information is retrieved from the Wi-Fi network by Zou (2018) and this data, in conjunction with user requirements, is used to minimize the energy consumption of all the lights while ensuring that the user requirements are met. This research conducted a 24-week test in a commercial space and demonstrated the energy benefit of Zou's algorithm. Koroglu (2014) introduces a distributed illumination balancing algorithm that controls light levels in a space where the zones are not sequestered. The Williams (2012) literature review compiles and compares energy savings findings for the major lighting control strategies implemented in commercial buildings, from occupancy-based lighting control, daylight-based control, control based on personal preferences, and institutional tuning.

Conclusions from a few other research efforts of note to this project's efforts include:

- Magno (2015) proposes "[a] novel system to control LED lighting with a low cost and low power wireless sensor network ... [which] requires the deployment of complementary sensors with Zigbee radio... experimental results indicate that the proposed system outperforms the state-of-the-art with a significant reduction of power consumption and cost."

- Dikel (2018) demonstrated "… substantial energy savings potential (and other potential benefits) associated with a high-resolution sensor network combined with a spatially defined and granular LED lighting system… networked and solid-state nature of LEDs encourages the co-location of sensors to provide a real-time, high-resolution sensor network. High density of sensors supports more accurate occupancy sensing, permitting substantially shorter timeout periods and localized daylight harvesting, to ensure that electric lighting is only provided where it is needed, when it is needed, and in the amount it is needed, within zones of a few square meters."

- Peruffo (2015) considers "daylight and occupancy adaptive control for a wireless mesh networked lighting system with multiple sensor-equipped luminaires and a central controller. … The light and occupancy sensors respectively determine net average illuminance and occupant presence within their sensor fields-of-view and report these values to a central controller [which] computes dimming levels [via] stand-alone proportional–integral control law … To make the performance of the lighting system robust to wireless impairments, transmission redundancy and enhancements in the controller are considered. The performance of the proposed system is evaluated for an example open-plan office lighting model under different daylight and occupancy scenarios and a ZigBee wireless network."

# Report Organization

Chapter 2 describes the development of low-cost, wireless and energy harvesting sensors that can connect to existing lighting control systems using an open API. These sensors were designed in a way that would allow building owners and managers to extend the reach and capability of already-installed lighting control systems in a simple and cost effective manner. The project also supported further developments and a lab evaluation of an effective task ambient daylighting system that integrates sensors with data-driven daylighting control using an open API. This technology, the "Readings-At-Desk" (RAD) system, uses illuminance measured at the desktop, with user-desired illuminance inputs, to control overhead lights. The chapter also details the research team's efforts to develop a new reference data model for improved interoperability with other lighting systems that could be used to communicate between existing lighting systems and the developed low-cost sensors. The activities leading up to development of the new model (identifying research gaps; listing of topics necessary for a standard data model; examination of existing standards; analyzing them for consistency, coverage, and quality; and recommendations for best practices) are discussed, and the proposed data model is presented, as well as a mapping of the data model elements to lighting controls standard digitally addressable lighting interface (DALI) 2.0, currently in development.

Chapter 3 outlines efforts to create content that could be the basis for standardizing user interfaces for networked lighting systems.  Building occupants find many modern lighting systems confusing to understand and operate. To address this problem, manufacturers could design their products to a user-interface standard that could be adopted in the United States at the national level and eventually internationally to make products more effective at saving energy. The premise underlying the effort is that consistent controls help humans understand the capability and status of lighting controls they encounter and more easily express their preferences.

Chapter 4 discusses some of the efforts and challenges related to developing methods for evaluating and specifying lighting systems performance, focusing on energy-reporting capabilities. Examples of outcome-based evaluative metrics are proposed for lighting design and performance that could be validated through lighting controls energy self-reporting. The chapter presents a review of several current technologies for their ability to offer this information, including a quantitative evaluation of the effectiveness of networked lighting systems' energy reporting capabilities to provide outcome-based metrics (energy usage over time, as opposed to prescribed lighting power densities). Energy monitoring from select networked lighting controls systems was validated for accuracy by testing in LBNL's FLEXLAB®.

Chapters 5, 6, and 7 cover technology transfer, benefits to California, and future research direction. These chapters summarize outcomes of the research efforts toward these ends and provide a picture of where research efforts might be directed in the future to continue progress in developing flexible networked lighting systems that reliably save energy.

# CHAPTER 2:
# Sensor-Rich Networked Lighting Systems

## Summary

Advanced lighting controls are among the rapidly evolving technologies that use wireless communications, embedded sensors, data analytics, and controls to optimize building systems in real time. One of the main project goals was to develop new networked lighting controls solutions with dense sensor packages that could be implemented in the built environment in locations that more accurately represent occupants' experience of the space, thereby providing better control points.

To this end, the project developed a low-cost sensing, distributed intelligence and communications platform, the PermaMote self-powered, sensor and controller for lighting applications. The PermaMote includes multiple sensor types (light level, light color, motion, temperature, humidity, pressure, acceleration, and so forth) as well as energy harvesting capability, contained in a small and light form factor, and uses industry-standard networking protocols, along with a new reference lighting data model, for improved interoperability with other lighting systems. The project also further supported developing an effective task ambient daylighting system that integrates sensors with data-driven daylighting control using an open API. This technology, the "Readings-At-Desk" system, uses illuminance measured at the desktop, with user-desired illuminance inputs, to control overhead lights. The RAD sensors located at the desktop, easily integrate with commercially available Zigbee-controllable lamps and luminaires for a low-cost networked lighting control retrofit.

## Development of PermaMote

The research team developed a low-cost sensing platform with distributed intelligence and communications. The PermaMote is a self-powered sensor platform for lighting applications, with multiple sensor types (light level, light color, motion, temperature, humidity, pressure, acceleration). The energy harvesting capability of the PermaMote permits it to operate for an indefinite period in areas with regular access to light, avoiding the expense of battery replacement. The small size and weight of the PermaMote, shown in Figure 1, allow it to adhere to almost any surface in the work environment, which permits more accurate measurement and control of illuminance on the work plane. The high level of integration and standardization allows production of PermaMotes at a projected high-volume cost that is much lower than current commercially available self-powered sensors.

**Figure 1: PermaMote Design**
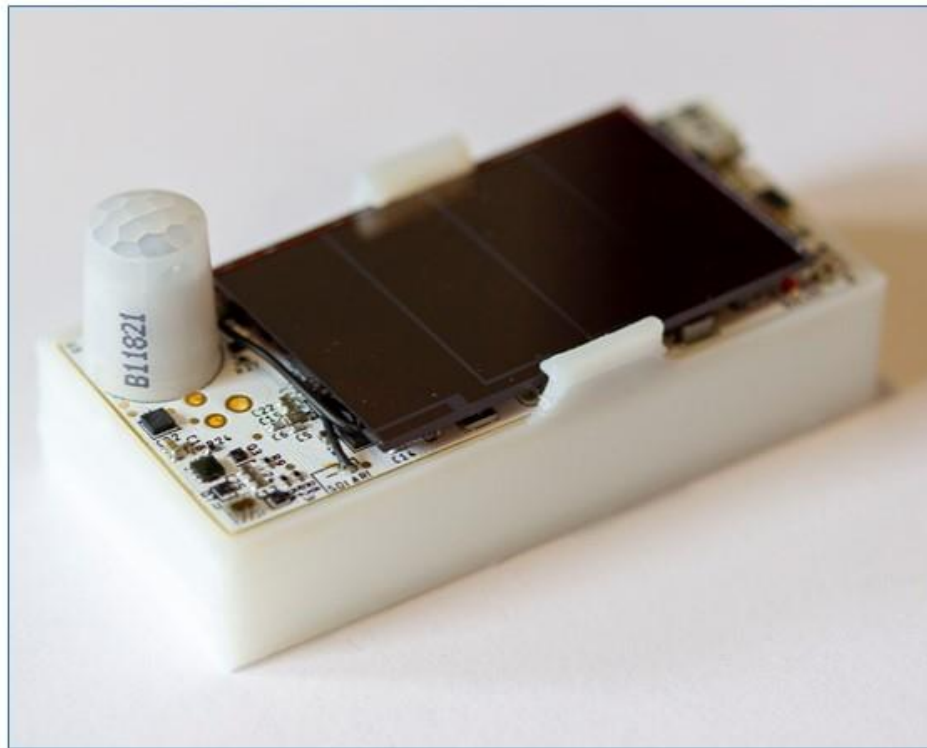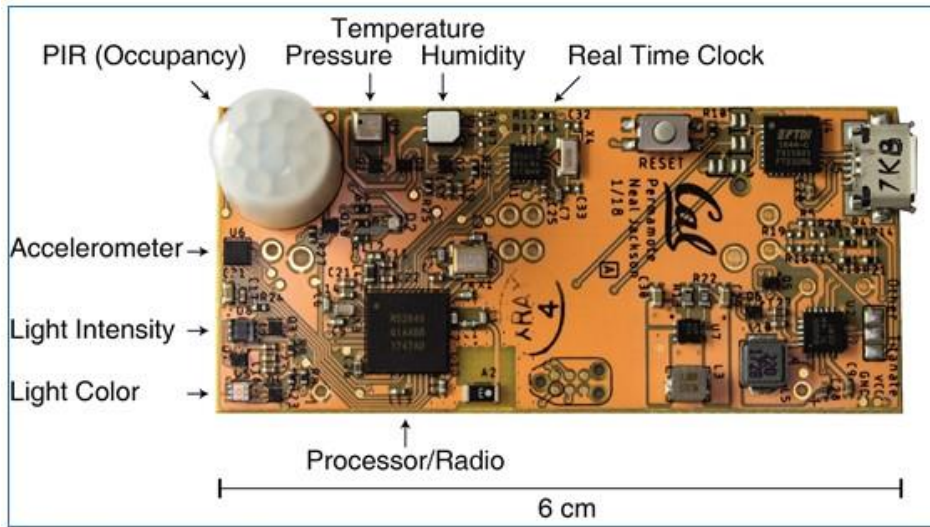


*Source: Lawrence Berkeley National Laboratory*

Most existing commercial lighting control systems have sensors that are wired into existing luminaires or connected to the building's electrical backbone. To capture maximum energy savings from lighting control, highly granular control over primary and task lighting is required as well as the ability to measure a number of important variables like occupancy. These two critical gaps in technology were addressed by developing low-cost, wireless, and energy harvesting sensors that can connect to existing lighting control systems using an open API. Having these would allow building

owners and managers to extend the reach and capability of already-installed lighting control systems in a simple and cost-effective manner.

The PermaMotes are capable of implementing most major lighting control strategies such as occupancy-based control, daylight-integrated control and personal as well as institutional tuning (institutional tuning refers to dimming lighting fixtures below their original nameplate ratings to achieve appropriate light levels at the task plane). The sensors will be calibrated for two particular use cases that are most common in commercial buildings: 1) perimeter private office with single occupancy, and 2) an open plan office with multiple occupants. Based on the use cases and a market survey of existing specifications of sensors being used in commercial lighting control systems, specific functional specifications for the sensors were decided upon.

In addition, cost targets for each sensor module were developed based on prevailing costs and predicted reduction in the near future based on economies of scale. Accordingly, it is expected that the sensor module designed as per the specifications will cost approximately $15 to $20 per unit at high volume of 10,000 or more units. The system lifetime is assumed to be between 5 and 10 years and will be determined by the final design and implementation. The batteries present in the sensors, which are rechargeable and are charged by the on-board photovoltaic panel, are likely to be the most critical factor in determining lifetime.

# Development of Readings-At-Desk Controller

This project also focused on refining and field-testing a novel daylight harvesting system. This device is a lighting controller called the Readings-At-Desk controller, which is designed for placement within office users' workstations. The RAD controller: 1) measures the amount of light present in the workstation, 2) allows users to define how much light they desire to have in the workstation, and 3) wirelessly communicates to wirelessly controllable overhead lighting systems that illuminate the workstation to the extent that measured light levels match requested light levels where possible. Users interact with the RAD controller by adjusting a slider that corresponds to the light level they desire, and the system automatically adjusts to maintain this light level as daylight levels increase or decrease.

Typically lighting control systems use daylight sensors located at the ceiling-plane. The advantage of using sensors that are co-located at the occupants' work-plane rather than at the ceiling-plane is clear. It is simply more accurate to measure work-plane illuminance directly than to try to estimate it from afar (that is, 5–8 feet above, or more, in the ceiling-plane depending upon the fixture or sensor location). Lighting conditions vary greatly within a space and throughout the day in non-linear ways that are extremely difficult to accurately model. Consequently, control systems that adjust lights based on ceiling-located sensors often over-dim or under-dim. In fact, many systems will over-dim for parts of the day (depriving users of needed lighting service) and under-dim at other times (missing opportunities for energy savings).

This project extends the RAD controller research and development that was originally funded by the California Energy Commission's (CEC's) Energy Innovations Small Grant (EISG) program. The EISG project explored the feasibility of a local-sensing approach to daylight harvesting and resulted in four prototype systems. In these prototypes, the RAD controller was housed in an LED task light—a convenient location as the task lamp has power that can be used by the RAD controller, is likely to be placed at a location where lighting is needed, and allows a light sensor to be placed on the top of the task light head—a location where it is unlikely to be shaded or obstructed. These prototypes required a second piece of hardware to be installed in the ceiling to control the overhead lights. The ceiling device would receive a Wi-Fi signal from the RAD controller (for example, turn light up one step) and convert this to a 0 – 10-volt (V) control signal for controlling 0 – 10-V ballasts or drivers.

## Refinement of Readings-At-Desk Controller

Starting with an initial field test, researchers then turned their attention to developing the next generation of RAD controller. Refinements of the new RAD controller were driven by the following three factors:

1. Results from initial field test: While the results from the initial field test were largely positive, there were a number of performance and user interface items that were identified as areas for potential improvement. These included developing a more robust networking architecture, simplifying systems installation associated with the control of the overhead lamps, and developing a more intuitive user interface.

2. Changes in the Marketplace: Several years had passed between the initial development of the original RAD controller and the initiation of this new development phase. In the meantime, the wireless lighting controls landscape had been evolving rapidly and in ways that presented new opportunities for the RAD controller. Specifically, the emergence of open wireless lighting control architectures, such as Zigbee, allowed researchers to focus entirely on the workstation-based controller that then could wirelessly connect and control any lamps or luminaires that were based on these open architectures. This approach had the advantages of simplifying system design and removing the significant installation and cost barrier associated with the prior system's ceiling controller.

3. Focus on Commercialization: Initial prototypes were constructed primarily as a "proof-of-concept" with little attention or intent placed on commercialization, resulting in systems that would be impractical and expensive to commercially produce. In developing the new generation RAD controller development, researchers developed "pre-commercial" prototypes where cost and scalability were important design considerations and constraints.

The development of the new RAD controller culminated in the design and production of a custom circuit board (see Figure 2) and associated software that used a microcontroller with an integrated Zigbee radio.

**Figure 2: New Generation Readings-At-Desk Controller Circuit Board**
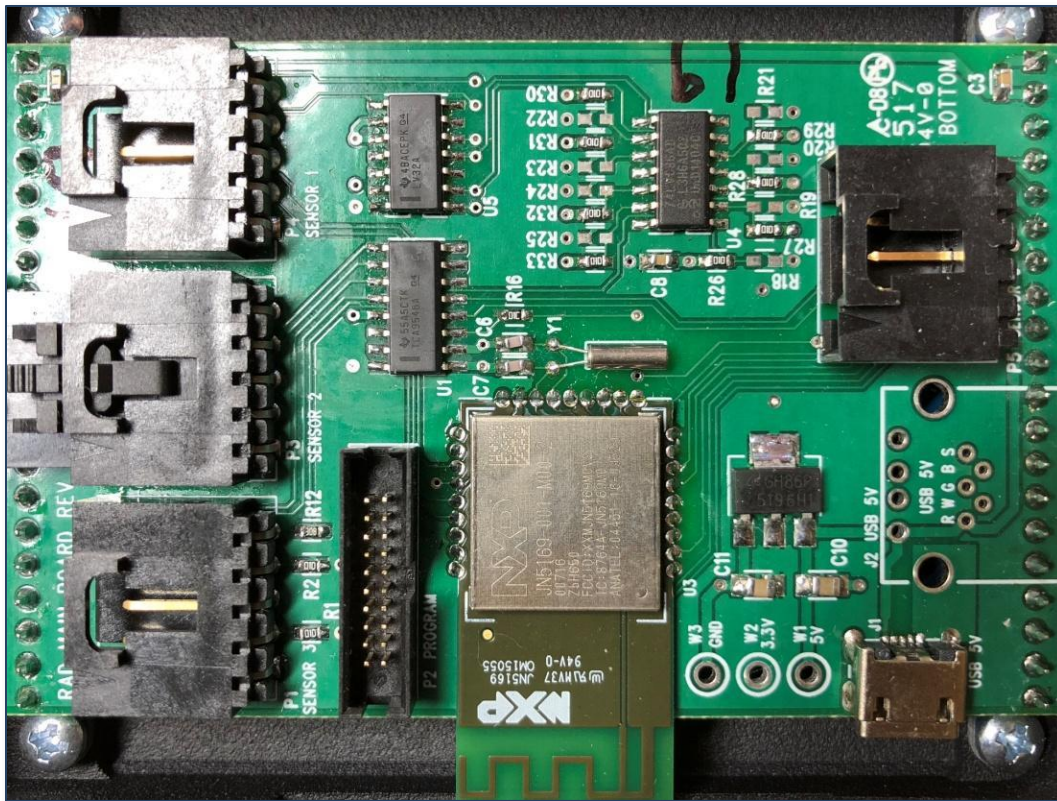


*Source: Lawrence Berkeley National Laboratory*

Key technical specifications of the RAD controller include:

- NXP JN5169 low-power Microcontroller with integrated Zigbee radio
- 2.8" color touchscreen display
- Tri-stimulus color sensor
- Three additional I2C sensor sockets for additional measurement needs (for example, temperature, volatile organic compounds (VOC), other light spectra, and so forth)
- Four additional digital inputs (including occupancy sensor measurements)
- USB powered

RAD controllers were produced and ultimately field tested in two different form factors. Figure 3 below shows the first embodiment in which the RAD controller is housed in a custom 3D printed case approximately 3" x 2" x 1" and is designed to either sit on the users' desk near their primary work area or mount to their monitor. In the photo on the left, the light sensor is seen on the top of the RAD controller while the photo on the right shows the touchscreen that displays the current light level and allows users to increase/decrease their requested light level by dragging a virtual slider.

**Figure 3: Desktop Versions of Readings-At-Desk Controller**



*Source: Lawrence Berkeley National Laboratory*

The photos in Figure 4 show another embodiment in which the RAD controller is integrated into a task lamp. This embodiment places the light sensor remotely to the top of the task lamp where it is unlikely to be shaded and is closer to the user's eye level.

**Figure 4: Task Light Integrated Version of Readings-At-Desk Controller**



*Source: Lawrence Berkeley National Laboratory*

Figure 5 presents a schematic of the RAD controller operation from either of these embodiments. As shown, the RAD controller receives input information on actual light levels (as measured from the sensor) and requested light levels (from user interface) as inputs to its control algorithm. These are used to create output Zigbee control commands to the connected Zigbee lamps and/or luminaires.

