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FINAL PROJECT REPORT**

ACHIEVING ENERGY-EFFICIENT LIGHTING IN CALIFORNIA

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Prepared by: California Lighting Technology Center at UC Davis

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PREFACE

The California Energy Commission Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The Energy Research and Development Division conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The Energy Research and Development Division strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

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- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

Realizing Energy Efficient Lighting in California is the final report for the Realizing Energy Efficient Lighting for California program (contract number 500-08-053) conducted by the California Lighting Technology Center, University of California - Davis. The information from this program contributes to Energy Research and Development Division's Buildings End-Use Energy Efficiency Program.

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

ABSTRACT

To address California's critical need for targeted, practical technology improvements that reduce lighting energy use and advance building energy-efficiency, in 2009, the California Energy Commission initiated a comprehensive lighting research, development, demonstration and outreach program in partnership with the California Lighting Technology Center. The program's goal was to achieve new, energy-efficient lighting, daylighting and fenestration solutions for California. As part of the program, the California Lighting Technology Center addressed the application of light-emitting diode technology and advanced lighting and fenestration control systems as primary tools to achieve deep, sustained electricity savings. In addition, researchers examined multiple, other emerging technologies and design strategies for their performance, cost-effectiveness and energy savings potential. Key projects included evaluation of plasma technology, organic light-emitting diodes, and direct current lighting microgrids. In combination with these technical activities, the program also delivered targeted market transformation support for the California Energy Commission's technology portfolio in order to achieve increased market penetration of its lighting, daylighting, and fenestration solutions.

Keywords: Lighting, daylighting, fenestration, LED, OLED, adaptive, plasma, envelope, luminaire, market facilitation, CLTC, electricity, energy savings, energy efficiency, lighting controls

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EXECUTIVE SUMMARY

Introduction

For more than 35 years, California has a documented and demonstrated record of prioritizing energy efficiency as an energy resource. This has led to progressive building and appliance efficiency standards and other state legislation that calls for aggressive reductions in California's building energy use for new construction and existing facilities.

The California legislature mandated lighting electrical energy use in the state's commercial and residential building sectors which must continue to be reduced. Assembly Bill 1109, requires that between 2007 and 2018, electricity use reductions must reach 50 percent for residential interior lighting and 25 percent for commercial interior and outdoor lighting.

In 2009, to address the state's critical demand for targeted, practical technology improvements to reduce lighting energy use and advance building energy-efficiency, the California Energy Commission (Energy Commission) partnered with the California Lighting Center (CLTC) in a new lighting program. This multi-year program focused on lighting research, development, demonstration and outreach to achieve new, energy-efficient lighting, daylighting and fenestration (window) solutions for California. Nearly three dozen unique projects were aimed at specific lighting technologies, strategies or building sectors. They addressed some of California's most pressing lighting energy needs including reducing California's outdoor lighting energy footprint; developing and commercializing new electric lighting control systems that shrink system commissioning and recalibration needs; and developing and publishing industry-leading learning tools on the state's complex and dynamic energy efficiency regulations.

Project Purpose

In California, lighting accounts for 35 percent from commercial and 22 percent from residential electricity use. Numerous opportunities are currently available to reduce this use by continuing to improve source or system efficiency, reduce operating hours and decrease reliance on grid-connected power sources. The CLTC used light-emitting diode (LED) technology and advanced control systems to achieve deep, sustained electricity savings. In addition, researchers examined multiple emerging technologies and design strategies to better understand their performance, cost-effectiveness and energy savings potential. Key projects included evaluating plasma technology, organic LEDs, and direct current (DC) - lighting microgrids.

The program also delivered targeted outreach and technical support for the Energy Commission's Research and Development technology portfolio to increase the market for lighting, daylighting, and window design technologies. This support included increasing customer awareness of energy-efficient lighting products and best practices, and educating Californians on their operation, safety, and codes and standards requirements.

Project Results and Benefits

Between 2008 and 2010, researchers found total electricity use, across the commercial and residential sectors declined, resulting in a similar decline in lighting electricity use. Residential

lighting electricity use per occupied California household is down by more than 7 percent during this period. Commercial interior lighting electricity use is down by approximately 13 percent and outdoor lighting electricity use has declined by nearly 6 percent.

During the last seven years, researchers evaluated and identified a portfolio of commercially available products and energy-efficient design strategies for residential and commercial applications that have helped reduce electricity use. Demonstrated savings range from a low of 5 percent to 90 percent depending on the application (Table 1). Adaptive outdoor lighting solutions, for example, is clearly an effective strategy to mitigate energy waste and light pollution, repeatedly and consistently demonstrating 50 to 60 percent energy savings by using occupancy-controlled, adaptive lighting for parking lots, parking garages, building perimeters and other related outdoor lighting applications. This technology matured from laboratory prototype to commercial technology and is now required by California law to be installed in a variety of outdoor areas.

Table 1: Estimated Electricity Savings from Key Program Technologies and Strategies

Program Focus	Estimated Savings	Baseline
Adaptive Outdoor Lighting	40% - 90%	Static HID luminaires
Smart Fenestration	5% - 25%	Static windows and skylights
Adaptive Indoor Lighting	40% - 80%	Fluorescent lighting, Title 24 – 2013 compliant
Residential LED Lighting	50% - 80%	Incandescent and Fluorescent screw-base lamps
Novel Office Lighting Design	35% - 45%	Title 24 – 2013 LPD for offices

Residential lighting also showed significant energy savings for California consumers. Replacing existing incandescent downlights with dedicated LED downlights or retrofit kits containing LED replacement lamps delivers energy savings of approximately 80 percent.