**Figure 5: Control Schematic for Readings-At-Desk Controller**
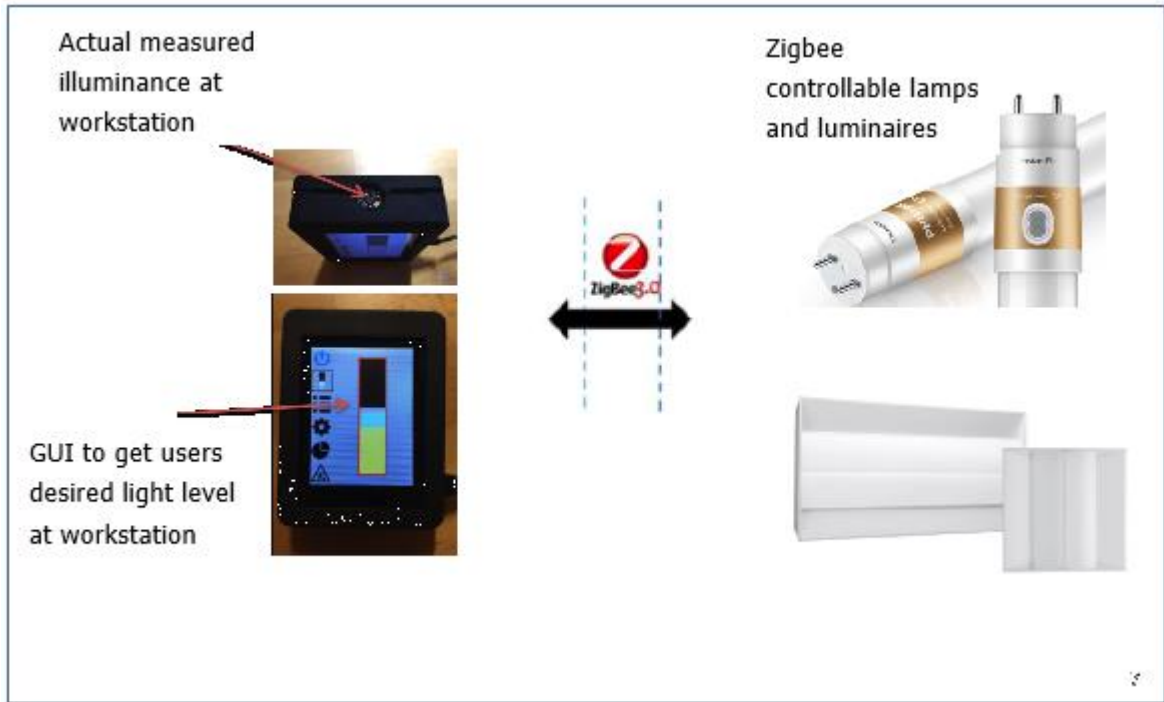


*Source: Lawrence Berkeley National Laboratory*

These systems were built, tested, and refined over a several-month period. Ultimately 20 RAD controllers (10 desktop, 10 task lamp integrated) were produced for field-testing. The researchers note that several industrial partners provided significant in-kind contributions during this project. These include a close collaboration with LightCorp, which provided the tasks lamps that were used and provided significant engineering support in modifying these task lamps to accept the RAD controller and associated sensors. The researchers also acknowledge the significant assistant provided by Philips Lighting. Philips provided pre-production prototypes of their Zigbee controllable EasySmart TLEDs during the project's development phase and provided valuable engineering support related to Zigbee software development.

# Lab Testing of Networked Lighting Systems

## Testing of PermaMote Sensors

### Functional testing

The occupancy and light sensors integrated into the PermaMote were first tested in the lab to verify performance. Further details on functional testing of the sensors are provided in Appendix B.

For occupancy, a protocol was defined for lab testing carried out to characterize the PermaMote sensor's ability to detect motion, per the performance targets from the sensor specification. The PermaMote's performance was characterized according to principles laid out in the NEMA WD 7-2011 (R2016) Occupancy Motion Sensors Standard.

The PermaMote occupancy sensor was found to be responsive to motion, within expected sensitivity based on manufacturer specification on field of view for the sensor at the mounting height tested (9' 4"). For major motions (subject movement between 3' by 3' cells under sensor), the detection area was around 21' x 18', close to our sensor specification of 20' x 20' (albeit that specification was for 8' mounting height). For minor motions (smaller motions within the 3' by 3' cell) the field of view was found to be around a 6' radius from sensor center, better than the sensor specification requirement of 5' x 5' detection area.

A test protocol was also developed for the light sensor. The objectives of light sensor testing were to characterize the Mote sensor's ability to measure visible light intensity (in lux) as well as color parameters (red, green, blue, or RGB, counts) that can be converted to color temperature (in degrees Kelvin). The performance of two PermaMotes was evaluated under several light sources and different conditions. Performance was characterized against reference lighting intensity and color temperature measurements from a lab grade spectral illuminance meter, with a second photosensor serving as a check against the reference meter.

The PermaMote sensors were found to be proportionally responsive to light intensity, in agreement with the reference illuminance measurements. Dynamic range was found to be from zero to over 4000 lux, well over the 2500 lux specification. However, the sensitivity of the sensors appears to be low, and may require some adjustment to sensitivity settings or post processing. For light levels below 1000 lux as measured by the reference sensor, the sensors' illuminance measurements were found to be about 20 percent lower than actual illuminance as measured by the reference sensor. At lower light levels the sensors more closely matched reference measurements and at higher light levels the Mote sensors were found to deviate further.

The research team measured color temperature (CCT, Kelvin) and spectral data by the reference sensor as well. The PermaMote sensors measured RGB (analog), which could be post-processed to CCT for comparison with measured CCT results.

**Integrated System Testing**

With the PermaMote sensor package successfully characterized through sensor testing (post design), it was then important to test PermaMote sensors' functionality when integrated into a lighting system architecture. Prior to deploying sensors and controls in occupied space, basic functionality of the integrated system (PermaMote communicating with a lighting controller and light source) had to be proven. Several tests were carried out to ensure stable and proper operation. The PermaMotes were paired with wirelessly controlled LED replacement lamps (TLEDs) for fluorescent fixtures. The system architecture that was implemented for the functionality and performance tests is shown in Figure 6.

**Figure 6: Zigbee TLED Controlled by Intelligent Task Light**
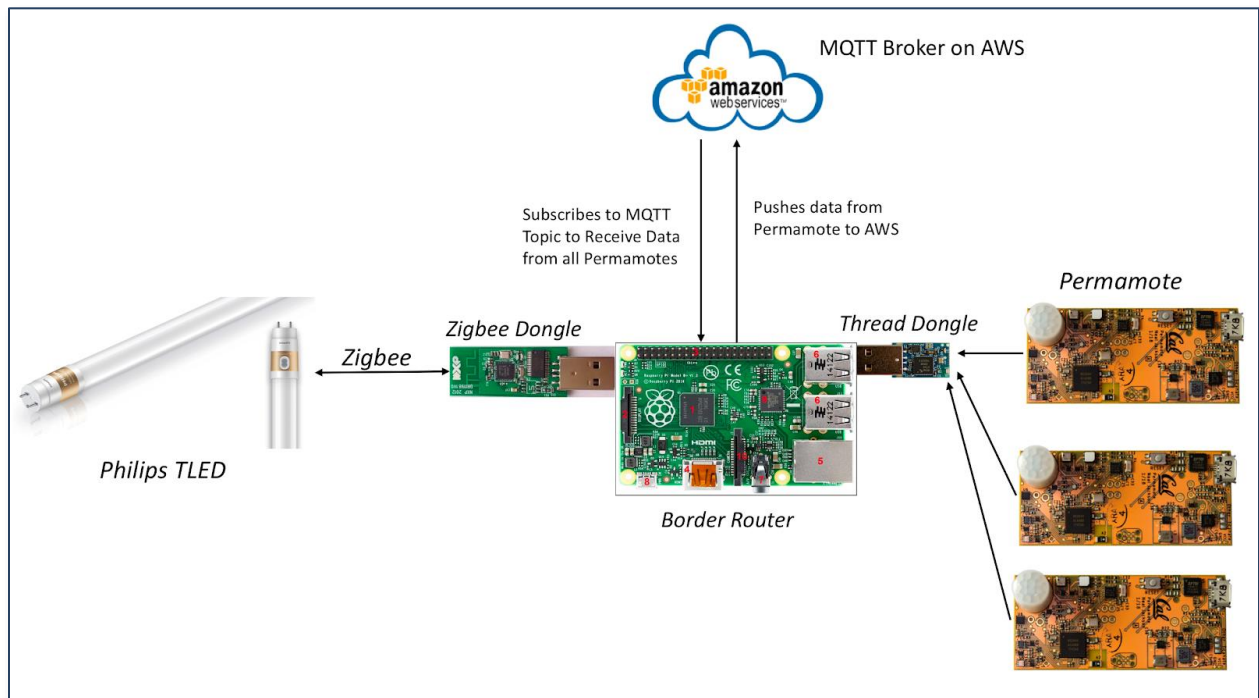


*Source: Lawrence Berkeley National Laboratory*

Once the functionality of the occupancy control and daylighting control features were proven, the PermaMotes were ready for performance testing in an occupied environment over time, to measure and verify operation and energy savings in a more "real-world" implementation. This test was designed to characterize performance of the wireless control, self-powered features, and daylighting and occupancy sensing performance. A networked lighting system of that architecture was set up for installation in the FLEXLAB® Lighting and Plug Load occupied testbed, which is a cubicle-style open office environment with a typical pattern of occupancy during workdays. The layout for this test is shown in Figure 7.

This project tested the daylighting and occupancy functions and the lighting and energy performance of the wireless self-powered sensors for control of overhead lighting via

wirelessly controlled LED replacement tubes. The FLEXLAB® testing consisted of three occupied offices with south-facing windows; a reference office with basic scheduled lighting control, and two test offices where the PermaMote lighting controls were implemented. All offices had suspended direct/indirect two-lamp T8 fluorescent fixtures.

PermaMotes were placed at identical locations in each office (on the desk surface, as well as on cubicle walls and the ceiling). Several PermaMotes were placed in each office to capture spatial variations in illuminance measurements. In the reference office, the devices only measured and reported light and occupancy. In the test offices, the PermaMote occupancy sensors were used for automated on/off control and the photosensors were used to measure light levels and control the electric lighting to dim or brighten to meet setpoint.

**Figure 7: Sensor Layout for Performance Test in FLEXLAB®**
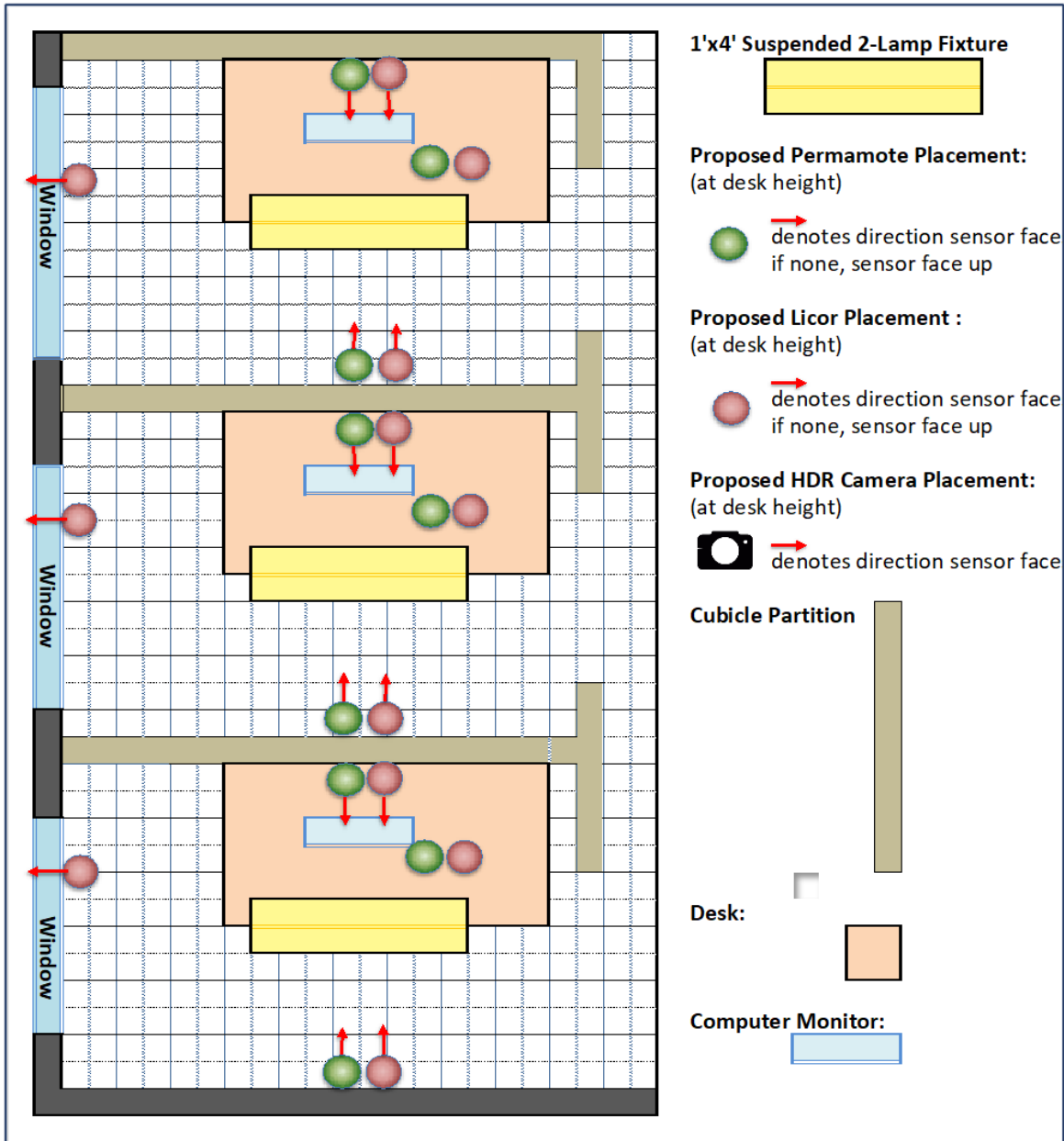


*Source: Lawrence Berkeley National Laboratory*

The devices used in the test setup were PermaMote sensors, wirelessly controlled TLEDs and compatible suspended direct-indirect fixtures, and sensors and loggers to obtain reference illuminance levels for comparison. A Wattstopper digital lighting management (DLM) system was used to control a baseline lighting system (same fixture and TLEDs but programmed only for scheduled daily on/off operation).

Glare parameters were measured in the test space through time (weekend test only to avoid disturbing occupants with high dynamic range [HDR] cameras) to compare with data from the wireless sensors to establish relationships between spatial illuminance variations and measured glare data, using daylight glare probability as measured by

HDR cameras and comparing HDR data to illuminance data. The setup for this test is shown in Figure 8.

**Figure 8: Sensor Layout for Glare Testing in FLEXLAB®**
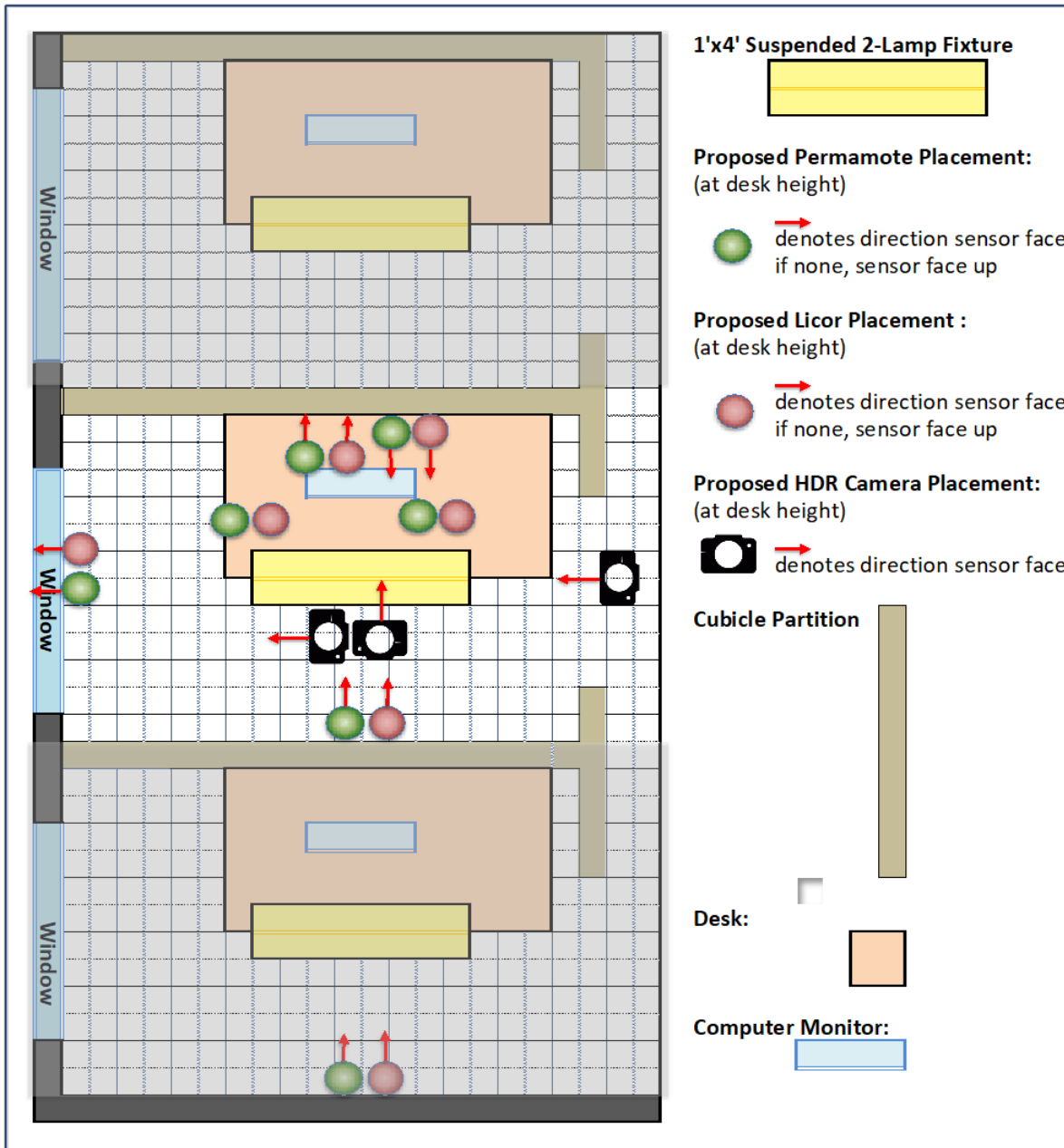


*Source: Lawrence Berkeley National Laboratory*

Overall the PermaMotes performed as intended during the integrated testing of daylighting and occupancy control. They were successfully integrated into the lighting system via the architecture previously described and successfully controlled the lights based on sensor inputs and controls programming. The energy-harvesting feature of the motes also worked well; they operated successfully for the full two-week period.

*Occupancy*

Since PermaMotes are wireless and self-powered they can be placed anywhere in the office that is practical. In this test, the desk-based PermaMote that was used for daylight control was also used for occupancy control. It was found that the PermaMote on the wall and on the ceiling in cubes 1 and 2 had more reliable occupancy readings (closer to the reference narrow-field ceiling-mounted Wattstopper occupancy sensor) than the desk-based sensor, especially in Cube 1 as shown in Figure 9. A future implementation of the system could rely on the desk sensor for light level control and a sensor elsewhere for occupancy control.

**Figure 9: Occupancy Test Results from PermaMotes**
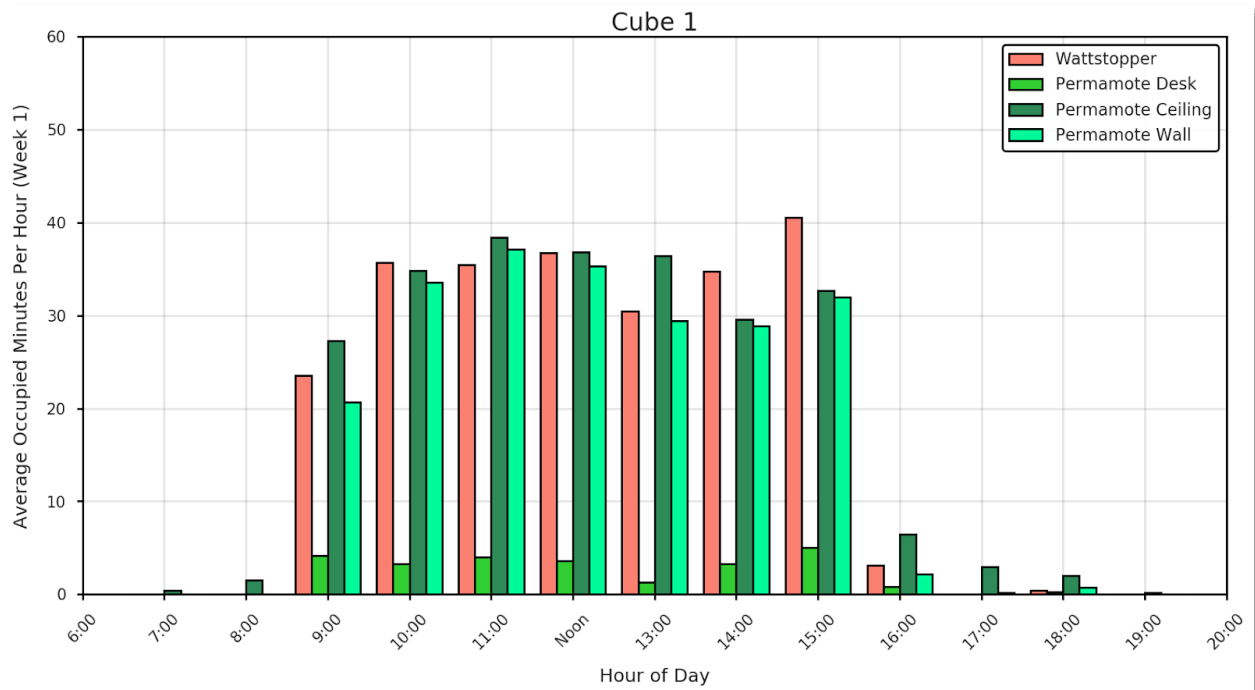


*Source: Lawrence Berkeley National Laboratory*

*Light Levels*

During the experiment, light levels were measured by PermaMotes placed at each cube's desk as well as on the ceiling over the desk facing down and on the nearest wall behind the desk, facing the desk. An example of the light levels measured through time at these various locations is shown in Figure 10.

**Figure 10: Light Testing of PermaMotes in FLEXLAB®**
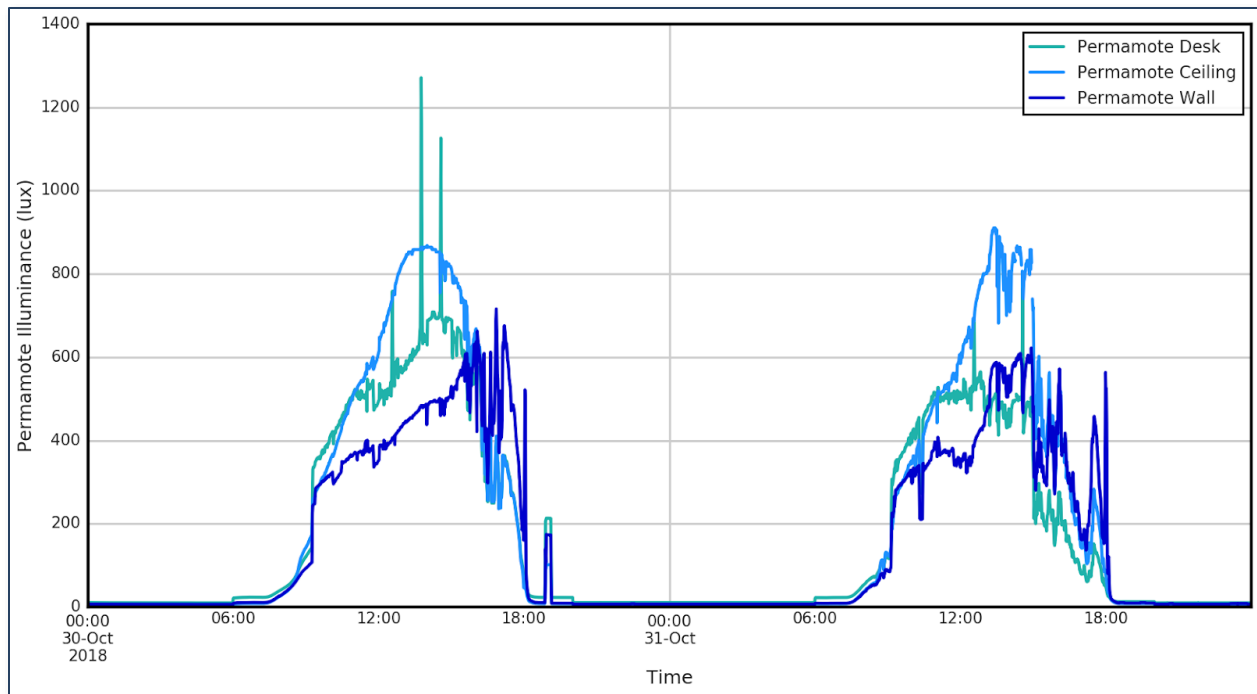
The premise of most closed-loop daylight control systems is to use a ceiling-mounted photosensor as the control point that is used to determine how much electric light to provide a space, even though the desk is the primary target of illuminance. The light at the ceiling will not be the same as at the desk, so the ceiling-based sensor approach assumes a consistent relationship between the illuminance at the one location and the other (that is, a consistent ceiling to task ratio). Typically, during set up and commissioning, the lighting system would be designed and possibly tuned to meet the desk illuminance target (in the absence of daylight) and whatever light level is measured by the ceiling sensor during commissioning as the daylighting setpoint that the system tries to maintain.

However, this premise will only maintain the intended desk illuminance target accurately if the relationship between the desk and ceiling illuminance is roughly constant and proportional. The PermaMote system avoids any uncertainty as to the relationship between illuminance in some other location in the office and the illuminance at the desk because the sensor can be placed directly on the desk. Consider the ceiling to desk illuminance relationships in Cube 1 illustrated below in Figure 11. For Cube 1 a ceiling mounted light sensor would have been a poor control point for lighting the desk, as the two were not well correlated.

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**Figure 11: Light Level Correlation Between Reading at Desk and Reading at Ceiling**
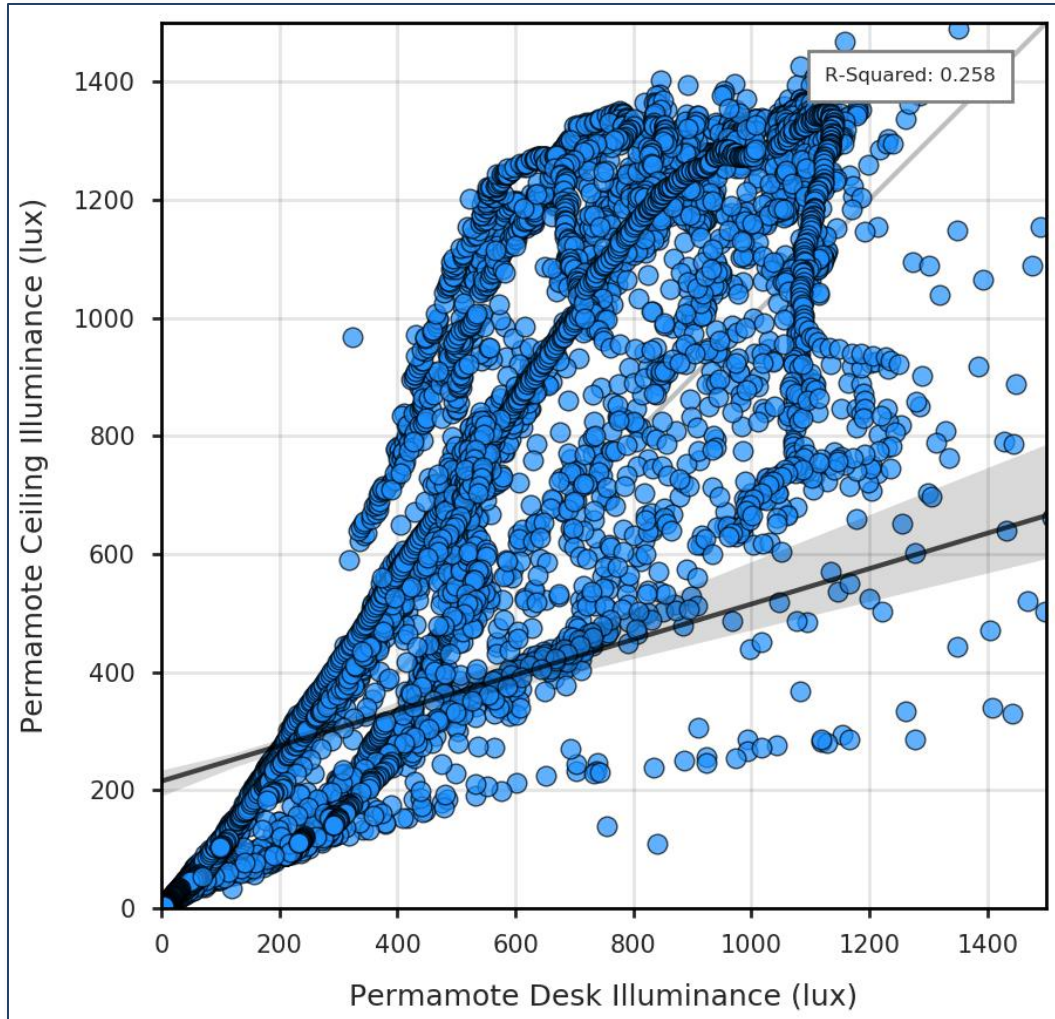


*Source: Lawrence Berkeley National Laboratory*

*Lighting Energy Savings*

The reference office, Cube 3, was controlled by a networked room controller with on/off relay scheduled to operate the fixture from 6:00 a.m. to 8:00 p.m. The networked controller required around 1 watt (W) of standby power to operate. The test cubes, 1 and 2, relied on the wireless controls in the on-board LED lamps to operate. The LED lamps also require some standby load to maintain wireless connectivity for controls purposes, measured at around 3W per fixture for the two lamps.

With the occupancy control and daylight dimming features, cubes 1 and 2 saved an average of around 73 percent energy for the week-long test period: 0.10 to 0.13 kilowatt-hour per day (kWh/day) compared to 0.44 kWh/day as shown in Figure 12. This result is impressive but it should be noted that for cubicle 1 and to a lesser extent, cubicle 2, the occupancy sensor of the desk-mounted PermaMote underestimated occupancy so the LED lights were sometimes off when an occupant was present and

they should have been on (even if dimmed due to daylighting). Therefore, the energy savings are greater than what would be expected if a different occupancy sensor location, such as the wall or ceiling, were used as the control point.

**Figure 12: Comparison of Average Hourly Energy Consumption Across Test Cubicles**
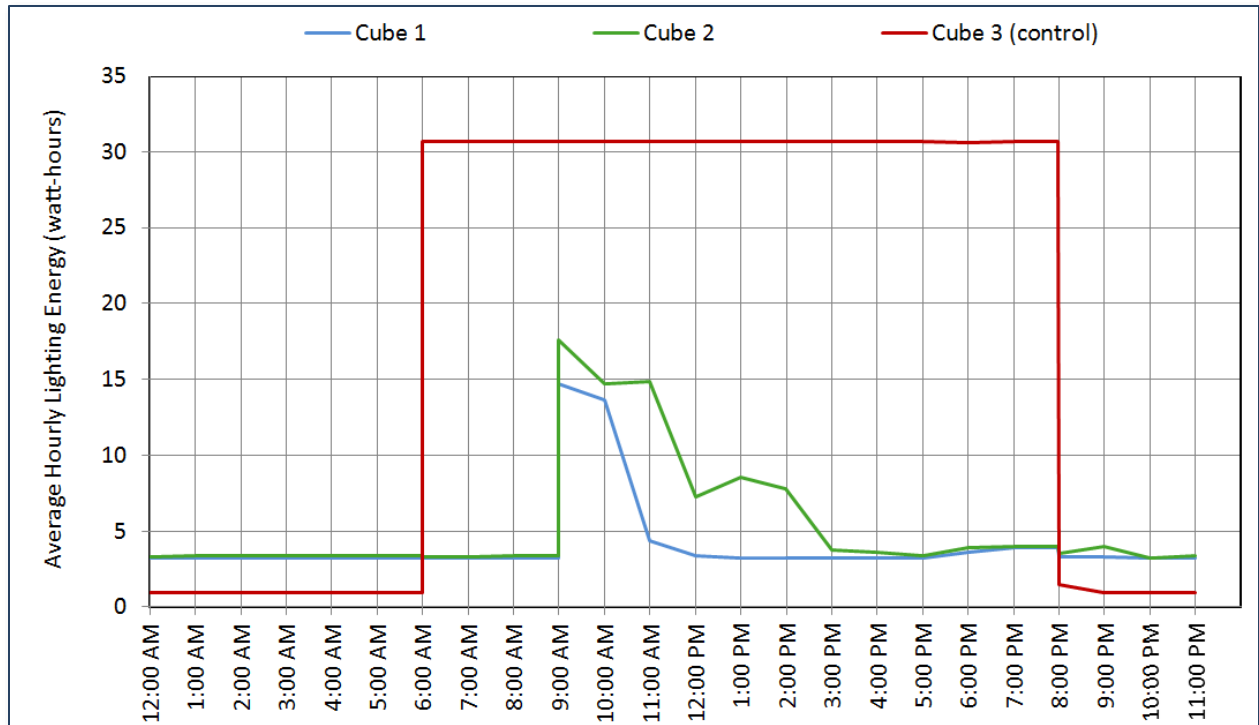


*Source: Lawrence Berkeley National Laboratory*

The box plots in Figure 13 portray the distribution of lighting power levels and desktop illuminance levels (as measured by the PermaMote) for the time periods during which the test offices were occupied according to the PermaMote sensor. These plots illustrate the median hourly (e.g., 1:00 p.m. to 1:59 p.m.) power and light levels in the offices, when occupied. The general trend in the plots is that the fixtures are at or near full power in the morning when the occupant arrives but daylight levels are low, and the fixtures are dimmed or turned off later in the day when the light level is at or above the programmed setpoint (the test cubicles faced toward the west, so they received greater daylight illumination in the afternoon).

**Figure 13: Cube 1 Hourly Distribution of Fixture Power and PermaMote-Measured Desk Illuminance (Occupied Periods)**
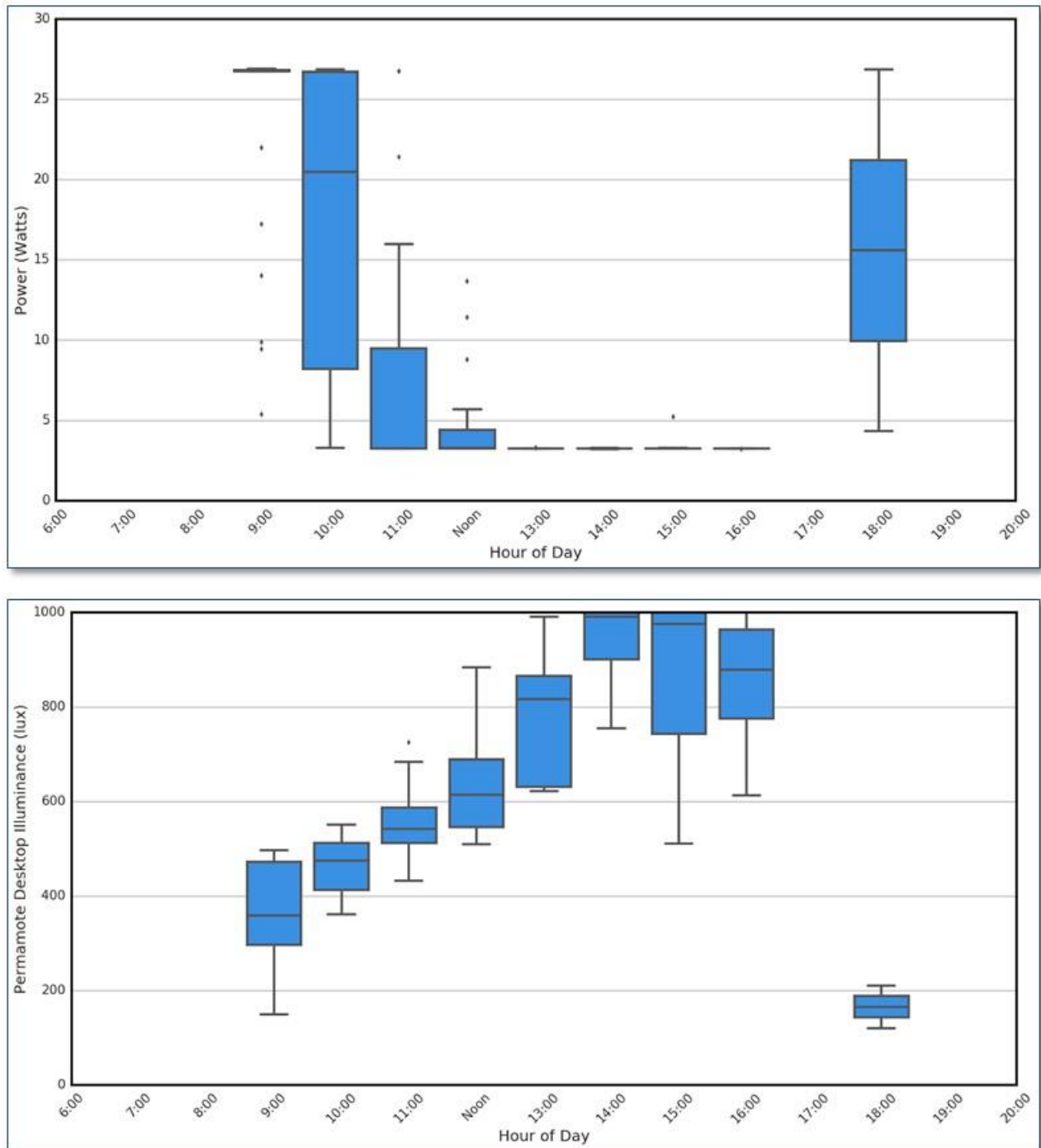


*Source: Lawrence Berkeley National Laboratory*

Another way of examining the daylight dimming behavior of the fixtures is to see whether the system adequately maintains the lighting setpoint, as shown in a scatterplot of illuminance and fixture power levels for all occupied instances in the dataset (Figure 14).

The fixtures are at lowest power (off, but with some standby load) for most of the illuminance data points above the 500 lux target. These data points are essentially measurements of only daylight. The trends then show a range of fixture power levels for which the desk illuminance is around 500 lux, indicating a mix of daylighting and electric power that sum to the lighting target. Finally, at full fixture power there is a range of illuminance values from near the set-point to well below it. These are essentially measurements of diminishing and zero daylight, and full electric light, which alone is insufficient to meet the 500 lux target.

**Figure 14: Lighting Power for Varying Illuminance Levels at Desktop with Set-Point of 500 Lux**
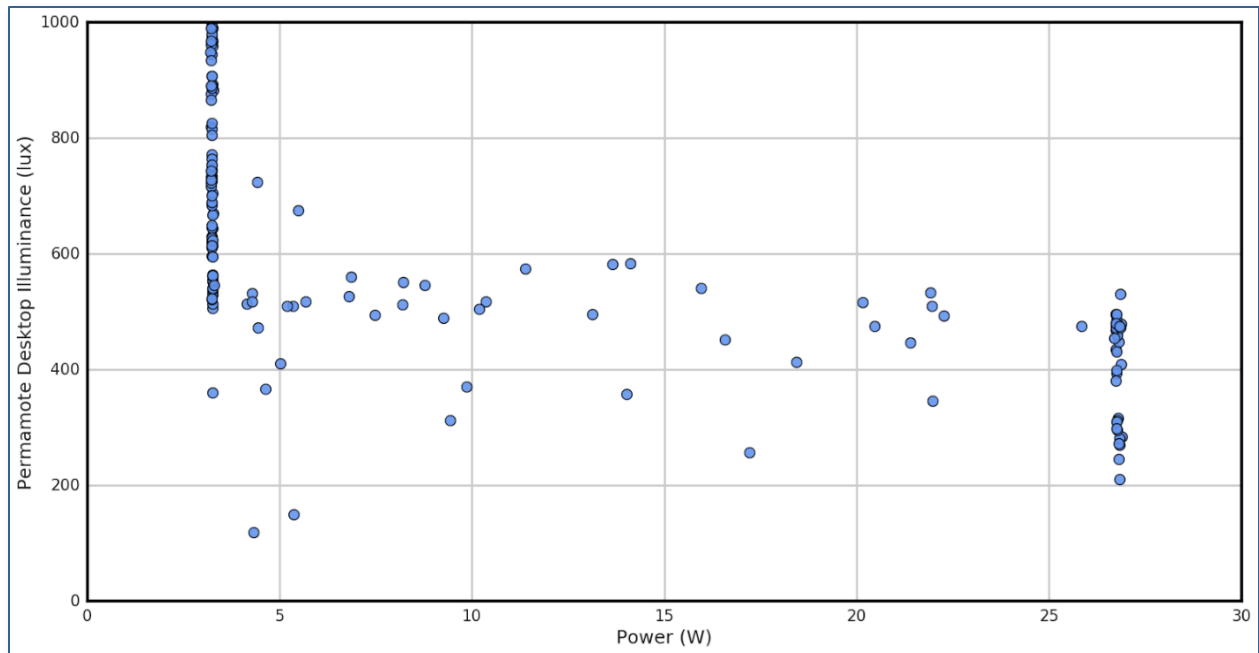


*Source: Lawrence Berkeley National Laboratory*

*Preliminary Glare Analysis*

Glare measurements were taken throughout a test office over the course of two days (November 10–11, 2018) at two locations: the occupant's desk chair at seated height and facing the window (worst case condition) and the cubicle entryway at standing height also facing the window wall. Along with glare, which was characterized with the DGP metric and measured using the HDR cameras and processors, illuminance was measured for locations throughout the office with the PermaMote sensors and with Licor illuminance sensors. For the two-day dataset of illuminance and glare, simple correlations were computed between each measurement point based on least squares regression to evaluate which illuminance measurement locations had the strongest correlation to the glare values. Subsequently a simple machine learning exploration of the data was done using a single two-layer neural net model to predict glare at the desk location from all of the illuminance data points. The model was able to accurately predict DGP with an average accuracy of 91 percent, and an average error of 0.024. As

this simple model was only trained with the two days and for one specific glare location at the desk, the results are overfit but help prove the concept that glare can be predicted from illuminance measurements such as those provided by PermaMotes used throughout an office environment. More data collection and computation will be necessary to further explore the possibility of using wireless illuminance sensors in an office to predict glare for the occupant, which the research team intends to pursue in future work.