The program also conducted numerous outreach and educational events to support these technical activities including seminars, daily support for inquiries and requests on general illumination topics; speaking engagements at the local, state and national level; and promoting Energy Commission research development and development (RD&D) lighting technologies at industry trades shows and conferences. Outreach activities also focused on developing application guides, technology fact sheets, case studies, and similar materials for Energy Commission stakeholders. Researchers also created and enhanced multiple websites to support RD&D technology; support for the development of new product and building standards; and utility and case study development, market analyses and other tools. These activities were critical in communicating the benefits of Energy Commission-sponsored research, development and demonstration.

CHAPTER 1:

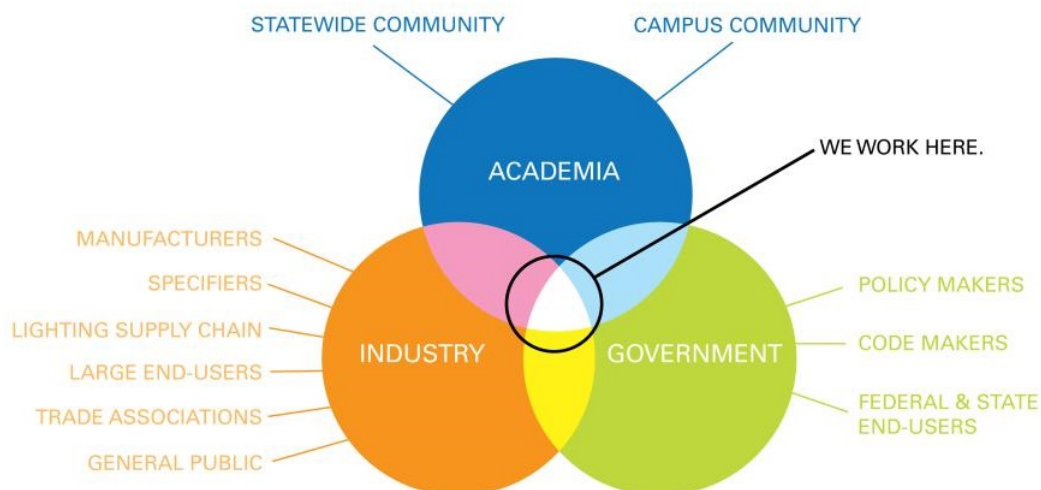
Background and Introduction

Beginning with the introduction of state building energy efficiency standards in 1978, and continuing through present, California has a documented and demonstrated record of prioritizing energy efficiency as an energy resource. This prioritization has led to progressive building and appliance efficiency standards and other state legislation that calls for aggressive reductions in California's building energy use, both in terms of new construction and existing facilities.

In alignment with these priorities, the California Lighting Technology Center (CLTC), part of the University of California, Davis (UC Davis), was established in 2004 as a joint partnership between UC Davis, the California Energy Commission (Energy Commission), the United States Department of Energy (DOE) and the National Electrical Manufacturers Association (NEMA). CLTC's mission is to advance the state of energy efficient lighting and daylighting technologies to address California's aggressive energy reduction goals.

Working in partnership with designers, manufacturers, end users, utilities, government agencies, and others, CLTC commercializes energy-efficient lighting and daylighting technologies, producing new technologies, inventions, patents, and license agreements. CLTC also provides engineering specifications, market research, resources, lighting guides, working papers, and white papers. The center conducts technology demonstrations, and publishes reports and case studies on these projects. The center's faculty and staff also provide curriculum and instruction for education and training courses, in addition to conducting workshops, seminars and outreach activities.

Figure 1: CLTC Partner Domain



Source: CLTC

To address California's critical need for targeted, practical technology improvements that reduce lighting energy use and advance building energy-efficiency, in 2009, the Energy Commission initiated a comprehensive lighting research, development, demonstration and outreach program in partnership with CLTC to achieve new, energy-efficient lighting, daylighting and fenestration solutions for California. The program was composed of nearly three dozen unique projects, each aimed at a specific lighting technology, strategy or building sector.

These projects have addressed some of California's most pressing lighting energy needs. Examples include development and widespread adoption of adaptive, outdoor lighting to significantly reduce California's outdoor lighting energy footprint; development and commercialization of novel electric lighting control systems that reduce system commissioning and recalibration needs as compared to traditional devices; and development and publication of industry-leading learning tools to better inform California citizens on the state's complex and dynamic energy efficiency regulations.

The Program was composed of projects aligned with the following topics:

- Smart Fenestration and Daylight Optimization
- Core Daylighting
- Daylight Harvesting Control Systems
- Adaptive Outdoor Lighting
- Adaptive Indoor Lighting
- Residential LED Lighting
- Emerging Light Sources and Design Strategies
- Workforce Development and Education
- Policy, Codes and Standards Development

CHAPTER 2:

Technology Development and Demonstration

The program supported product evolution in the laboratory and deployment success in the marketplace. Multiple energy-efficient lighting and daylighting solutions and strategies are now commercially available to California consumers. These advancements occurred because of the broad support and flexibility afforded to research, development and demonstration (RD&D) as part of the program.