Figure 15 shows a correlation table for all of the illuminance measurement points (licor values) and the glare measurement points (DGP cameras). Red indicates values with an $R^2$ closer to one and blue indicates an $R^2$ closer to zero. Figure 16 shows the glare prediction made by the machine learning neural net model using the illuminance values as inputs.

**Figure 15: Correlation Table for Glare Analysis**
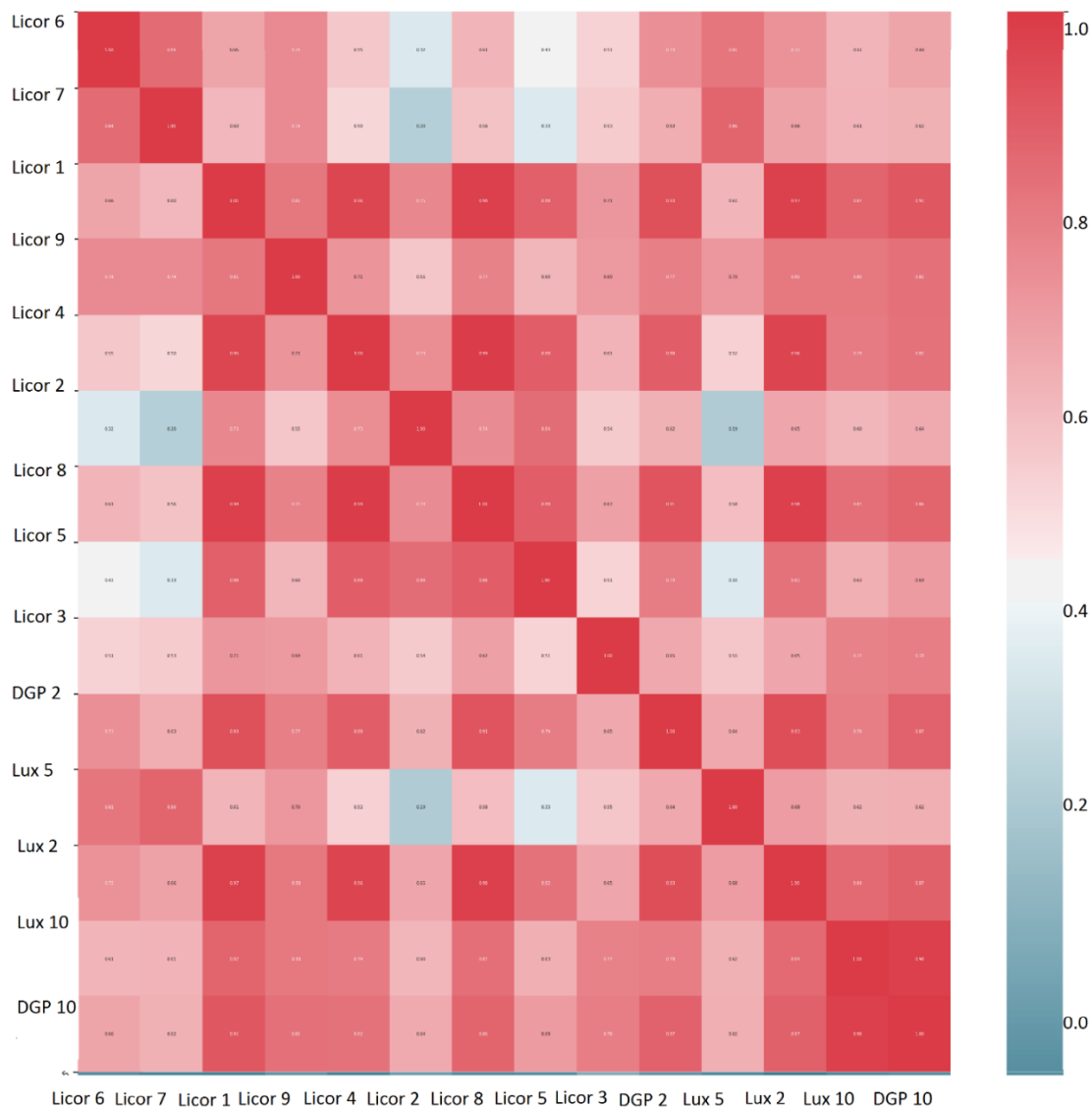


*Source: Lawrence Berkeley National Laboratory*

**Figure 16: Glare Prediction Using Illuminance Measurements and Machine Learning**
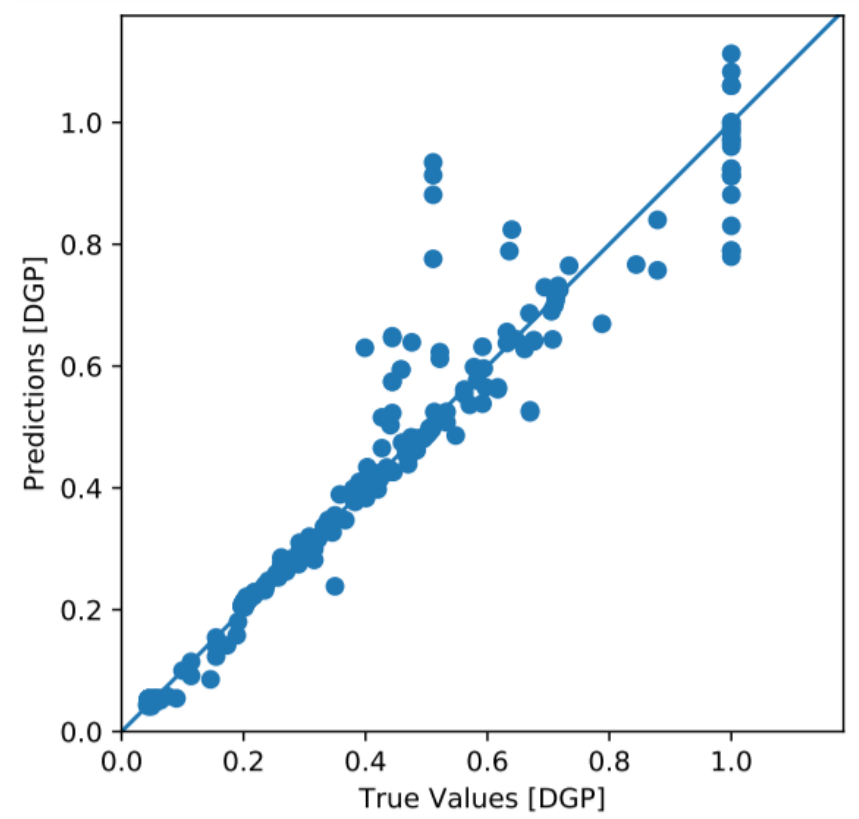


*Source: Lawrence Berkeley National Laboratory*

## Testing of the Readings-At-Desk Controller

### Initial Field Test

The RAD controllers used in the initial field test were produced during a previous EISG project and were housed in LED task lamps. The initial field test involved testing three of these systems for six weeks in LBNL's FLEXLAB® Lighting and Plug Load occupied test bed. Figure 17 shows one of these prototypes installed on the desk of one of the participants of the initial field test. These initial prototypes had a liquid crystal display that provided a readout of how much light was falling on the task lamp (from daylight and overhead lighting) and how much light the user was currently requesting. It also included push buttons that allowed users to increase or decrease the requested light levels. The LED task light itself was controlled separately and its light output was not affected by the RAD controller or changes in daylight levels.

**Figure 17: Initial Readings-At-Desk Controller Prototype Installed in FLEXLAB®**



*Source: Lawrence Berkeley National Laboratory*

Figure 18 shows an example of the primary data recorded and analyzed during this field test. The top graph shows a two-week period for one RAD controller, while the bottom graph shows a more detailed view of two days during this period. On these graphs, the requested light level (blue line) and measured light level (red line) are displayed, in values of lux, as indicated on the primary y-axis. The relative luminaire power is shown in green in values displayed on the secondary y-axis (for example, luminaire at full power = 100 percent; luminaire fully dimmed = 12 percent; luminaires off = 0 percent).

During the test period, all prototypes performed as expected, increasing the luminaire light output (and associated power) when daylight was limited and decreasing light output when daylight was abundant. This pattern is seen in the bottom plot in Figure 18, with the daily pattern of the luminaire dimming to minimum power as the sun comes up and ramping back up to full power at night. The bottom plot shows a cloudy day followed by a sunny day. The cloudy day has variable daylight, which requires more active changes in electric light to maintain a desired overall light level, while the sunny day has smoother changes in daylight and the required luminaire's response.

**Figure 18: Two Weeks of Data from One Readings-At-Desk Controller (top) and Close-Up View of Two Days (bottom)**
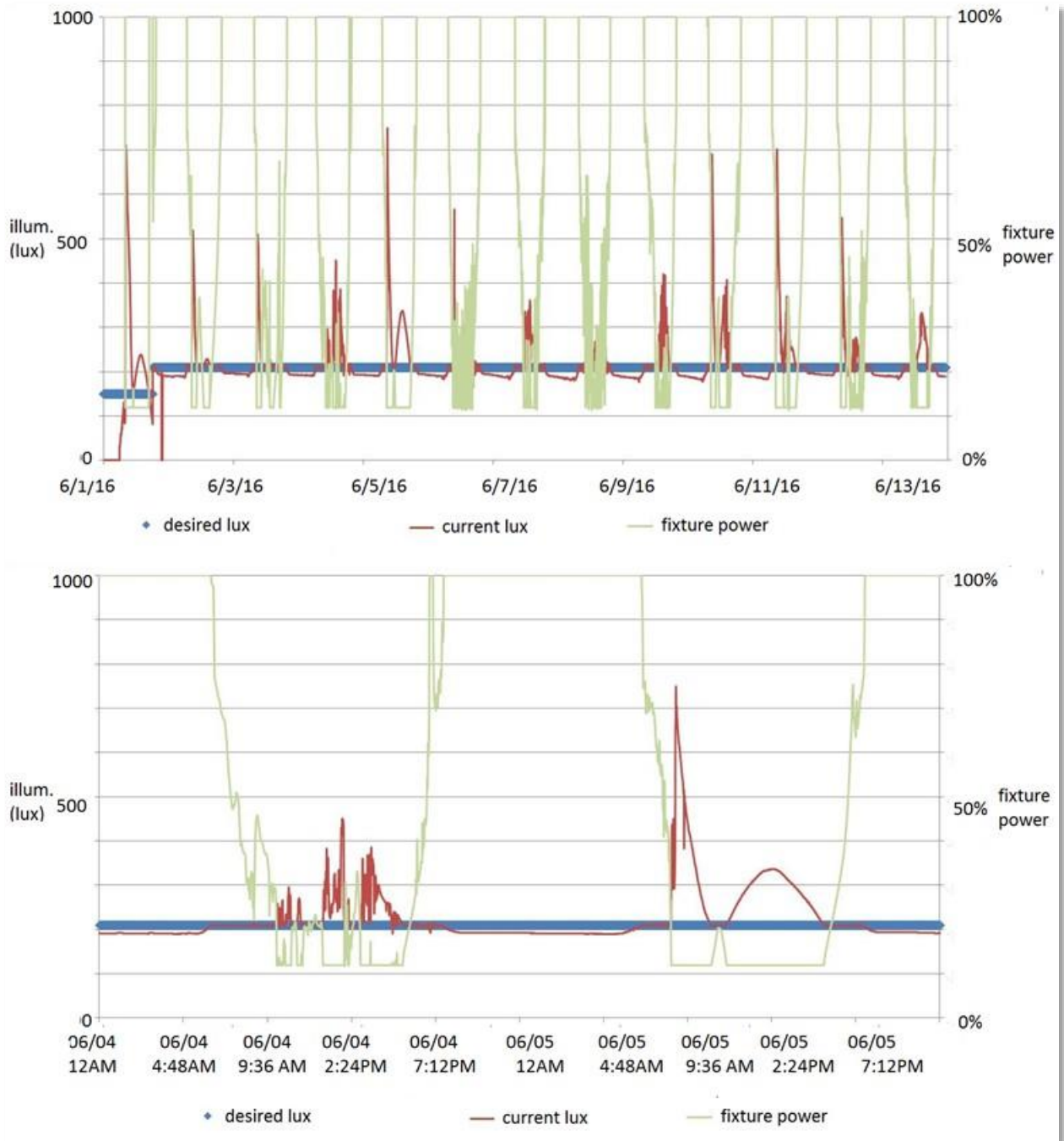
Other findings from Field Test #1 included the following:

- One of the RAD controllers was placed in a location with very high daylight levels. The overhead lights in this cubicle were found to be at a minimum level nearly 100 percent of the time because the user-requested level was nearly always less than the daylight level. A second location had low daylight levels and

the user had a preference for very high light levels. Thus, the user requested the maximum light level setting, and the overhead lights in this cubicle were found to be at a maximum level nearly 100 percent of the time. The third cubicle was "just right" and with user-requested levels in the same range as daylight levels. Consequently, this cubicle typically saw the full range of daylight dimming during each day.

- Users typically placed the task lamps where they had desk space available rather than where they needed lighting or in an ideal location for a sensor. In several cases, the lamps were placed very near the window. This resulted in the sensor on the lamps seeing a significantly higher level of light than the users did, resulting in overly aggressive dimming of the overhead lights. After a week or so, these lamps were moved to more central locations in the office and functionality improved.

- After systems were set up and functioning well, users rarely adjusted user set points during the test period. That is, they simply left the system alone and did not increase/decrease the light levels based on time of day, weather, tasks they were doing, or other factors.

- In discussions with users after the field test, they indicated that the existing user interface was confusing.

- Users also indicated that a RAD system without a task lamp may be a good idea, as it could be more easily placed at locations closer to the user.

**Field Test #2**

Field test #2 also took place in LBNL's FLEXLAB® Lighting and Plug Load occupied test bed and tested the updated RAD designs shown previously in Figure 3 and Figure 4. In this test, five desktop and four task lamp-integrated RAD controllers were installed and monitored over a six-week period. Figure 19 shows desktop and task lamp-integrated RAD controllers in use during the field test. The objectives of Field Test #2 were the same as the initial field test: to assess the performance of the (now updated) RAD controller to perform as designed in real-world applications and to assess the user experience with the system.

**Figure 19: Field Test #2 Included Desktop (left), and Task Lamp-Integrated (right) Readings-At-Desk Controller Versions**



*Source: Lawrence Berkeley National Laboratory*

At the beginning of the field test, the existing fluorescent lamps in the office luminaires were re-lamped with Philips EasySmart TLEDs in each test office. Each RAD controller was then wirelessly paired to the TLEDs that were associated with the office in which the RAD controller was placed. Researchers then triggered the RAD controller's calibration routine in which the TLEDs were commanded to their brightest setting and then slowly dimmed in approximately 250 discrete steps. This allowed the RAD controllers to map the controlled TLED's contribution to the measured illuminance at the RAD controller's location. This allows the RAD controller to, among other things, calculate daylight levels continuously during normal operation.

Shortly after the RAD controllers were installed, the systems underwent a number of on-site validation tests. One test was to simulate and vary "daylight" and confirm that the RAD controllers appropriately adjusted TLED light levels. Figure 20 shows a graph of the results for one of these validation tests. In this graph, Cmd2 is the light level value the user requests, Elec2 is the light level provided by the TLEDs, Day2 is the light level provided by daylight, and Lvl2 is the level to which the TLEDs were commanded. Cmd2, Elec2, and Day2 are shown in lux and are plotted against values on the primary y-axis; Lvl2 is numerical value between 1 (fully dimmed) and 253 (full light output) that represents the level of the TLED and is plotted against the values on the secondary y-axis. The x-axis is the time of day that this test was conducted (the test was conducted after dark to eliminate the effect of actual changes in daylight). During this test, six simulated daylight levels were evaluated over a 30-minute period, resting for 5 minutes each at the following levels: 1 lux, 16 lux, 53 lux, 148 lux, 190 lux, and 230 lux. The Cmd2 level was maintained at 173 lux during the entire test.

During this test (and all other similar validation tests conducted) the RAD controller adjusted lights as expected. Initially, the user was asking for more light (Cmd2 =173 lux) than the electric light could deliver (Elec2 = 103 lux) even when the lamps were at full power (Lvl2 = 253). The first two increases in daylight had no effect on the system because the combined daylight (16 lux and then 53 lux) and electric light levels (103

lux) were still less than what the user requested (173 lux). When daylight was increased to 148 lux, the TLEDs appropriately dropped to a level where they only provided 25 lux, allowing daylight plus electric light to match the user-requested levels. As daylight increased beyond 173 lux, the TLEDs were reduced to their dimmest level.

**Figure 20: Field Test #2 Readings-At-Desk Controller Starting Verification Testing Graphs**
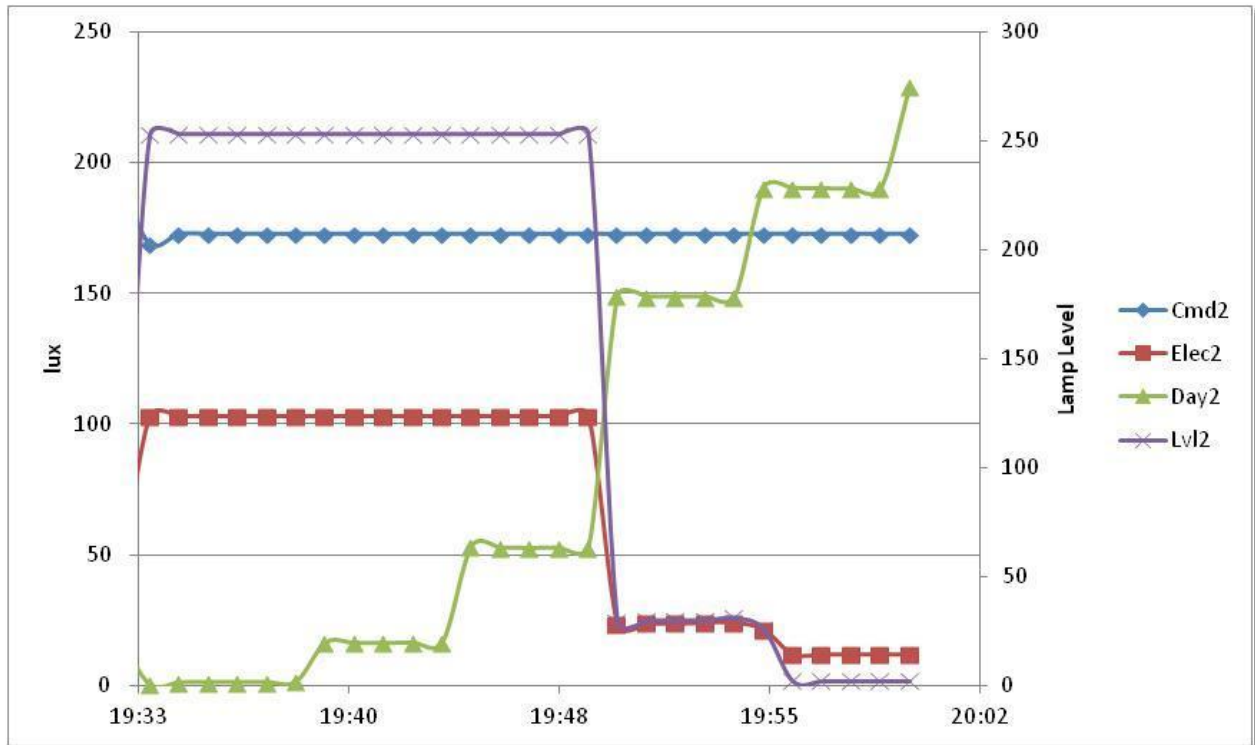


*Source: Lawrence Berkeley National Laboratory*

Figure 21 illustrates the performance of one of the RAD controllers during one typical week of testing. This week had a variety of sunny (smooth, continuous orange peaks) and cloudy (choppy and/or short orange peaks). The users turned their lights off over the weekend (period where only orange daylight levels are larger than zero). Users adjusted their requested level a few times (where the blue light adjusts). During all periods, the RAD controller operated as expected, turning the TLEDs up or down, based on daylight availability.

**Figure 21: Performance of One Readings-At-Desk Controller During One Week of Testing**
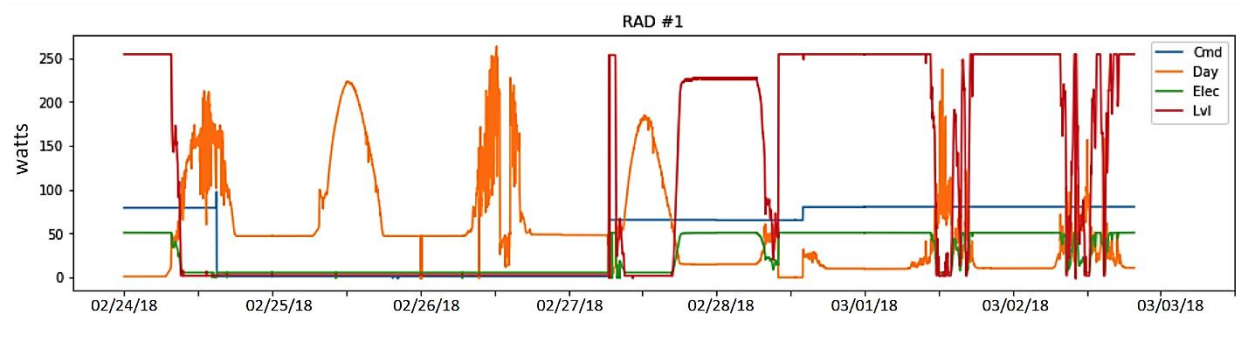


*Source: Lawrence Berkeley National Laboratory*

Data similar to that shown in Figure 21 were collected for all nine RADs during the entire six weeks of testing. The research findings regarding these data and the field test generally include the following:

- With some exceptions (discussed below) all nine RAD controllers performed as expected during the field test, appropriately adjusting electric light levels based on daylight conditions and/or user requirements.

- In rare cases (approximately five times during testing) RAD controllers would "lock up." During this condition, control over lights would be lost (and light levels frozen at their last commanded level) and the user input screen nonresponsive. This condition would typically be resolved by power cycling the RAD controller. Researchers believe they have identified and addressed the software bugs that contributed to these events, but internal testing continues.

- Researchers also encountered issues related to data acquisition (for example, the collection of the light and user request data versus time that has been shown). During early periods of the field test, some RAD controllers stopped collecting data, requiring the researchers to reset them. These RAD controllers still controlled the TLEDs appropriately during these periods. Researchers identified and addressed the software cause of this error during the field-testing.

- Lastly, the researchers note that most of the spaces included in this study received very high levels of daylight during all working hours. Consequently, several of the participants in the study turned their lights off completely for long periods of the test. Other users kept their lights on but had user-requested light levels that were low enough that the TLEDs were fully dimmed from dawn to dusk. The remaining users had higher requested light levels and/or lower daylight levels to the extent that they had a more "active" daylight-harvesting pattern.

User feedback was largely positive. Some users noted that they still found the user interface to be confusing while other users indicated they appreciated ability of the RAD controller to allow them to adjust their light levels. Other users noted that they did not

use their lighting much during testing because of the high levels of daylight in their offices (consist with the previous data discussion).

# Open Communication Standards

As part of the research to develop an open API for allowing facility managers and owners to extend the reach of wired lighting systems, the research team developed a reference data model that could be used to communicate between an existing lighting system and the low cost sensors developed in this project. With that motivation, the research team surveyed existing standards with the objectives of first understanding what has already been developed, and then identifying research gaps that need to be addressed before a complete data model can be described. Using this analysis, the research team created a list of topics necessary for a standard data model for lighting applications. Then the team examined existing standards for how they address these topics for relevant information; analyzed them for consistency, coverage, and quality; and made recommendations for best practices and where further research is needed.

The core purposes of the investigation were to determine:

- Types of information to be represented for lighting applications
- Specific data elements to include
- Names for those data elements
- Data encoding (units, enumerations, and so forth)

In addition to the project team's research, LBNL has been engaging with the ANSI Committee C137, which is in the process of creating an ANSI standard for lighting control systems, to develop a standard data model that will be a part of the eventual standard. The current working version of this project's data model has been adapted for this project to avoid redundancy of work. The adapted data model is summarized in Table 1.

## Table 1: Proposed Data Model

| Data Element Name | What This Data Element Represents | Units | Semantic Representation | Data Type |
|---|---|---|---|---|
| Group ID | Identifier for a group of devices that are operated together, e.g., all lights in a room | | | |
| Scene Parameters | The characteristics comprising a scene | | | |
| Illuminance Target Level | Illuminance level above or below which an action occurs | Lux | TargetIlluminance | Float |
| Device Serial Number | Self-explanatory | | EntityModel | Text |
| Device Firmware Version Number | Self-explanatory | | EntityFirmware | Text |
| Device Hardware Version Number | Self-explanatory | | EntityHardware | Text |
| Device/Luminaire Location | Information as to where lights are placed such as room/cubicle/fixture description | | DeviceLocation | Text |
| Sensor Location | Information as to where sensors are placed such as room, surface, workplane description | | SensorLocation | Text |
| Light Source CCT | Light source set CCT | Kelvin | LightCCT | Float |
| Sensor CCT | CCT detected by the sensor | Kelvin | SensorCCT | Float |
| Time of Day | Self-explanatory | | TimeStamp | Float or Text |
| Individual Sensor Occupancy | Status of individual occupancy/vacancy sensors within a room or area. | | OccupancySensorState | |
| Room Occupancy | Current status of overall room or area occupancy, include time since last change. | | RoomOccupancyState | |
| Individual Daylight Sensor | Status of individual daylight/photo sensors within a room or area. | | DaylightSensorState | |

| Data Element Name | What This Data Element Represents | Units | Semantic Representation | Data Type |
|---|---|---|---|---|
| **Individual PhotoSensor Levels** | Status of individual photo sensors within a room or area. | | LightSensorState | |
| **Illuminance level** | Measured illuminance at a light sensor | Lux | LightSensorLevel | |
| **LightLevel** | Illuminance level in a given space | Lux | RoomLightLevel | |
| **Luminaire Group Status** | Status of a group of luminaires within a room or area, this may also be called a zone (i.e. light level, CCT, energy) | | | |
| **Room Zone Levels** | Electric Lighting status and control of each Zone | | | |
| **Relay Status & Control** | Status and control of individual relays (on/off) | | | |
| **Device On/Off state** | Current (i.e., last known) state | | OnOff | |
| **LightState** | Light point is on or off | | LightState | |
| **Dimmer Status and Control** | Status and control of individual dimmers (light level, on/off) | | | |
| **LightDim Level** | 0–100% of dimming level of light. (Full on to full off) | | LightDim | Float |
| **Preset Status and Control** | Status and control of presets within each space, room or area. | | | |
| **Room Preset or Mode** | Preset status and control | | | |
| **Scene ID** | Identifier for a set of characteristics that are activated together | | | |
| **Room DR Mode** | Status and control of DR mode | | | |
| **Device Energy Consumption** | Self-explanatory | | CumulativeEnergy | Float |
| **Power Consumption** | Self-explanatory | | PowerLevel | Float |

*Source: Lawrence Berkeley National Laboratory*

The project team also created a mapping between the proposed data model in Table 1 with the updated digitally addressable lighting interface (DALI) standard. This was done in two steps: first was to identify the relevant parts of the DALI standard from the project's perspective and the second was to map the functions specified in the standard with those in the proposed data model.

Since the DALI standard has specific enumerations for various parameters, the LBNL mapping of the proposed data model with DALI is only limited to whether the particular parameter is represented or not. Also, as the updated DALI standard is still being published, there are certain fields that are proposed for inclusion in the future. Table 2 presents the mapping between the proposed data model and DALI 1.0 as well as 2.0.

**Table 2: Digitally Addressable Lighting Interface and Lawrence Berkeley National Laboratory Data Model Mapping**

| Data Element Name | DALI Specification & Enumeration |
|---|---|
| Group ID | Groups |
| Scene parameters | Scenes: int 0-15; Fadetime: .1sec -16 minutes as encoded octet. |
| Illuminance target level | NA |
| Device serial number | NA |
| Device firmware version number | NA |
| Device hardware version number | NA |
| Device/Luminaire Location | NA |
| Sensor Location | NA |
| Light source CCT | RGB, RGBWAF, xy |
| Sensor CCT | TBA |
| Time of day | NA |
| Individual Sensor Occupancy | Occupancy sense: Movement as bit; Occupied as 2 bits |
| Room Occupancy | TBA |
| Individual Daylight Sensor | NA |
| Individual PhotoSensor Levels | Photocell input: int 0-1023 lux |
| Illuminance level | TBA |

| Data Element Name | DALI Specification & Enumeration |
|---|---|
| LightLevel | Level: int 0-254; Fadetime: .1sec -16 minutes as encoded octet. |
| Luminaire Group Status | TBA |
| Room Zone Levels | Group: int 0-15 |
| Relay Status & Control | Analog input |
| Device on/off state | Switch input |
| LightState | Level control |
| Dimmer Status and Control | Switch input |
| LightDim Level | Level: int 0-254; Fadetime: .1sec -16 minutes as encoded octet. |
| Preset Status and Control | NA |
| Room Preset or Mode | NA |
| Scene ID | TBA |
| Room DR Mode | Load Shed Condition: int 0-3 |
| Device energy consumption | TBA |
| Power consumption | TBA |

*Source: Lawrence Berkeley National Laboratory*

As can be seen, certain parameters (identified by "TBA") are proposed to be added as part of the DALI 2.0 standard while others have not been specified in the existing standard.

## Summary of Communication Standards Findings

The way DALI is structured as a protocol restricts its ability to be extended to newer applications in the connected lighting space. DALI 2.0 is intended to make adoption by wireless lighting systems easier with specific requirements for wireless control devices as well as sensors; however, its market adoption cannot be assured. LBNL will continue to work with the ANSI committee and through it with the Digital Illumination Interface Alliance, which is also a member of the committee, to add the missing fields as part of DALI 2.0. The research team has also proposed the adoption of the open API by networked lighting control system manufacturers for improving the interoperability throughout the industry.

# CHAPTER 3:
# Intuitive, Standardized User Interfaces for Networked Lighting Systems

## Purpose and Scope

In parallel, and complementary to, the efforts to develop the energy saving sensor-rich networked lighting controls detailed in Chapter 2, the research team also created content that could be the basis for a user interface standard for lighting controls. This could be used immediately by manufacturers in designing products, could be adopted at the United States national level, and eventually could be adopted internationally. The scope of this effort includes controls experienced by people in their ordinary home and work lives. Out of scope are professional controls, as might be used in theaters or other venues for which controlling lighting is a principal job function (though these could be designed in accordance with the common standard).

The premise underlying the effort is that consistent controls aid in humans' understanding the capability and status of lighting controls they encounter and being able to most easily express their preferences. As people are more likely to expend effort to gain more illumination than to get less, this should save energy. As consistent controls are no more expensive to manufacture than inconsistent ones, there should be no effect on manufacturing cost.

Technical standards have the characteristic that if the standard doesn't exist, it is impossible for a single manufacturer to implement or gain the benefits of the standard. User interface standards have this same feature.

Humans rely on user interface standards in many aspects of everyday life, from the symbols and colors on vehicle dashboards to the layout of phone keypads and more. Lack of these would incur costs, energy waste, and for vehicles, injury and death. Lighting has been remarkable in its lack of use of standards. While some conventions have at least national consistency—for example, in the United States the "up" direction is generally used to switch a light on—the reverse is true in many parts of the world.

### Problem Statement

Increasing lighting system complexity leads to user confusion. Conventionally, lighting was only on or off, so a single switch with two states was all that was needed for control. As each room had just a few distinct lights, the whole system of controls was fairly simple. Over time, the number of potential variables in how lighting can be controlled has grown, and now includes dimming, light color, occupancy sensing, daylight sensing, and scheduling. The number of controls that have multiple features, and their sophistication, is growing rapidly. In the absence of any common language for

lighting controls to communicate their capabilities and status to the user, most remain opaque. Those controls that do include user interface elements do so in an ad hoc and inconsistent manner. Often the result is that users get less light or the wrong type of light for their needs. Even more often, more light is delivered than is needed, thereby wasting energy.

This effort builds on the concept of network communications between two digital devices. Communication between devices and human beings can be readily seen as an extension of this, as standards are required for communication to be successful. Languages are essentially communication standards, as are color coding of traffic signal lights and much more. As we network ever more devices to each other, it is ever more important to effectively "network" people with the digital systems, through effective user interfaces.

In discussing the open systems interconnection model of networked communications, user interfaces are commonly called the "8th Layer" (the model itself having seven layers).

## Key Innovations

This project has developed and proposed the world's first lighting control user interface technical standard. If successful, the terms and symbols in this standard could be as widespread as the symbols on automobile dashboards or the arrangement of numbers and symbols on the standard telephone keypad. It brings together some concepts and content that exist in current standards and products, as well as some content that is entirely new. Examples of the latter include a proposed new symbol for occupancy, a new idea for how to conceptualize light temperature, and a symbol to embody that concept.

The attachments to the lighting control user interface standard report have the technical content of the research findings from surveying products, and a recommended user interface standard and rationale. This chapter focuses on the process underlying that content. That process begins before the project and extends after it; standards processes are years long and require ongoing commitment.

## Pre-Project Activities

LBNL was able to engage in this project as a result of prior CEC-funded work on user interface standards. This began in 2000 with a project on power control, which can be summarized as "how we turn things on and off." At that time, there were individual user interface elements (for example, symbols, terms, colors), but no overall standard on the topic to tie them together. In addition, the world was moving from a situation in which there were two basic power states (on and off) to many power states. That project concluded that there should be three power states, with sleep an intermediate state between on and off. The research culminated in a recommended standard on the topic. A follow-up project, also CEC-funded, enabled the work to be brought through

the Institute of Electrical and Electronics Engineers Standards Association and emerge, two years later, as IEEE 1621.

That initial work established the foundations for understanding user interface standards as an energy efficiency resource. It was clear that the principle could be extended to other domains of energy use, with lighting and climate control the two most obvious candidates. The approach is to create a dictionary of individual elements with associated meaning. Symbols are the most obvious of these, but other elements can be terms, colors, physical mappings, sounds (and more recently audio input), haptic content, and critically, metaphor. A core example of metaphor is the use of "sleep" in the power control context, which has an associated symbol, color, terminology, and facilitates people thinking and speaking of a device "going to sleep" or "waking up." Collections of elements work together as units of meaning.

In 2009, the CEC funded a project for background research on the topic of a lighting control user interface standard. This project extensively reviewed existing standards and a wide variety of products. It concluded that there was no standard—national or international—directly on the topic, but a significant amount of generic user interface content that could be applicable. It also identified some initial categories in which to organize user interface information and a potential future standard. All this set the stage for the current project.

# Project Activities

## Survey

The first and biggest part of the project was to extensively survey and digest the content of user interfaces on products for sale today (Nordman et al., 2017a). This covered a wide range of devices for residential and commercial contexts, traditional and networked/connected, simple and complex, hardware-based or display-based, and more. Products from more than 20 manufacturers were assessed. The list of topics has evolved slightly from the early work through this project. The list in this survey is:

- Lighting in general
- Scenes
- Switching (static)
- Color control
- Dimming/brightness (static)
- Shading control
- Dynamic control
- Other topics

This survey provided the raw data that was part of the input to the later process of crafting a proposed standard.

## Standards Organizations

A goal of the project was to craft content for a potential standard, and present it to a suitable standards development organization . This would serve several purposes, including giving the content much more credibility, engaging key manufacturers in the content, and providing a mechanism for periodic review and updating of the content.

Early on, the project team identified the National Electrical Manufacturers Association (NEMA) as the organization best suited to host the content resulting from this project. In principal, the content should be in an international standard, for example, with the International Organization for Standardization (ISO), which covers a wide variety of standards, the International Electro-Technical Commission (IEC), which covers electricity and electrical devices in many respects, or the International Commission on Illumination (CIE), which covers many aspects of lighting. The ISO and IEC have an extended set of standards that cover symbols, and there are several ISO standards on indicators and actuation. LBNL has tried to work with both organizations in the past but with almost no success. In general, one has to persuade the country as a whole to join a committee (which requires multiple companies, fees, and years of commitment to participate), and to regularly attend meetings, which are almost always outside the United States. This is in general not feasible. While CIE would seem to be an obvious choice, no individuals or committees within CIE that find the UI topic of interest have been identified, so attempting to work with CIE on this topic would likely not succeed, and in any case, would also require considerable time and attending meetings outside the United States.

Within the United States, NEMA's membership covers the vast majority of the market in the country for lighting controls, and it sponsors the ANSI Lighting Systems Committee (C137). No other United States organization is as related to controls design. C137 has on its membership all of the leading manufacturers of lighting controls in the country. Finally, NEMA staff encouraged participation.

The Illuminating Engineering Society (IES) could also host standards development, but it is mostly oriented to individuals who work on the science and application of lighting, rather than manufacturers. It does have a Light Control and Luminaire Design Committee, but conversations with representatives of the IES and NEMA, and many individuals, have always pointed to NEMA rather than the IES as the best host and no other likely alternative has been identified.

### National Electrical Manufacturers Association Standards Processes

The research team has been in contact with NEMA staff since early 2016, including periodic meetings at its offices, committee meetings, or conferences. Interactions with the C137 committee, which normally meets twice a year, have been as follows.

- In March of 2017 the team presented to the C137 committee remotely, to outline the possibility of and need for a user interface standard and request that the committee consider this.

- In August of 2017 the team presented the concept and the specific proposed content for a user interface standard in person. At that meeting, an ad hoc committee was formed to discuss whether a standards project should be started. This was the only meeting LBNL attended in person. Phoning into meetings was not always an option.

- The ad hoc committee met twice, the second time in early 2018, and voted 8-2 in favor of starting a project on the topic, the first step to creating a standard. This recommendation then went to the full committee.

- At the spring 2018 C137 meeting the user interface topic was near the end of the agenda and by the time it came up a quorum was no longer present and no action was taken.

- At the fall 2018 C137 meeting the topic did not come up because the meeting was closed after one day due to a hurricane in the local area.

- At the spring 2018 C137 meeting, it was again at the end of the agenda and a quorum was not present to take an action, but four company representatives volunteered to work with LBNL on preparing material needed to move the project forward at the next meeting. As part of this LBNL will work with the volunteers to create "PINS" language as the basis for the project initiation proposal. There was a new staff person for the committee running this meeting, which may enable progress to occur more expeditiously.