2.1 Electric Lighting and Controls

In California, lighting accounts for 35 percent and 22 percent of commercial and residential electricity use, respectively.¹ Numerous opportunities exist to reduce this use through improvements in source or system efficacy, reduction in operating hours and reliance on grid-connected power sources. As part of the program, CLTC addressed the application of advanced control systems as a primary method to achieve deep, sustained electricity savings. In addition, researchers examined multiple emerging technologies and design strategies for their potential, savings contributions. Key projects included evaluation of plasma lighting, organic lighting-emitting diodes (OLEDs), and DC-direct lighting microgrids. Highlights are provided as part of this report. Details of each Program effort are provided in separate report Appendices A-P.

2.1.1 Adaptive Outdoor Lighting

Adaptive outdoor lighting is defined as lighting that's provided where and when it is needed based on actual conditions present in the illuminated space. In the outdoor environment, light levels may be adapted based on a variety of conditions such as traffic volume, vehicle or pedestrian speed, traffic composition, the potential for pedestrian conflict, recommended ambient illuminance and weather.

Today, few installed outdoor luminaires include advanced controls to adjust light output to appropriate recommended levels based on actual environmental conditions. Traditional outdoor lighting design practice is limited to constant light output based on "worst case" conditions. This approach often over-illuminates outdoor areas while wasting energy by providing maximum light output regardless of real-time requirements. Real-time requirements are dependent on the state of the space which varies over time. For instance, if the space is vacant the illuminance levels required for this space would be based on the system owner's security and safety requirements only, and not recommended light levels based on occupied use of the space.

¹ Values obtained from the California Energy Commission.
<http://www.energy.ca.gov/research/buildings/lighting.html>.

Figure 2: Adaptive Outdoor Lighting at UC Davis



Photo credit: CLTC

Adaptive lighting requirements are greatly affected by recent standards and legislation. The California legislature has mandated a reduction in lighting energy use in the commercial and residential building sectors per Assembly Bill (AB)1109, the California Lighting Efficiency and Toxins Reduction Act (AB 1109, Huffman, Chapter 534, Statutes of 2007). Per AB 1109, California must reduce its lighting energy use between 2007 and 2018 by 25 percent for commercial outdoor lighting. At the federal level, the goals of AB 1109 align well with the United States Environmental Protection Agency (EPA) greenhouse gas reduction (GHG)goals (EPA-2009 GHG goals).² President Barack Obama’s Executive Order (EO) 13514, “Federal Leadership in Environmental, Energy, and Economic Performance,” introduced new greenhouse gas (GHG) emissions management requirements, expanded water reduction requirements for federal agencies, and addressed waste diversion, local planning, sustainable buildings, environmental management, and electronics stewardship. Optimized lighting achieved through the use of next generation adaptive outdoor luminaires has the potential to help reduce California outdoor lighting energy use as required by AB1109 and also lower overall GHG emissions as mandated by EO 13514.

The program included RD&D of local and distributed, adaptive outdoor lighting systems. At the local level, researchers addressed smart luminaires. At the campus level, efforts focused on application of networked communication and wireless controls to combine multiple outdoor lighting zones into one cohesive system.

² Information regarding EPA goals may be accessed at <http://www.epa.gov/oaintnrt/practices/eo13514.htm>.

2.1.1.1 Smart Luminaires

Most commercial and industrial buildings utilize wall-mounted or pole-mounted luminaires for outdoor common area and security lighting. High pressure sodium (HPS) lamps are the most common lamp type used with these fixtures; however, HPS has poor color rendering and has limited compatibility with lighting controls. Such deficiencies, combined with extended nighttime operating hours, make these luminaires a good choice for retrofit with emerging, high-efficiency alternatives combined with advanced lighting controls. Alternatives such as LED and induction technology can offer greater efficiency, improved color rendering and controllability, both optically and in combination with dimming, occupancy and photo controls.

Researchers partnered with multiple lighting manufacturers to develop and demonstrate smart, outdoor luminaires for post, pole and wall-mounted applications. Efforts focused on development of luminaire performance specifications and components necessary to effectively integrated adaptive control devices into traditional outdoor luminaires. In some cases, projects utilized existing, commercially available equipment in novel ways, while in others, researchers developed entirely new solutions for the outdoor market. Following development work, many technologies were evaluated as part of field installations in order to refine designs and validate performance. Outcomes of this work are provided in CHAPTER 4: Program Outcomes. Details on all outdoor, adaptive RD&D activities is provided in APPENDIX A: Adaptive Outdoor Lighting.