Standards development is usually a slow process, but this has been especially so. In addition to the hurricane, the retirement of the most supportive person and committee chair a few months later in August 2017 slowed the process even more than usual. Standards processes are not predictable in when they start, finish, or speed up or slow down. While this current project will come to a close before the next C137 meeting, LBNL intends to continue to participate. Many individual staff from lighting control companies have expressed support for the concept in discussions.

**International Commission on Illumination**
LBNL has monitored activities of the International Commission on Illumination (CIE), the international standards body relevant to lighting, to see if there was any interest in the user interface standard topic. To date there has been none but it did seem clear that if there were to be any activity it would be within its Division 3: Interior Environment and Lighting Design. CIE is based in Austria, and usually meets in Europe or other places outside the United States. In 2019, CIE is meeting in Washington, D.C., and an abstract on the topic was accepted for this meeting. This will be after this project concludes, but LBNL intends to bring the lighting user interface topic to this meeting to see if international interest can be sparked. This would most likely be an activity subsequent to completion of consideration by ANSI/NEMA. Commonly standards are first developed at some national level and then moved to the international stage.

# Proposed Scope, Content, and Rationale

This standard defines user interface elements for manufacturers to use in the design of lighting controls. It is applicable to hardware controls, software displays, and documentation. The proposed standard was created foremost for controls experienced by people in their ordinary lives, at home, work, or elsewhere. However, it may also be used for professional controls that are only used in the course of a job function (for example, large building central controls or theatrical controls). The controls may be dedicated lighting controls, controls for many purposes, such as home automation systems, or controls with some other specific primary function, such as shading/lighting coordination with HVAC for efficient thermal comfort.

The standard covers the following topic areas: Lighting in General, Basic Switching, Brightness, Dynamic Control, Color, and Other Topics. The standard addresses visual elements (terms, symbols, and colors), dynamic elements (indication and actuation), audio elements (sounds and words), and tactile elements (identification and actuation). The standard does not cover ergonomic or safety issues that might be associated with lighting controls.

Prior to the August ANSI/NEMA C137 meeting, LBNL completed the Proposed Lighting Control User Interface Standard along with Appendix C. Lighting User Interface Standard – Background and Development. The proposed standard was written in the form and language of a technology standard so that a standards committee could adopt it with modest effort. This also showed the proposal's practicality. It was assumed that any standards process would modify the proposal, perhaps to change some material, likely to drop some, and less likely to add some. Manufacturers were requested to provide comment but none did, and said that they would prefer to do so in the context of an actual official process.

The proposed content and rationale are summarized in the following infographic, and more details on content and rationale are provided in appendices C and D.

# CHAPTER 4:
# Verifiable Performance for Networked Lighting Systems

## Scope

Increasing lighting control system complexity, in terms of algorithms and networking, poses operational risks caused by incomplete specification, misconfiguration, or incompatibilities between system components. These problems range from the traditional under-/over-dimming and annoyance to more systemic failures attributable to complex algorithms and communications. Lighting systems integration from multiple manufacturers carries a heavy "integration tax" for the labor needed to design, specify, custom program (during commissioning), and troubleshoot each building installation. The goal in this testing was to develop a new method for evaluating and specifying lighting systems' performance, to ensure that flexible, networked lighting technologies achieve their full potential. In conjunction with this purpose, the research team developed a set of evaluative metrics and reviewed current technologies for their ability to offer this information.

To investigate these issues, particularly with respect to automated energy-reporting features from networked lighting controls systems, LBNL used the FLEXLAB® research facility to test several current technologies. Experiments were conducted in which systems were installed and addressed to controllable lighting loads and commissioned to operate and dim lights based on various conditions. Lighting energy use was measured by the lab as a reference to compare against system self-reported energy usage. This allowed the research team to evaluate the lighting systems' ability to provide performance metrics (actual energy usage over time) useful for outcome-based code development and compliance.

Originally, the team set out to specify a software that could be developed to transform the event data implicitly collected by modern lighting controls into a stream of lighting energy use (kWh) data that continually tracks the real-time energy consumption of the lighting system at sufficiently fine temporal and spatial resolution. This single-software energy monitoring method was to be validated for accuracy by testing it in FLEXLAB®'s controlled laboratory environment. However, based on the process of setting up and carrying out lab evaluations of the lighting systems, it became evident that a single-software framework to interpret the reports from various systems was not workable or necessary for the task. Lighting control system manufacturers saw early results and enhanced their control system technology to monitor "real" energy rather employ fixture energy lookup tables. The systems' own energy reports were compared to reference measurements to determine suitability for performance testing and validation. This work will extend in future research, to evaluate the performance of current code-

minimum lighting systems in relation to these metrics and to provide the information and foundation to shift code development toward an outcome-based method.

## Tasks

The following tasks were completed as part of this activity:

- Developed proposed lighting system performance evaluative metrics and proposed a set of metrics applicable to whole building and lighting system level retrofit applications that can be used to determine the installed systems' performance.

- Evaluated several commercially available, networked lighting control systems to describe the types of data they produce in standard operation, and the interfaces for accessing these data.

- Software specification and development:
    - Developed a software specification that transforms event data implicitly collected by intelligent, networked lighting controllers into a stream of lighting energy use (kWh) data and other metrics that continually track the real-time, lighting system energy consumption at sufficiently fine temporal and spatial resolution.
    - Prepared a software validation test plan that describes the testing to be done at LBNL's FLEXLAB® facility to validate lighting monitoring system accuracy. Three lighting control systems were selected for validation testing.

- Developed a test method for verifying lighting monitoring software performance accuracy.

- Conducted the validation testing in FLEXLAB®.

- Prepared a validation testing report and protocol that summarize the validation testing results conducted in FLEXLAB®, including a comprehensive framework for determining performance metrics for these lighting systems, along with a proposed testing protocol.

# Topics and Outcomes for Further Development

## New Performance Metrics for Lighting System

In building energy code requirements for commercial lighting systems, an outcome-based code model would move from lighting power density (LPD) prescriptions to energy usage intensity (EUI) prescriptions for different use cases and space types.

LPD (watts/ft$^2$) as the focus of building energy code requirement is an incomplete and imperfect option. Consider that a high-wattage lighting system that is rarely on or is always operated at dimmed or reduced power, (analogous to partial load performance of a chiller) may be less energy intensive than a lighting system with a lower

"nameplate" wattage that is operated continuously at full load. Especially with the state of dimmable modern lighting technologies, the simplified concept of lighting power density as a catch-all lighting performance metric loses meaning.

A more effective metric for capturing the actual energy effect of a lighting system over time is EUI ($kWh/ft^2$/year). Like LPD, it is normalized to the building area, but unlike LPD, the energy usage intensity of a system is not bound by the nameplate performance at maximum load, but rather reflects the actual operating characteristics of a system over time. Annual EUI reflects the total energy usage over that timeframe without respect to simple installed power density totals.

The drawback with EUI historically as a prescriptive requirement was that energy usage of a system, post-installation and through time, was unknowable, at least not without significant measurement and verification effort. In-situ monitoring of a lighting system's performance, energy usage, or even simply operating hours, while useful for research and for the curious building manager, was hardly a practical option for code compliance. At best, energy usage could be estimated based on LPD and assumed operating hours (per year for example), but those estimates would be imperfect. On the other hand, with known quantities of light fixtures and known fixture areas, it has always been straightforward enough to calculate LPD for a new building or renovation project—hence code's traditional reliance on the LPD metric as the figure of merit for lighting systems requirements.

## Outcome-Based Code Compliance Through Software Validation and Self-Reporting

Traditionally lighting energy performance for a new lighting system has been estimated *ex ante*, based on lighting power density and various assumptions about operating hours. Modern networked lighting control systems, however, can provide much deeper insight into how and when lights in a building are used. With lighting endpoints networked together in a connected architecture that is supervised centrally, trending of operation and performance of components in the system and the system as a whole is possible. Baseline conditions can also be established, from which to determine improvements over, or adherence to, a future performance code level.

With the advent of energy reporting features from many networked lighting control systems, it is possible in theory to track lighting energy outcomes from a new lighting system *ex post*. If self-reported demand and energy usage from lighting systems is found to be reliably accurate (within an acceptable tolerance), building codes for lighting systems could move from the lighting power density prescription approach to an outcome-based energy usage approach—for example, a maximum EUI allowance per space type. The lighting system performance as quantified by the system's energy reporting could constitute the means of verification for the purposes of code compliance. Policy makers, regulators, utilities, and end users would all be similarly

served by reliable self-reporting, as all have an interest in knowing whether and how a new networked lighting system delivers on expected efficiency gains.

It is conceivable that the front-end software of networked lighting control systems could be equipped with simple energy reporting modules for code compliance that aggregate space types and report energy usage after system start-up. First year energy data reports for measurement and verification contractors and regulators could be automated for each of the space types defined in code and present in the building—for example, conference room, lobbies, classrooms, large and small offices, and others. With the facilitation of energy self-reporting, American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) 90.1, IECC, and California Title 24, space-by-space LPD requirements could be transitioned into EUI requirements. For example, consider Title 24 space-based lighting power determinations. The Area Category Method lists LPD values for various space type, such as Corridor, Restroom, and Stair, $(0.6W/ft^2)$; Office more than 250 $ft^2$ $(0.75W/ft^2)$; Offices less than or equal to 250 $ft^2$ $(1.0W/ft^2)$; and Lobby $(0.95W/ft^2)$. This method could be revised to focus on the actual performance of the lighting systems in those spaces if lighting energy usage in those spaces could reliably be determined through networked lighting controls' self-reporting. Whole-building LPD as a compliance method could also be transitioned to EUI requirements or allowances.

Built-in energy reporting modules could include different categories for the various building codes that may apply to a project. Parameters like room cavity ratio and daylighting zone designation could all be used by the software for compliance calculations. These types of simple dynamic features would tailor energy self-reporting to the building characteristics and code requirements that flow from them. Modules for carrying out the functional testing requirements that are already in Title 24, IECC and other codes for lighting controls, could equally be set up in networked lighting controls software to streamline compliance and enforcement.

## Energy Reporting Requirements in Current Networked Lighting Controls Specifications

The Design Lights Consortium (DLC) defines a networked lighting control system as "consisting of an intelligent network of individually addressable luminaires and control devices, allowing for application of multiple control strategies, programmability, building- or enterprise-level control, zoning and rezoning using software, and measuring and monitoring" (https://www.designlights.org/workplan/networked-lighting-controls-specification/).

The DLC's lighting controls specification includes details on energy reporting from networked systems. Energy reporting capabilities had not previously been a required feature set to meet the specification, but that is changing this year. Per the latest published version of the specification (V3.0), energy reporting is defined as "the capability of a system to report the energy consumption of a luminaire and/or a group

of luminaires. The use of energy monitoring on dedicated lighting circuits is also acceptable." The current version of the policy clearly lays out the future direction of the specification, which will transition energy reporting from an optional to a required feature. The means of energy reporting will then transition from either measured or calculated approaches being acceptable to a measurement-only approach, with an option for calculated reporting if a standard that guarantees accuracy is developed in the meantime.

> In V4.0, to be released June 1, 2019, Energy Monitoring will become a required capability. Manufacturers will report the method of monitoring (direct or calculated), and the accuracy of measurement that is direct. In V5.0, to be released June 1, 2020, calculated methodologies will not be accepted as meeting the energy monitoring requirement unless supported by a new ANSI standard that specifies the accuracy of the methodology. If an ANSI standard to support the methodology is not developed, then only direct measurement methods will be accepted and manufacturers will self-report the accuracy of the direct measurement method.

## Future Metrics and Dimensions of Lighting Quality

While not expressly related to tracking energy performance for code compliance verification, the research team tracked other metrics and dimensions of lighting performance evolving in the marketplace due to technological and research innovations. For example, commercial tunable white LED fixtures now available allow for operating profiles that adjust intensity and color through the day to provide visual comfort and increase health benefits while saving energy. These systems will often be implemented with networked lighting controls capable of effecting new lighting control strategies. Per the U.S. Department of Energy (U.S. DOE), "color-tunable LED[s] are a… growing product category. Beyond energy efficiency … potential benefits include improved health and well-being… there is reason to believe that color-tunable [LEDs] will gain market share" (https://energy.gov/eere/ssl/led-color-tunable-products).

Tunable lighting systems are intended to improve visual and health benefits while continuing to enable energy savings; coupled with connected controls they can enable dynamic lighting strategies, including demand response opportunities. As this emerging technology is adopted, it is critical that designers, utilities, and program implementers understand the strategies that provide visual and health benefits for least energy cost.

However, the impacts and benefits of tuning color and intensity in buildings, while not yet fully developed as design criteria for lighting systems, will eventually require the introduction of additional lighting quality dimensions to building codes. Similar to the outcome-based energy intensity approach, these lighting quality metrics will most likely have time-variant components and will therefore require some level of monitoring and/or self-reporting. In other words, a prescriptive constant unit (such as LPD) will probably not be appropriate for health and well-being lighting strategies, which will

almost certainly involve varying lighting intensity, and probably spectral content, through time, over daily and perhaps seasonal periods.

# Laboratory Testing of Advanced Networked Lighting Controls Systems in FLEXLAB®

## Objective

The goal of the FLEXLAB® experiment was to operate three advanced networked lighting controls systems with energy reporting capabilities (measured or calculated), primarily to compare reported lighting energy use from the controls system to FLEXLAB®-measured lighting energy. The project team installed two lighting systems in a test cell side-by-side and operated those systems for two weeks with various operating parameters detailed in the following text. The project then evaluated another networked lighting system: the existing dimmable lighting system and networked controls in the FLEXLAB® 4th-floor Lighting and Plug Load testbed. Similar to the other test, FLEXLAB® measured data was compared to energy reporting from the testbed lighting controls system.

The three networked lighting systems tested in FLEXLAB® facilities for this effort were:

- Fifth Light (Cell 1A)
- Enlighted (Cell 1A)
- Wattstopper (4th-floor testbed)

### Lighting and Controls Systems Details

1. Fifth Light lighting controls system
   a. Enterprise controls cabinet and server
   b. Two-wire (DALI) network between fixtures, sensor, controls cabinet and server
   c. Two-row, six-fixture segments
   d. 2 X 12' pendant fixtures (4' controllable sections)
      i. 1 X LED
      ii. 1 X fluorescent (dimmable T8)
   e. Ceiling-mounted photosensor

2. Enlighted lighting controls system
   a. Controls server and laptop
   b. Network switch and gateway
   c. 2 X 4' LED pendant fixtures with embedded sensors and controls

3. Wattstopper Digital Lighting Management system, with dimmable T5HO fluorescent fixtures
   a. Controls and fixtures already installed in Lighting and Plug Load Testbed
   b. 2 X 4' dimmable T5HO direct/indirect pendant mounted

All fixtures were powered by above-ceiling outlets that were individually monitored over time by the FLEXLAB® data acquisition system. The layout of the test setup for systems one and two in FLEXLAB® cell 1A is illustrated in Figure 22. Photos of the setup are presented in Figure 23.

**Figure 22: Test Setup for Testing Systems 1 and 2**
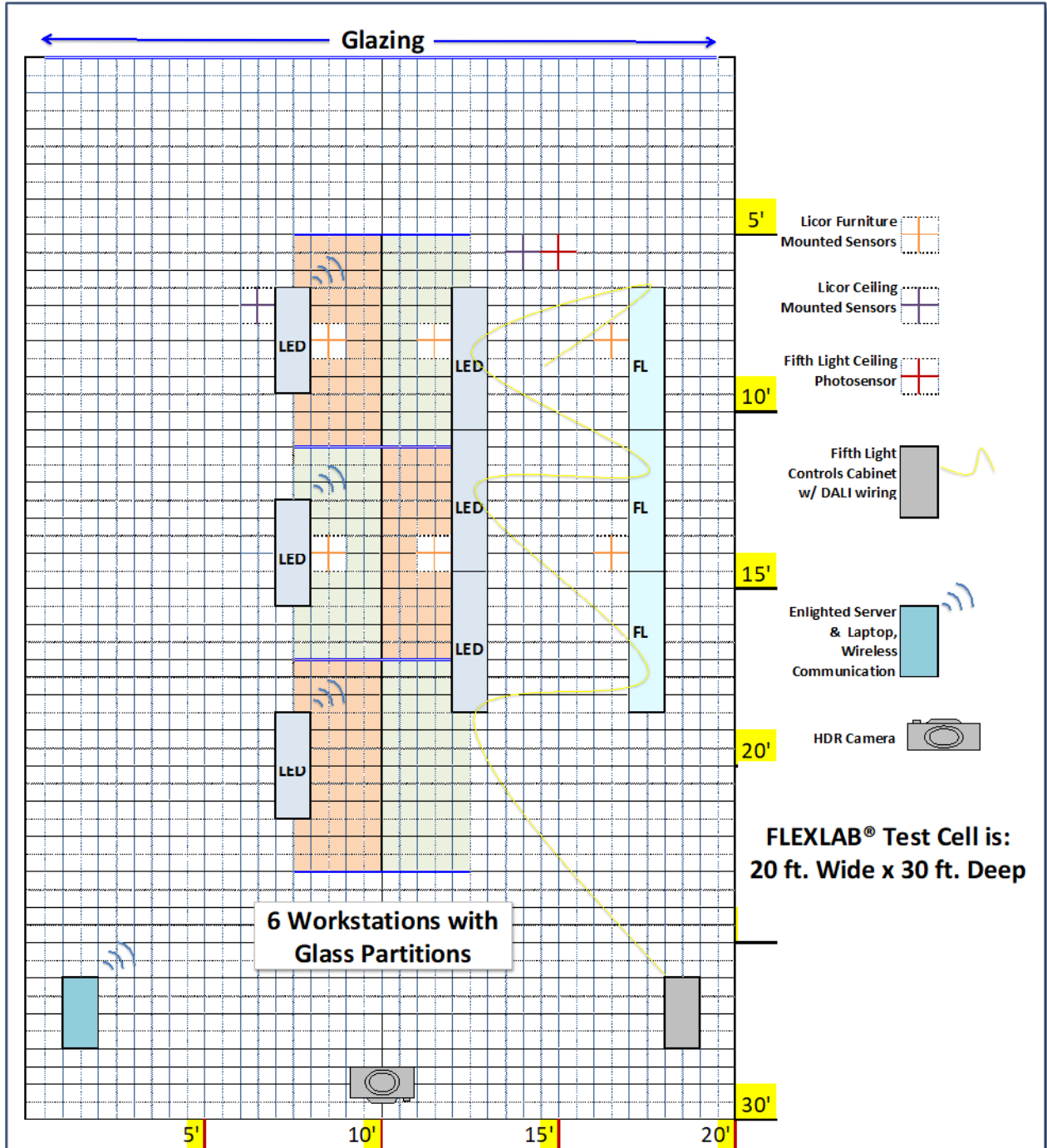


*Source: Lawrence Berkeley National Laboratory*

**Figure 23: Photos of Test Setup in FLEXLAB®**
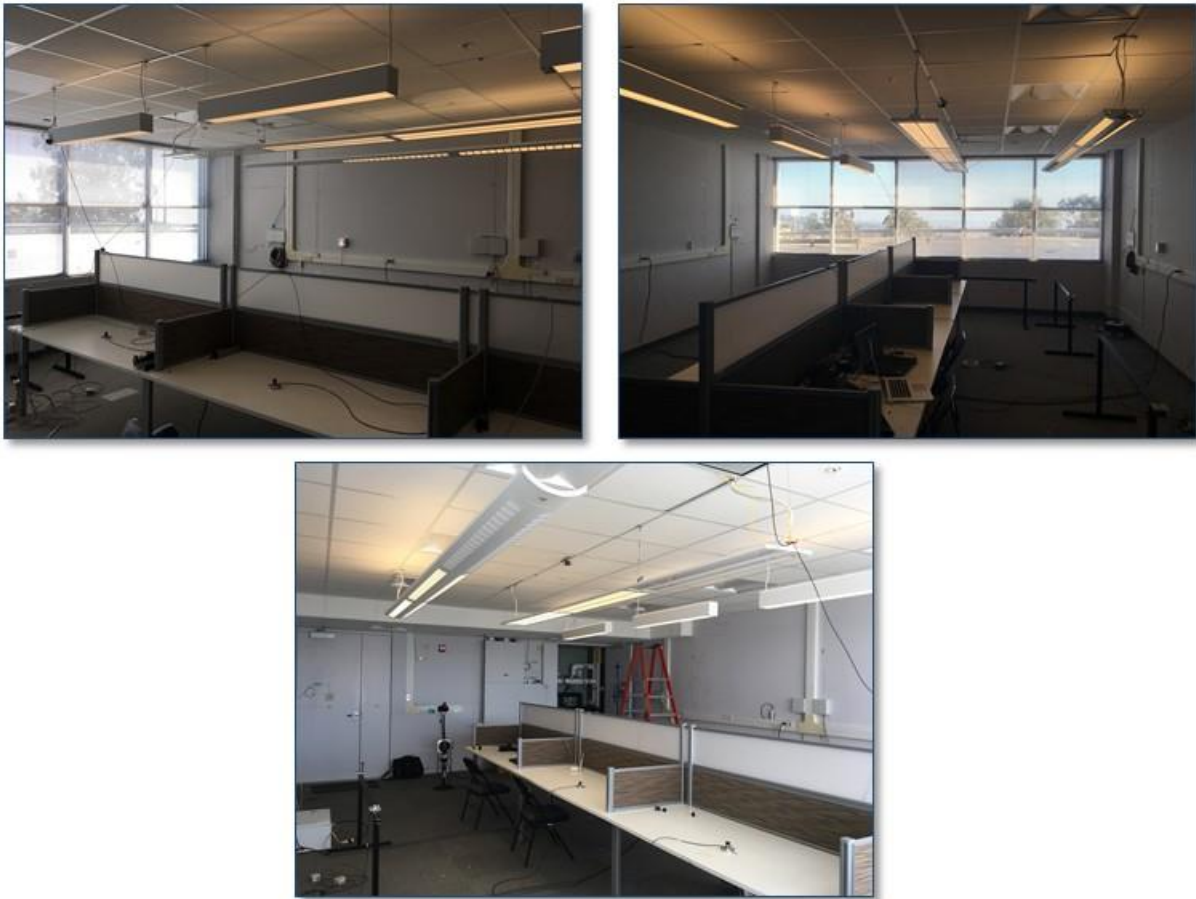


*Source: Lawrence Berkeley National Laboratory*

## Test Operation

- FLEXLAB® 1A Experiment (Fifth Light and Enlighted): Aug 28 – Sept 10, 2017.
    - Daily operation of fixtures, and collection of reported energy and lighting data from controls front-ends and from FLEXLAB® data acquisition system
    - Scheduled operation 7:00 a.m. – 7:00 p.m.; 12-hour per day on/off cycle with daylight dimming
    - Both systems self-reporting on lighting energy as well as continuous energy monitoring via FLEXLAB®
    - An array of daylight harvesting protocols run during test period
- FLEXLAB® Lighting and Plugload Testbed Experiment (Wattstopper DLM): Feb 2019.
    - Continuous operation of fixtures in one cubicle office; pushing different dimming signals to the lighting load periodically, and collection of reported

lighting data from BACNet server via python script and from FLEXLAB®
data acquisition system

## Data Collection

The power and energy consumption data from the three networked lighting control
systems were directly collected from each system's energy reporting software front-
end. The reference data for power and energy use were collected using the FLEXLAB®
data logging system.