Figure 3: Smart Wall Packs and Post-Top Luminaires

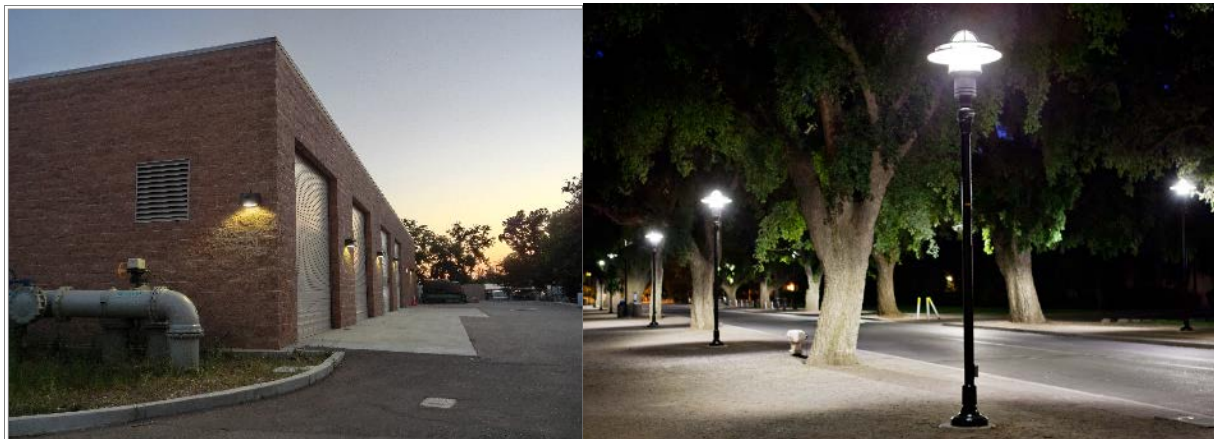


Photo credit: CLTC

2.1.1.2 Networked Lighting Systems

Networked lighting control systems have the potential to save significant amounts of energy and add substantial amenity to both interior and exterior applications. Compared to traditional outdoor lighting, networked systems offer a wide variety of additional options and features. Fully programmable schedules with nearly seamless dimming and energy use logging have the capacity to yield immense energy savings. Proximity sensors and direction of travel (D.O.T.) capabilities can increase these numbers. Automated failure alarms reduce downtime and the need for routine maintenance checks, enhancing safety while reducing maintenance costs. In

addition, networked communication can allow first aid and emergency services to override the system settings if needed.

Typical controls for exterior lighting are simple relays activated by a photocell. They turn lights on at dusk and off at dawn. Networked control systems available today predominantly rely on wireless radio frequency (RF), power line communications (PLC), or a combination of both communication technologies to network individual light fixtures.

Figure 4: Networked, Adaptive, Outdoor Lighting



Photo Credit: CLTC

Research efforts focused on development and evaluation of RF, mesh-network technology for the outdoor lighting environment. Researchers partnered with several technology providers able to adapt and support networking solutions and their incorporation into traditional outdoor luminaire product portfolios. Following development work, many technologies were evaluated as part of field installations to refine designs and validate performance. Development and demonstration outcomes are provided in CHAPTER 4: Program Outcomes. Details on all outdoor, adaptive, networked lighting RD&D activities is provided in APPENDIX A: Adaptive Outdoor Lighting.

2.1.2 Indoor Lighting Solutions and Strategies

Over the last 15 years, rising electricity prices and concerns about climate change have helped drive the lighting market's shift towards the manufacture and use of more energy efficient light sources (DOE 2009). As a result, lighting energy use in the United States dropped nine percent annually between 2001 and 2010, despite the number of installed lamps growing by 18 percent (Navigant Consulting, 2012). A contributing factor to the reduced energy use during this period was the emergence and market adoption of solid-state lighting (SSL). This technology, when combined with appropriate lighting controls and installed in accordance with a best-in-class

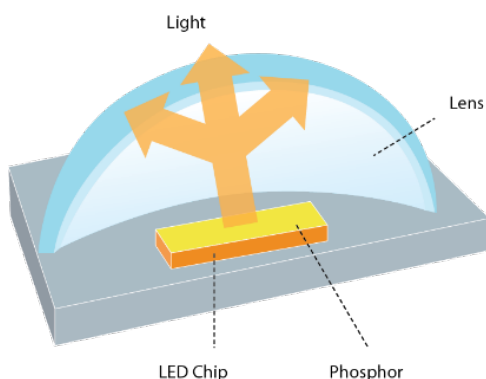
design, has the potential to reduce indoor lighting electricity use by 50 percent or more as compared to traditional solutions.

2.1.2.1 Solid State Lighting

Improved LED technologies have the potential to significantly increase the market share in residential and commercial applications. Market projections indicate LED technology capable of competing with incandescent in terms of color quality will capture about 20 percent of the commercial market by 2019. Similar market penetration rates are expected for the residential sector (Navigant Consulting. 2010).

Today, there are two primary types of SSL technology: inorganic LEDs and OLEDs. LED technology is well-suited for directional applications, leveraging the point source LED to achieve a higher coefficient of utilization as compared to omnidirectional light sources such as fluorescent and incandescent. Since general-illumination LED technology emerged, innovative optical design strategies have allowed the technology to be an appropriate light source for a wide cross-section of applications including indoor ambient illumination, back-lighting, accent lighting and outdoor lighting.