Figure 24 shows a plot of measured reference data from FLEXLAB® for the two lighting
control systems tested in parallel in cell 1A. Figure 25 shows the reference measured
data for the third system, evaluated in the FLEXLAB® Lighting and Plug Load testbed.

**Figure 24: Plot of FLEXLAB® Measured Lighting Power Data for Test of Fifth
Light and Enlighted Networked Lighting Control Systems**
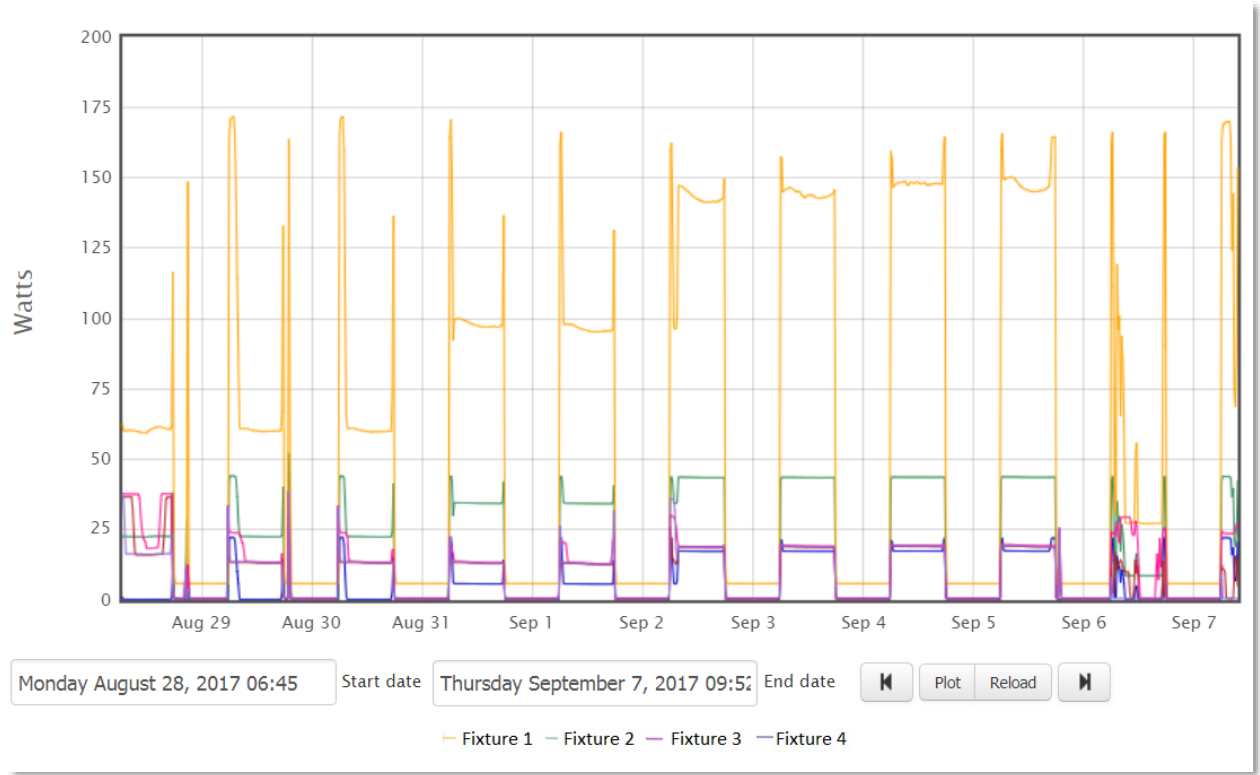


*Source: Lawrence Berkeley National Laboratory*

**Figure 25: Plot of FLEXLAB® Measured Lighting Power Data for the Lighting and Plug Load Test of Wattstopper DLM Networked Lighting Control System**
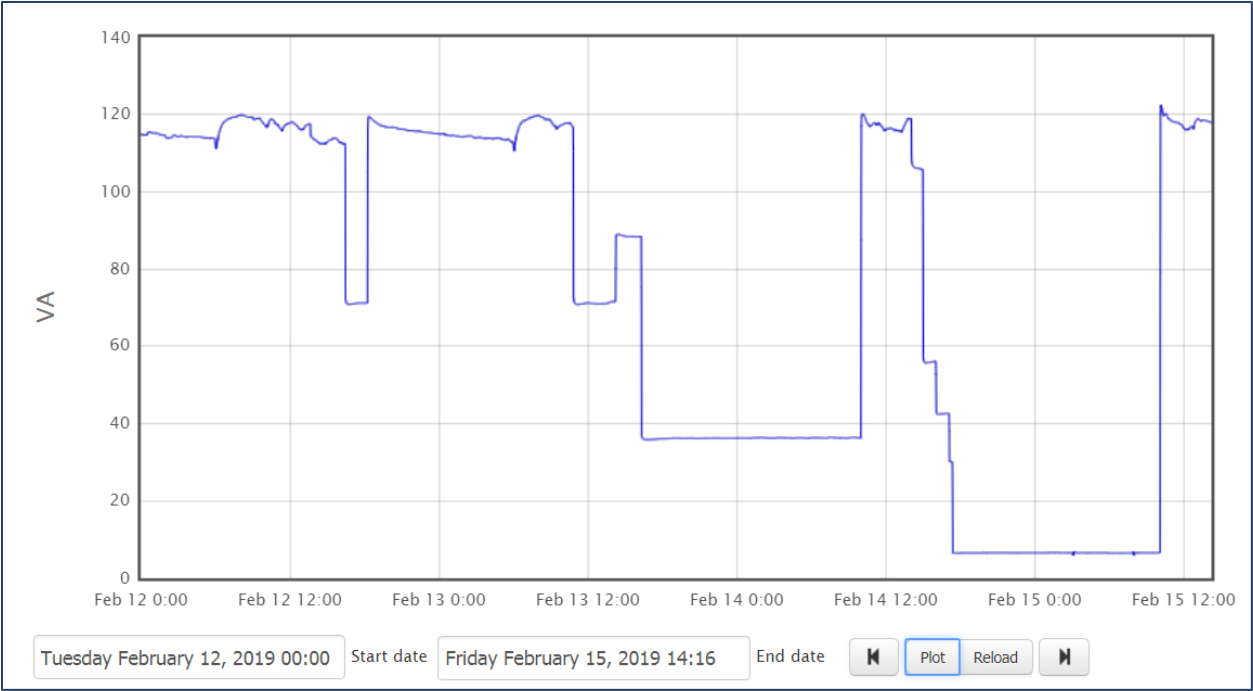


*Source: Lawrence Berkeley National Laboratory*

The Fifth Light system evaluated in the 1A test provides energy data based on a calculated method; in other words, the system does not directly measure energy throughput from controller to light fixture, but calculates it based on assumptions regarding lighting load at different control conditions. Figure 26 is a screen shot of energy and power reports from the system; file data outputs are rows of data for the last 24 hours.

**Figure 26: Screen Capture of Fifth Light Energy Report**
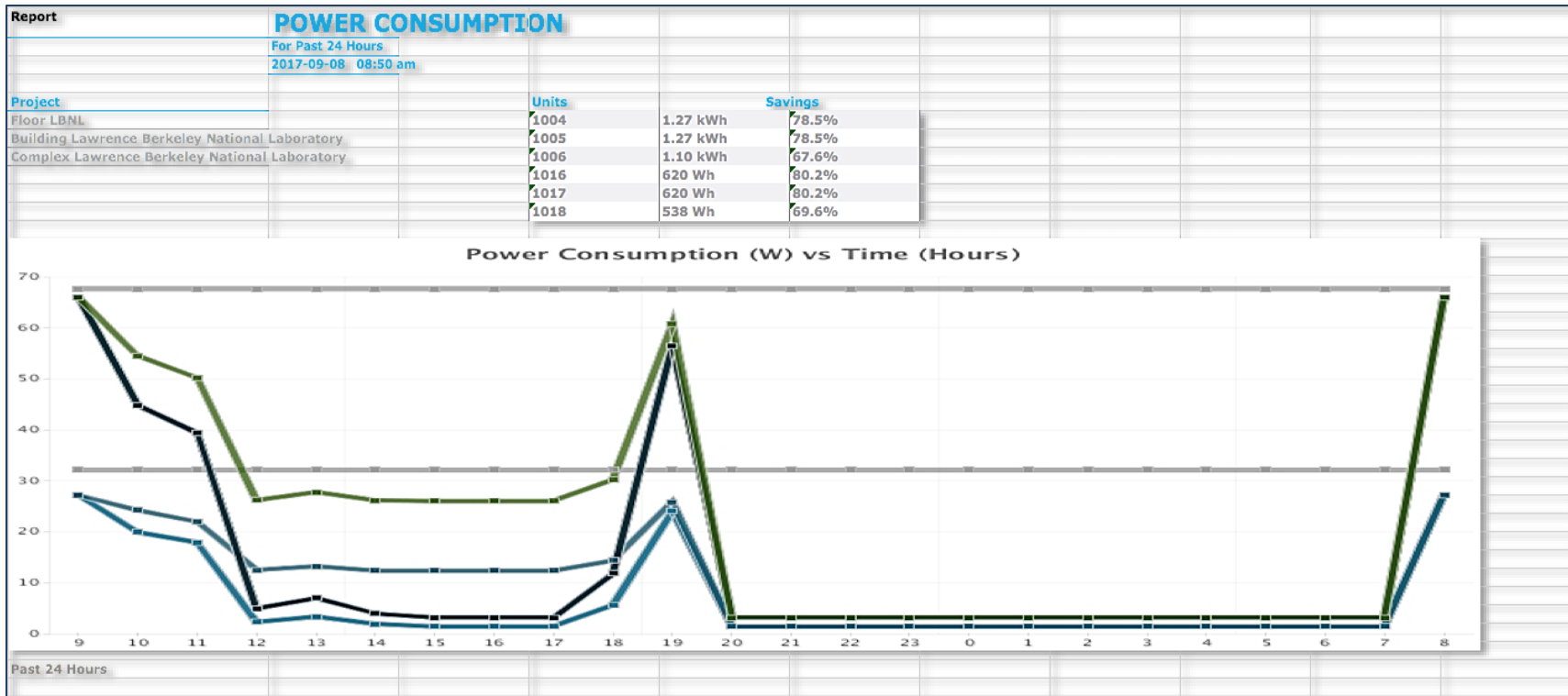


*Source: Lawrence Berkeley National Laboratory*

The Enlighted system, which was tested in the 1A experiment, provides energy data based on a measured method; the system has power monitoring circuitry on each controller to measure throughput to connected loads.

Finally, the Wattstopper DLM system, which was evaluated in the Lighting and Plug Load testbed, provides data via a measured method as well, with power measurement circuitry on each room controller. For this system, a custom method of retrieving energy data was developed. Lighting power data were collected from the network bridge and room controller via BACNet protocol:

1. Connect to the BACNet network
2. Get the BACNet device ID of the particular room controller
3. Python script running on server connected to BACNet router and DLM system polls the register of the room controller where lighting power value is stored and writes value to file

## Analysis and Results

This section presents the analysis of the data collected during the FLEXLAB® experiments. The overall goal of the analysis was to evaluate the difference between reported lighting energy from the networked lighting controls systems and FLEXLAB® measured lighting energy as the reference. This then helps determine whether reported energy from networked lighting controls is a reliable measure for use in validation and compliance, such as what would be required for the outcome-based lighting code approach.

The accuracy of energy reporting from systems that measure power for connected lighting loads (systems 2 and 3, with integrated measurement circuitry in the controller or on the lighting circuit) is compared to a system (system 1) that relies on inputs and assumptions during setup to calculate reporting energy values, to determine which methods are reliable enough for code validation.

One day of hourly averaged data for each system test is presented here. The three systems were operated for several days over different conditions, but the hourly averaged data are shown to simplify the comparative analysis. Systems varied somewhat in the format of reported data, so data for all three were normalized to a common energy metric, watt-hours/ft$^2$, based on reported power or energy divided by an area derived from the experimental set-ups. The conversion of the data to an EUI metric is critical for outcome validation wherein a prescribed energy budget for a space type would be compared to energy usage over time as reported by the controls system.

The quantitative outcomes from the three systems tests are illustrated in the plots presented here. System 1 relied on user inputs during commissioning to calculate the energy usage values that were reported by the system software. In the test the nameplate full power wattage of the LED fixtures controlled by the system was entered into the commissioning software. This step is crucial, as incorrect assumptions about

connected lighting load almost guarantee erroneous energy reporting. Systems 2 and 3 measured connected loads directly to perform energy reporting. The direct measurement approach mitigates the risk of user errors during commissioning that results in energy reporting errors down the line being mitigated.

As shown in Table 3, one of the networked lighting systems that measures energy data for reporting purposes (System 2) does reliably report lighting energy usage. The data flowing from this system would likely serve as a good basis for monitoring and reporting energy usage over time. The other system that measures lighting load rather than calculating it provides a report with daily error (defined here as difference between measured and reported energy divided by measured daily energy total) between 5 percent and 10 percent. It is not clear whether this level of accuracy would be considered reliable for code compliance validation.

In contrast to the two systems that measure energy, the one that calculates it based on inputs during commissioning provides an energy report with a high daily error; in this case, the reported energy value for the day was more than 25 percent greater than the measured value as shown in Figure 27, Figure 28, and Figure 29. This discrepancy means that the reported energy is most likely not accurate enough for code compliance validation. The discrepancy could be either worse or better if different input assumptions were entered during commissioning. The risk is that this step is not performed properly, and that even if it is, the calculation method misses other factors about actual performance (fixture dimming behavior at different control signals, for example).

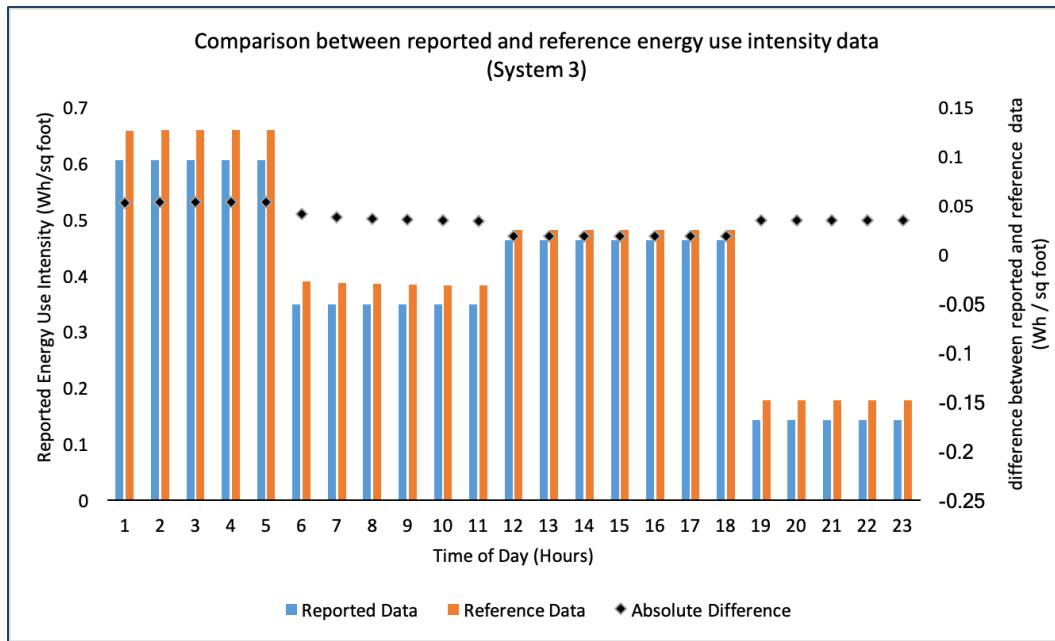**Figure 27: Comparison Between Reported and Reference Data from System 1**
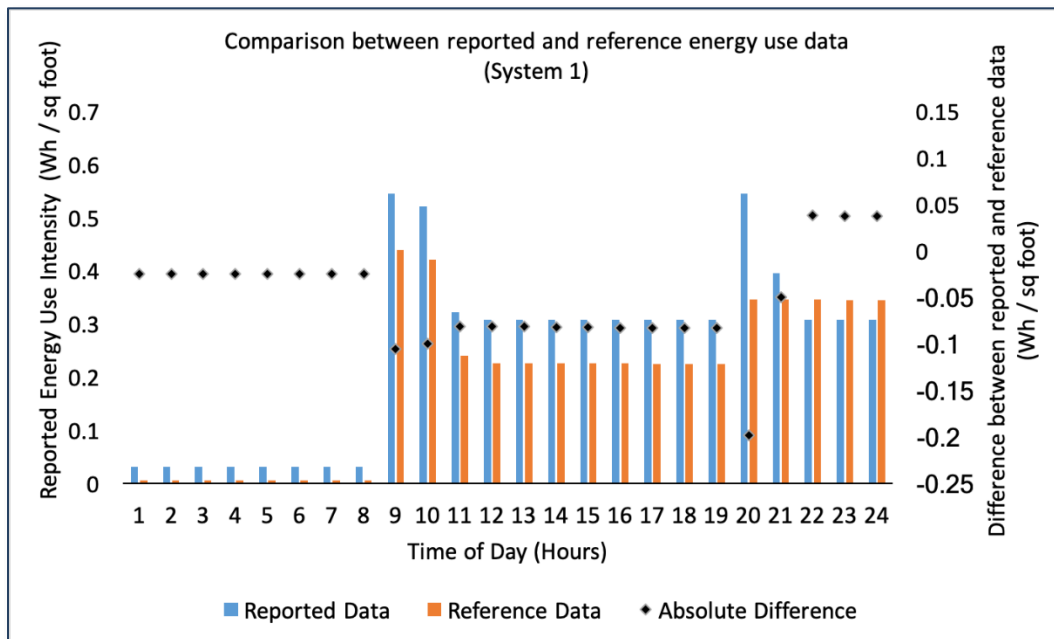