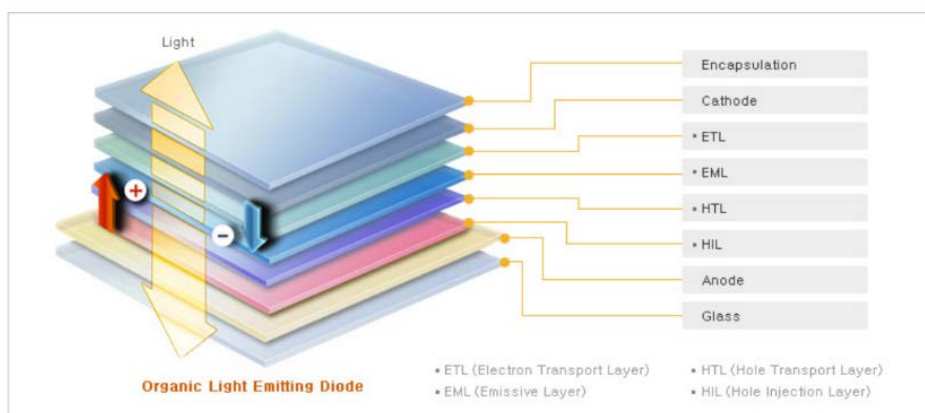
Figure 5: LED Chip



Source: CLTC

In contrast to LEDs, the OLED form factor is ideal for luminaire designs requiring diffuse planes of light. Appropriate OLED applications including general service, back-lighting and accent lighting. Compared to LED technology and other traditional light sources, OLED technology offers more flexibility in the fixture design with respect to its ability to bend or curve. OLED integration into furniture and other planar objects found in the built environment is an additional, unique application for this source.

Figure 6: Organic Light Emitting Diode



Source: LG Chem

Due to technology advancements and design innovation, commercialized LED and OLED lighting products compete directly against each other in several applications including general service, back-lighting and accent lighting. LED lighting currently offers high-efficacy, high-quality performance at a lower cost than OLED lighting products. OLED development trails LED, but has the potential to achieve significant market adoption once lighting costs and performance of OLED luminaires become equivalent to LED luminaires. Detailed information regarding the current state and expected potential of OLEDs may be found in APPENDIX D: Organic LEDs.

2.1.2.2 LED Replacement Lamps

Over the past five years, LED replacements for standard pin and screw-base fluorescent and incandescent lamps emerged as a viable alternative to traditional incandescent and compact fluorescent lamps (CFL). While the energy savings potential of LED replacement lamps as compared to traditional lamps is well publicized, a positive consumer perception of LED replacement lamps is necessary to achieve sustained market adoption and, consequently, long-term savings. To achieve positive consumer perception, LED replacement lamps should operate per manufacturer's claims over the life of the product and deliver similar, if not better, photometric and electrical performance as compared to the products they claim to replace. Near-term market acceptance will be driven by a lamp's initial performance and the lamp's ability to meet or exceed user expectations for characteristics such as initial light output, color, and dimming. Long-term market acceptance will be driven by the lamp's longevity and its electrical and photometric performance throughout its life.

CLTC completed an LED replacement lamp test program to verify manufacturer's claims regarding initial and long-term product performance. The test program focused on directional LED lamps designed to replace standard multifaceted (MR) and parabolic aluminized reflector (PAR) incandescent and halogen lamps. Test results provided information to assist in determination of in-situ lamp life, total light output, lumen maintenance, color maintenance, and flicker over the life of the products. Test conditions, including lamp orientation, housing configuration, and dimming level, were evaluated to understand their effect on each product's

electrical performance, photometric performance and lifetime. Project outcomes are provided in CHAPTER 4: Program Outcomes - LED Replacement Lamps.

Figure 7: LED Replacement Lamps under Test



Photo credit: CLTC

Appendix C contains information and all test results of electrical and photometric performance over time for LED directional replacement lamps evaluated as part of the program. Appendix C includes data collected on ten different products over the course of their first 5,000 hours of operation. Information on the program test methodology and test equipment is also included. Information and data for omnidirectional LED replacement lamps, collected in partnership with the California Investor-Owned Utilities (IOUs) may be accessed at <http://cltc.ucdavis.edu/publication/performance-testing-report-omni-directional-led-replacement-lamps>.

2.1.2.3 Residential LED Luminaires

In 2010, an estimated 9.2 million LED lamps were installed in the residential sector, accounting for 0.2 percent of the installed inventory of residential lighting. About one-third of these were screw-base lamps such as those used in table lamps and torchers. The remainder of the residential LED lighting is installed in specialty applications such as under cabinets and landscape areas (Navigant Consulting. 2012).

Widespread adoption of LED lighting is poised to be the single, largest advancement in lighting efficiency during the 21st century. In California, less than one percent of residential and indoor commercial light points use LED technology (DNV KEMA 2012). The residential sector is a significant future market for LED technology. It has significant untapped potential energy savings and underscores the importance of a comprehensive next-generation LED residential lighting and manufacturer training to target efficiency improvements.

LEDs have much to offer the residential lighting market. They can deliver improved luminaire and application efficacy, are long-lived and are well-suited for use with lighting controls. Because of their small size and directional light output, LEDs offer the potential to create luminaires with new form factors, shapes and optical distributions; however many luminaire

manufacturers continue to design new LED products to only meet typical performance levels of traditional luminaires.

As part of the program, researchers completed a general market analysis to catalogue standard residential luminaire types and determine those products with the most potential for savings due to a transition from standard to LED technology. Five luminaire types were selected for further research.

- Downlights
- Chandeliers
- Wall sconces
- Torchieres
- Task lamps

Estimates indicate these luminaires represent the majority of the residential market share. Downlights, chandeliers and wall sconces are permanently installed lighting. Torchieres and task lamps are portable units. Each luminaire type was reviewed to develop an initial conceptual design approach that included incorporation of LED technology. Parallel to this conceptual path, researchers collaborated with industry partners to gauge needs for brand aesthetics and manufacturability.

Researchers developed multiple luminaires as part of the program, and each reached varying degrees of maturity within the design process. Torchiere development focused on different LED technologies and appropriate heat sink engineering. Work on the task lighting focused on industrial design idea generation and conceptual development in an attempt to include aspects of the partner manufacturer's corporate identity. Figure 8 shows examples of permanent and portable luminaires with traditional and modern design variations indicating the range of possible aesthetics. For designs that culminated in prototypes or commercial products, CLTC conducted in-situ demonstrations to assess their performance under real-world conditions. Research outcomes are provided in CHAPTER 4: Program Outcomes - Residential LED Luminaires. Complete details are provided in APPENDIX B: Indoor, Residential LED Luminaires.

Figure 8: Interior Luminaire Development Diagram



Source: CLTC

2.1.2.4 Plasma Lighting

There is always a place in the lighting market for products that are capable of reducing cost through increased efficacy and luminaire lifespan. Light emitting plasma shows such promise. Plasma lamps operate on physical principles similar to those used in high-intensity discharge (HID) lamps, with two significant differences. In plasma lamps, the gas in the capsule is excited using focused radio frequency waves instead of by a high-voltage electric arc. RF excitation eliminates the need for electrodes within the lamp tube. Second, the plasma lamp is significantly smaller than a traditional HID lamp with the light-emitting capsule being approximately half the size of a jelly bean. Plasma lamps, in fact, were originally developed for video equipment such as projectors and television sets.

Light emitting plasma has the capability of a 50,000 hour lifespan compared to the approximate 20,000 hour lifespan of most metal halide sources. This is due to the absence of electrodes. In most traditional HID lamps, corrosion occurs around the electrodes as heated particles circulate in the lamp and collide with the glass near the base of the electrode. Also, in many HID lamps, bits of the electrode are vaporized and deposited on the interior walls of the lamp, which darkens the bulb. Both of these shortcomings are circumvented in a light emitting plasma lamp, potentially increasing its effective life.

Figure 9: Evaluation of a Plasma High Bay Luminaire at CLTC Test Facility



Photo Credit: CLTC

To move plasma lighting from concept to commercial solution, researchers collaborated with manufacturing partners to develop and evaluate plasma luminaires for high bay applications such as athletic facilities and warehouses. Prototypes were compared with other current high bay lighting options to understand performance levels and improvements necessary to allow plasma luminaires to compete in this commercial market. Detailed information on this research is provided in APPENDIX E: Plasma Lighting.

2.1.2.5 Direct-DC Lighting Systems and Microgrids

Advancements in photovoltaic panels, energy-storage technologies and direct DC lighting systems have made highly energy-efficient and self-sustaining residential and commercial buildings a near-term possibility. Significant advances in LEDs, photovoltaic arrays, wireless controls, and polymer lithium-iron batteries now warrant evaluation for use in forthcoming residential, commercial or industrial microgrid and direct-DC lighting projects.

To evaluate these technologies, researchers developed and installed a DC-lighting system powered by an islanded, DC microgrid. A microgrid is a small-scale power grid that can operate independently (“islanded”), or in conjunction with the main electrical grid. The demonstrated microgrid system drew power through five roof mounted solar photovoltaic panels; stored the energy with lithium-iron batteries; and uses that stored energy to power electric indoor lighting. The demonstration system was not connected to the grid and was self-sustaining (i.e. zero net energy). Information on this project is detailed in APPENDIX F: Direct DC Lighting Systems and Microgrids.

2.1.2.6 Adaptive Indoor Lighting

Many commercial and industrial facilities can benefit from the adoption of adaptive lighting strategies in their indoor work areas and secondary spaces. Adaptive lighting facilitates dynamic light level adjustment based on occupancy, daylight and scheduling. This energy

saving strategy is more often accepted by occupants of indoor secondary spaces because these are common spaces for which occupants do not feel individual ownership. Therefore, light levels and light level changes are not personal to occupants, and occupants are less likely to associate their individual preferences with the lighting system. Lack of assumed personal ownership over the lighting in a space allows for greater design flexibility; including periods of reduced illuminance to save energy.

As part of the program, researchers examined the application of adaptive lighting control strategies for many key indoor spaces. Through a series of field demonstration projects, researchers showed that adaptive lighting consistently saving 40-80 percent over traditional lighting systems. Demonstrated systems optimized light output and saved energy using a variety of control strategies including occupancy-based control, daylighting, high-end trim (tuning) and demand response.

Figure 10: Corridors and Stairwells Can Benefit by Using Adaptive Lighting Strategies