Source: Lawrence Berkeley National Laboratory

**Figure 28: Comparison Between Reported and Reference Data from System 2**
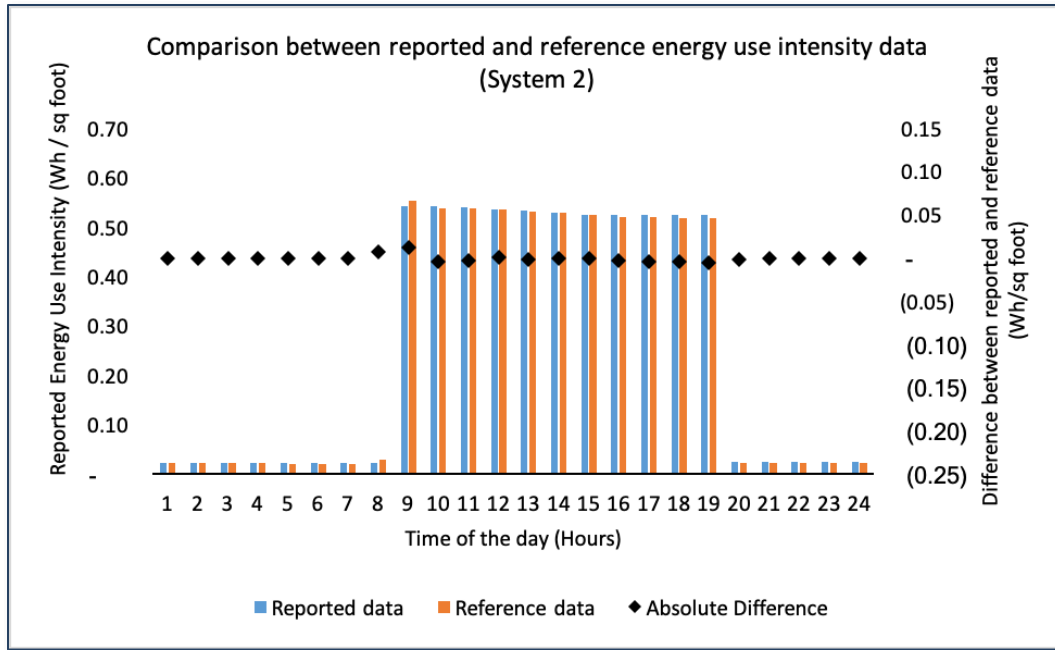


Source: Lawrence Berkeley National Laboratory

**Figure 29: Comparison Between Reported and Reference Data from System 3**



Source: Lawrence Berkeley National Laboratory

The energy monitoring methods of the three systems vary; in general, the measurement-based approach is more reliable, and therefore preferred for validation purposes. Based on this work, it does appear that networked lighting controls if designed and installed properly can be used for determining energy performance of lighting systems for outcome-

63

based code. Reliability is not guaranteed, however, as the variations in daily errors among the systems show. The accuracy of a system's energy reporting feature should be verified prior to its use as a means of validating energy performance over time.

**Table 3: Networked Lighting Control System Energy Reporting Data Compared to Reference Measurements**

| | Reference Energy Data (Wh/ft$^2$) | Reported Energy Data (Wh/ft$^2$) | Daily Error: Reported − Reference (Wh/ft$^2$) | Daily Error / Daily Total (%) |
|---|---|---|---|---|
| System 1 (calculated) | 4.66 | 5.95 | 1.29 | 27.7% |
| System 2 (measured) | 6.10 | 6.13 | 0.03 | 0.5% |
| System 3 (measured) | **9.86** | **9.07** | **−0.78** | **−7.9%** |

*Source: Lawrence Berkeley National Laboratory*

# CHAPTER 5:
# Technology Transfer

## Overview

Transferring and disseminating technology and concepts from the project to a wider audience of stakeholders was a foundational goal. At the outset, the research team drafted a technology transfer plan outlining strategies and tactics in support of knowledge transfer from the project's achievements to stakeholders and entities addressing the large, nonresidential customer segment, and to help promote the vision and potential of energy savings through advanced lighting and control technologies for the public good.

Technology transfer activities included formal and informal outreach, meetings, and conversations at academic, research, and industry events and conferences, as well as presentation of papers, findings, and research outcomes at various symposia. Project team members maintained contacts and communications with stakeholders, industry groups, and a broad audience of beneficiaries.

The networked lighting project presented posters at the 2018 and 2019 EPIC symposia. The 2019 poster is shown in Figure 30. A project website was also created to provide a convenient place to find material such as project research reports and standards proposals (http://lighting.lbl.gov/). The website includes the logo developed for the lighting control user interface standard, shown in Figure 31.
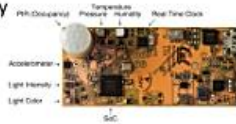
**Figure 30: EPIC 2019 Symposium Poster**



*Source: Lawrence Berkeley National Laboratory*

**Figure 31: Lighting Control User Interface Standard Logo**



Source: Lawrence Berkeley National
Laboratory

# Presentations, Posters, and Papers

- Presentation on some of this project's research efforts to global semiconductor IP company ARM at a meeting March 30, 2017 (*Developing Flexible, Networked Lighting Control Systems that Reliably Save Energy Task 3 – Task Ambient Daylighting Data-Driven Daylighting Control*)

- Presentation on project's research efforts to leading networked lighting controls company Enlighted; including to Tanuj Mohan, CTO; Evan Petridis, Chief System Architect; and Chip Poland, Director of Utility Programs

- Informal outreach at Lightfair 2017 and 2018 to support the project including meetings with industry stakeholders and suppliers (no official public presentations at these)

- Outreach at Strategies in Light conference and tradeshow, including a March 2016 presentation (this event is second only to the annual LightFair conference in attendance, and being in Santa Clara was cost-effective to attend)

- Paper presentation (*A Language for Light: A User Interface Standard for Lighting Control*, Bruce Nordman, Saikiran Dulla, Margarita Kloss, Lawrence Berkeley National Lab) at the 2017 Energy Efficient Domestic Appliances and Lighting (EEDAL) conference in Irvine, California

- Monthly briefings with U.S. DOE's Advanced Lighting Controls stakeholder call

- Poster presentation at the Semiconductor Research Corporation (university-research consortium for semiconductors and related technologies) TECHCON September 2018 conference in Austin TX, of PermaMote concept, features, design, and future work (*A Long-Lifetime Sensor Platform for a Reliable Internet of Things*) by Embedded Systems Research of UC Berkeley's Electrical Engineering and Computer Sciences

- Ppaper published by UC Berkeley researchers on the energy harvesting and sensing techniques embodied in the PermaMote design, *Reconsidering Batteries in Energy Harvesting Sensing*; presented to stakeholders at ENSsys 2018, the 6th International Workshop on Energy Harvesting and Energy-Neutral Sensing Systems, November 04, 2018, in Shenzen China

- Research paper published on the benefits of battery storage as deployed in PermaMotes, over capacitors, for energy harvesting sensors, *Capacity over Capacitance for Reliable Energy Harvesting Sensors*, by UC Berkeley researchers for IPSN 2019, April 16–18, 2019, Montreal, QC, Canada (the International Conference on Information Processing in Sensor Networks, IPSN, is a leading annual forum on research in networked sensing and control, bringing together researchers from academia, industry, and government)

- Poster presentation on the PermaMote technology at Secure Internet of Things Project (SITP) in June 2018, as well as at the Computing On Network Infrastructure for Pervasive Perception, Cognition, and Action (CONIX) Annual Review in 2018

# Standards and Data Model

Along with developing an open API for facility managers and owners to extend the reach of wired lighting systems, the research team developed a reference data model that could be used to communicate between existing lighting systems and low-cost sensors. LBNL has been involved in ANSI Committee C137, which is in the process of creating a standard for lighting control systems. As part of the committee's work, LBNL has been participating in the development of a standard data model that will be a part of the eventual industry standards. The project team also created a mapping between the proposed data model with the updated DALI standard, which is still being developed. LBNL will continue to work with the ANSI committee and through it with the Digital Illumination Interface Alliance, which is also a member of the committee, to add the missing fields as part of DALI 2.0, as well as to propose the adoption of the open API by networked lighting control system manufacturers for improving the interoperability throughout the industry.

The Lighting Control User Interface Standards survey results have also been shared with the NEMA C137 Lighting Systems Committee.

# CHAPTER 6:
## Benefits to California

Networked lighting controls systems hold the promise of unlocking significant new value by capturing detailed environmental and device level sensory information that address the shortcomings of traditional lighting control systems and reduce lighting energy use in commercial buildings, thereby helping to meet California's ambitious energy efficiency goals. They can also manage building lighting load precisely without negatively affecting lighting characteristics, such as dim level or color, so that user comfort is not affected. Overall benefits related to project outcomes include:

- Helping California achieve its policy goal of a 60 to 80 percent reduction in lighting energy use with an estimated 1,600 GWh/year statewide savings potential from these solutions.

- Reducing cost to install and commission advanced lighting controls in existing buildings (AB 758).

- Pervasive sensing and control that improve occupant satisfaction and productivity.

- Standard user interfaces that make lighting systems easier to use and avoid energy waste.

- New performance metrics that enable outcome-based codes.

On lighting energy savings, Williams, et al. (2012) found that advanced lighting controls using a combination of occupancy, tuning, and daylighting typically saved 38 percent of lighting energy use, and the best performing systems had close to 60 percent energy savings. The technologies analyzed and assessed in this research project will make it more likely that lighting control systems performing at the upper end of that savings range will be adopted, leading to an incremental 20 percent energy savings by these advanced systems (above the 38 percent average savings from advanced lighting controls). In addition, the lower system cost through lower-cost components and reduced installation costs should lead to higher market penetration. Taken together, at these assumed savings levels, these advanced systems can save about 1,600 gigawatt-hours (GWh) per year statewide in the commercial building stock if adopted in all office floorspace (assuming total indoor commercial lighting consumption of about 26,000 GWh/yr, about 8,000 GWh/yr for offices, and 20 percent incremental savings in offices), at an annual value of about $200 million ($0.12 to $0.14/kWh). Additional savings are achievable through different demand response strategies as will be documented in the project research products.

This project also directly supported technology development and innovation in California. Research efforts spurred novel lighting control systems research and

development by California researchers, students, and entrepreneurs. The RAD lighting controls system continues to advance in research and development efforts today, with National Institute of Health–funded lighting and wellness research underway in collaboration with the Lighting Research Center of Rensselaer Polytechnic Institute and U.S. DOE Small Business Innovation Research-funded research to refine control methods and evaluate HVAC interactions. As this technology matures and becomes available commercially, benefits will include California job and further energy savings opportunities. Likewise, the PermaMote technology development supported by this project included robust collaboration with graduate school research efforts at UC Berkeley. The self-powered wireless sensors produced through this effort show promise for future development and commercialization.

# CHAPTER 7:
# Summary and Future Research Directions

## Overview

Key project innovations arising from this research include using advances in low-cost sensors, wireless communication, computation, and data storage for:

- Energy harvesting sensors and open communication
- Desktop-based daylight sensing and control
- Intuitive, standardized interface elements for lighting
- Verification of performance and metrics through LBNL FLEXLAB® testing

## Sensor-Rich Networked Lighting

Advanced lighting controls are rapidly evolving, with wireless communications, embedded sensors, data analytics, and other features integrated in new systems to optimize building systems in real time. Through this project, promising new networked lighting controls solutions were developed with dense sensor packages that could be implemented in the built environment to more accurately represent conditions, thereby providing better control points.

Results include the low-cost sensing, distributed intelligence and communications platform, the PermaMote self-powered sensor and controller for lighting applications, and the Readings-At-Desk (RAD) system, using illuminance measured at the desktop, with user-desired illuminance inputs, to control overhead lights.

Functional testing of these systems yielded generally positive results; the technologies controlled lights as intended through the sensor inputs, programming, and wireless protocols used. Field evaluations of both systems proved viability in actual occupied office environments. It is expected that these technologies will continue to develop through further research efforts and eventually transition into commercial viability.

In addition to the project team's technological innovations, the research team developed a reference data model that could be used to communicate between existing lighting systems and low-cost sensors. LBNL has also been engaging with the ANSI Committee C137, which is in the process of creating an ANSI standard for lighting control systems. LBNL has been participating in the development of a standard data model that will likely be a part of ANSI's standard. Lighting control standard digitally addressable lighting interface (DALI) 2.0, currently under development, is intended to make adoption by wireless lighting systems easier with specific requirements for wireless control devices as well as sensors. LBNL will continue to work with the ANSI committee to add to DALI 2.0 as well as to propose the adoption of the open

application programming interface by networked lighting controls systems manufacturers for improving the interoperability throughout the industry.

# Intuitive Standardized Interfaces

Consistent user interface elements in lighting controls make them easier to understand and use and enable a person to match the desired light to the right area for the task or activity at hand. This efficiency not only benefits users, it saves considerable lighting energy and supports California's ambitious energy-saving goals. After extensive analysis of existing user interface standards and of controls found on diverse products in the industry, this project team developed standardized content for user interface elements and proposed it to the appropriate industry body for consideration.

More work is needed to take the content through the standardization process. Additional issues, such as control of light color in general and in lighting scenes, which were not addressed in this project, also need solutions to increase energy savings. Finally, follow-up work in a few years should assess the current state of controls to evaluate their evolution since this research and to guide updates to the standard.

# Verifiable Performance

With the advent of energy reporting features from many networked lighting control systems, and from the FLEXLAB® study of several systems, the research team found it is possible to track lighting energy outcomes from a new lighting system *ex post*. If self-reported demand and energy usage from lighting systems is reliably accurate (within an acceptable tolerance), building codes for lighting systems could move from the lighting power density prescription approach to an outcome-based energy usage approach. The lighting system performance as quantified by the system's energy reporting could constitute the means of verification for the purposes of code compliance.

The energy monitoring methods of the three systems studied varied; in general, the measurement-based approach was more reliable, and therefore preferred for validation purposes. Based on this work, it does appear that networked lighting controls, if designed and installed properly, can be used for determining energy performance of lighting systems for outcome-based code. Reliability is not guaranteed, however, as the variations in daily errors among the systems show. The accuracy of a system's energy reporting feature should be verified prior to its use as a means of validating energy performance over time.

Policy makers, regulators, utilities, and end users will be well served by reliable self-reporting, as all have an interest in knowing whether and how a new networked lighting system delivers on expected efficiency gains. Networked lighting control systems could be equipped with simple energy reporting modules for code compliance that aggregate space types and report energy usage after system start-up.

The effects and benefits of tuning color and intensity in buildings will also eventually require the introduction of additional lighting quality dimensions to code. Similar to the outcome-based energy intensity approach, these lighting quality metrics will most likely have time-variant components and will therefore require some level of monitoring and/or self-reporting as well.

# Ongoing and Future Work to Deliver Energy Savings

Standards development is historically a slow process. Although this research project will have ended, LBNL intends to continue its participation in the development of standardized user interface elements and is encouraged by support expressed by staff from lighting control companies. In addition, the researchers have several planned or pending projects that will build on the outcomes of this project, including:

- Demand Response Capability: Southern California Edison will be supporting a research and field-testing effort to explore adding demand response capabilities to the RAD controller. This project would involve software modifications to the existing RAD controllers and a field test of at least 30 RAD controllers.

- Smart Grid Integration: The U. S. Department of Energy will be funding a major research and development effort using the RAD controller to support smart grid systems. This project will involve major hardware and software updates to the RAD controller, which will be evaluated in LBNL's FLEXLAB® facility.

- Interoperability: Standardize the application-layer data model (ANSI/NEMA C137 Lighting Committee).

- Connected Lighting Systems: Perform field testing to validate end-to-end performance of these systems

- RAD System: Implement demand-response and circadian lighting capabilities.

  - The RAD technology founder has leveraged the developments from this project to get support from the U.S. DOE Small Business Innovation Research program, for which a successful Phase I project has already been completed and Phase II funding is being sought.

- User Interfaces: Standardize user interface elements through collaboration with the ANSI/NEMA C137 Lighting Committee.

- Lighting as a Flexible Load: Characterize how lighting systems can be a resource for the grid.

- Circadian Lighting: Understand how occupants interact with circadian lighting and how to implement circadian lighting as energy efficiently as possible.

# LIST OF ACRONYMS

| Term | Description |
|------|-------------|
| AB | Assembly Bill |
| ANSI | American National Standards Institute |
| API | Application Programming Interface |
| ASHRAE | American Society of Heating, Refrigerating and Air-Conditioning Engineers |
| CA | California |
| CCT | Correlated Color Temperature |
| CEC | California Energy Commission |
| CIE | International Commission on Illumination |
| $CO_2$ | Carbon Dioxide |
| DALI | Digitally Addressable Lighting Interface |
| DLC | Design Lights Consortium |
| DOE | Department of Energy |
| DR | Demand Response |
| EISG | Energy Innovations Small Grant |
| EPIC | Electric Program Investment Charge |
| EUI | Energy Usage Intensity |
| GUI | Graphical User Interface |
| HDR | High Dynamic Range |
| HVAC | Heating, Ventilation and Air Conditioning |
| IEC | International Electro-Technical Commission |
| IECC | International Energy Conservation Code |
| IES | Illuminating Engineering Society |
| IEEE | Institute of Electrical and Electronics Engineers |
| IoT | Internet of Things |
| ISO | International Organization for Standardization |
| kWh | Kilowatt-Hour |
| LAP | Lighting Action Plan |
| LED | Light-Emitting Diode |
| LPD | Lighting Power Density |
| NEMA | National Electrical Manufacturers Association |
| PG&E | Pacific Gas and Electric Company |

| Term | Description |
| --- | --- |
| RAD | Readings at Desk |
| RGB | Red, Green, and Blue |
| SBIR | Small Business Innovation Research |
| SCE | Southern California Edison |
| SDG&E | San Diego Gas & Electric Company |
| SoC | System on a Chip (integrated circuit) |
| TLED | Tubular LED (linear replacement lamp) |
| VOC | Volatile Organic Compound |

# GLOSSARY

| Term | Definition |
|---|---|
| API | Application programming interface, which is a set of communication protocols and tools for building software. |
| Demand Response | A mechanism through which an end-use's load profile is changed (by the user, a third party, or a utility) in response to system needs, often in return for economic compensation (e.g., payments or a different rate structure). |
| End Use | A service performed using energy (e.g., lighting, refrigeration) or a type of energy-using device (e.g., refrigerators, pool pumps). These end use and their demand for electricity make up customer load. |
| EPIC (Electric Program Investment Charge) | The Electric Program Investment Charge, created by the California Public Utilities Commission in December 2011, supports investments in clean energy technologies that benefit electricity ratepayers of Pacific Gas and Electric Company, Southern California Edison Company, and San Diego Gas & Electric Company. |
| Internet of Things (IoT) | The inter-networking of physical devices, vehicles (also referred to as "connected devices" and "smart devices"), buildings, and other items embedded with electronics, software, sensors, actuators, and network connectivity which enable these objects to collect and exchange data over a network without requiring human-to-human or human-to-computer interaction. |
| Sector | A market or population segment sharing common characteristics. For the purposes of this study, the relevant sectors are: residential, commercial, and industrial (which includes agriculture). |
| Smart Grid | Smart grid is the thoughtful integration of intelligent technologies and innovative services that produce a more efficient, sustainable, economic, and secure electrical supply for California communities. |
| Zigbee | An IEEE 802.15.4-based specification for a suite of high-level communication protocols used to create personal area networks with small, low-power digital radios, such as for home automation, medical device data collection, and other low-power low-bandwidth needs, designed for small scale projects which need wireless connection. Hence, Zigbee is a low-power, low data rate, and close proximity (i.e., personal area) wireless ad hoc network. |

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