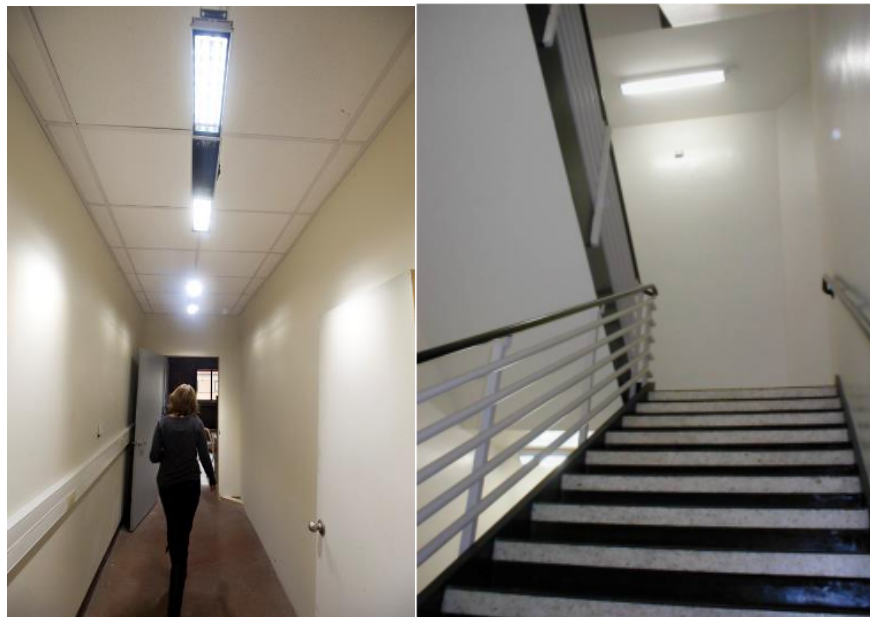


Photo credit: CLTC

The research team developed a system specification for smart corridor lighting that utilized intelligent control strategies to optimize safety and lighting performance with minimal overall energy use. Illuminance modeling was performed for both fluorescent and LED products to demonstrate expected light levels and associated energy use. Current codes and standards requirements were utilized to determine other aspects of the performance specification. Based on these specifications, researchers designed and installed prototype smart lighting in typical corridor spaces. A variety of control systems, luminaires and locations were utilized to create a diverse demonstration portfolio, which showcased the diversity and flexibility of the adaptive concept.

In addition to product development and demonstration, researchers completed market adoption and support activities to help accelerate industry uptake and influence future codes

and standards to ensure broad adoption of adaptive lighting strategies. Researchers worked closely with several manufactures on smart lighting products for corridors and integrated concepts into the California Advanced Lighting Controls Training Program (CALCTP) curriculum for electrical contractors.

Detailed information on secondary-space demonstrations is provided in APPENDIX I: Adaptive Lighting for Secondary Spaces. In addition, the Program applied these concepts and strategies to the agricultural sector. Details on adaptive lighting demonstration conducted in agricultural facilities is detailed in APPENDIX J: Smart Lighting for the Agricultural Sector.

2.1.2.7 Improved Office Lighting Design Strategies

The benefits of task/ambient lighting systems for commercial office environments have been demonstrated in previous PIER-sponsored research³. However, many office spaces that utilize task/ambient lighting systems experience an unfortunate side effect known as the “cave effect.” Low ambient light levels coupled with carefully controlled light on work surfaces (task lighting) leaves little available illumination on vertical surfaces. This can often make the space feel like a dark “cave” and it can be an uninviting environment for occupants. This project developed strategies and technologies to better direct ambient light on to walls and other vertical surfaces in order to minimize the cave effect in office environments. This research also demonstrated the potential to decrease overall ambient lighting requirements by making rooms appear brighter through the use of optimized light distribution strategies, which will contribute specifically to Zero Net Energy (ZNE) commercial building designs and in general towards the statewide efforts to reduce lighting energy use in the commercial building sectors. A full report on efforts related to improving commercial office lighting through thoughtful application of vertical illumination strategies may be found in APPENDIX H: Novel Office Lighting Design Strategies. Key outcomes are also provided in CHAPTER 4: Program Outcomes - Improving Office Lighting Design Strategies.

2.1.2.8 Dual-Loop Controls for Daylight Harvesting

Controlling electric lighting based on available daylight introduced through windows and/or skylights is critical to realizing the energy and economic benefits of daylight harvesting in commercial buildings. The most effective way to reliably determine available daylight is through the use of photo sensors. Traditionally, there are two main control strategies, both using a single photo sensor:

1. **Closed-loop photo sensing:** Using a photo sensor to sense daylight indoors, which is affected by the electric lighting being controlled
2. **Open-loop photo sensing:** Using a photo sensor to sense daylight outdoors, which is not affected by the electric lighting being controlled

Unfortunately, neither of these two strategies is effective in reliably determining available daylight indoors. While the closed-loop strategy has been recognized as more effective than the open-loop strategy, the closed-loop sensor signal is affected by changes in the geometry and

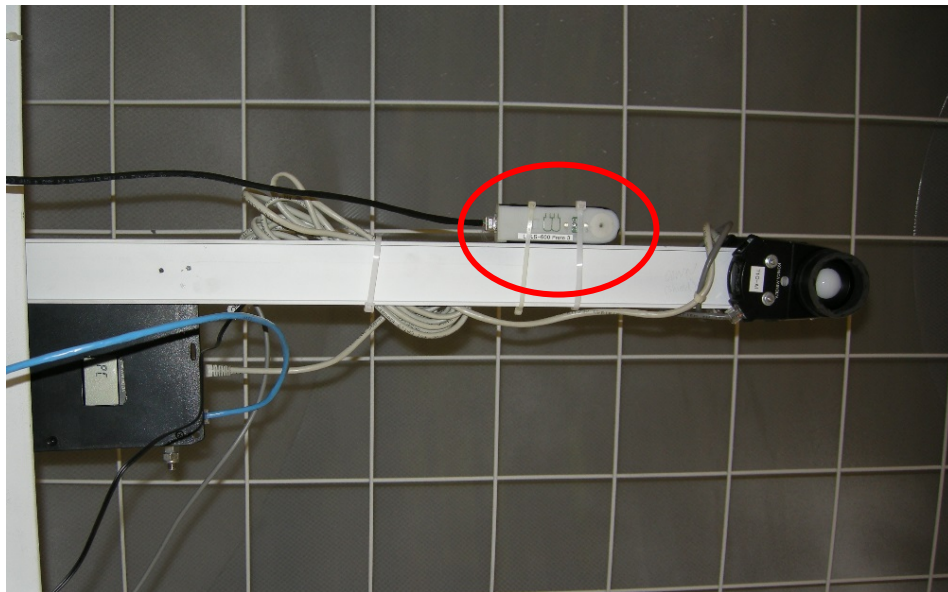
³ For instance CEC-500-02-004, M-18230, Task ambient lighting

reflectance of interior surfaces. This constitutes a major shortcoming as it greatly reduces the effectiveness and reliability of the closed-loop strategy. Changes to interior surface reflectance and geometry can be long-lived (as when new furniture or carpeting is introduced in a space), or they can be short-lived such as occupants moving in the space.

Researchers, with funding from the Building Energy Research Grant (BERG), created a proof-of-concept sensor to utilize both open-loop and closed-loop control strategies to provide more reliable electric light control for top-lit applications. The dual-loop sensor design consists of two sensors, an open-loop sensor facing towards the skylight (detecting daylight contribution), and a closed-loop sensor facing the control space, which is able to detect total light (daylight and electrical light) in the controlled space. By using both open-loop and closed-loop sensing, the dual-loop system can very reliably differentiate between daylight changes and interior changes. Moreover, it includes continuous automated commissioning of the closed loop sensor, which accounts for changes in the geometry and reflectance of interior surfaces.

Work conducted under the Program took the proof-of-concept, dual-loop prototype from the laboratory to the California market by partnering with lighting controls manufacturers in development, testing and deployment of a commercial dual-loop daylighting control for top-lit applications. WattStopper, an industry leader in lighting controls technology, manufactured a prototype, precommercial dual-loop sensor. CLTC first tested the prototype in its daylight harvesting laboratory then in the field at a local retail location.

Figure 11: Dual-Loop Laboratory Prototype and Precommercial Prototype



Laboratory prototype dual-loop system and precommercial prototype (circled in red) installed at a local retailer.

Source: CLTC

As part of the program, researchers also explored application of the dual-loop technology in side-lit spaces. Side-lit spaces pose more challenges than top-lit spaces, as windows are different from skylights in several key ways. Regularly spaced skylights provide fairly uniform daylight

levels, but daylight distribution through windows is very uneven, with much more daylight in areas close to the windows than in parts of the room distant from the windows. Daylight contributions from skylights also emanate from the same direction as contributions from electric lighting. With windows, the daylight enters the space from a different direction than the electric lighting.

Researchers examined the effects of sensor placement, sensor sensitivity and communication as part of a side-lit laboratory evaluation. A complete report on dual-loop daylighting controls for both top-lit and side-lit spaces is provided in APPENDIX G: Dual-Loop Daylighting Controls.

2.1.2.9 UltraSmart Indoor Lighting Systems

Building on dual-loop control strategies, researchers also explored the potential of next-generation adaptive interior luminaires and integrated control concepts as part of an UltraSmart Lighting System. The UltraSmart System utilizes luminaires with the ability to integrate with advanced environmental sensors and network with other luminaires to operate as a complete system configured for the unique performance requirements of their particular installation space.

An UltraSmart Luminaire prototype system composed of four luminaires was installed in CLTC's daylight harvesting laboratory. Each was equipped with communication and sensing hardware to enable intelligent, automated operation. Hardware included microcontrollers, communication links, photosensors, and photosensor baffles. The prototype system was controlled by the UltraSmart control algorithm developed by CLTC. The algorithm controlled the UltraSmart luminaires from an external computer also located in the daylighting laboratory.

Ultra Smart luminaires are capable of both stand-alone and networked operation. Because of this feature, the Ultra Smart Luminaire System can be implemented in a large number of applications. Applications range from single fixture or multiple fixture spaces controlled by a single Ultra Smart Luminaire to a multi-luminaire space where all luminaires are equipped with the Ultra Smart Luminaire Technology. Detailed activities conducted under the Program are provided in APPENDIX K: Ultra Smart Indoor Lighting Systems.

2.2 Daylighting and Fenestration

Daylighting is a valuable addition to the built environment. It provides significant, high quality light, with marginal power consumption attributed to additional heating, ventilation and air conditioning (HVAC) loads, which are typically significantly smaller than the lighting energy required by traditional electric lighting systems.

Implementing daylight harvesting strategies in commercial buildings is only partially being achieved, with focus mostly on electric lighting controls based on daylight availability. Complete implementation of daylight harvesting includes managing daylight penetration through windows and skylights. This improves the effectiveness of electric lighting controls, and also increases energy savings through reduced heating, ventilating, and air conditioning (HVAC) loads.

Controlling electric lighting for daylight harvesting has been very ineffective for two main reasons. The first is lack of reliability in sensing daylight changes and the second is occupants deploying window shades, sometimes for privacy but mostly to avoid direct solar penetration and associated glare. Adaptive envelope systems have the potential to improve the effectiveness of electric lighting controls for daylight harvesting, and also deliver significant energy savings and peak demand reduction by reducing HVAC loads.

2.2.1 Adaptive Envelope Systems

Adaptive envelope systems, such as smart window and skylight systems, use integrated dynamic subsystems such as adjustable glazings and shading systems that automatically adapt to environmental conditions such as occupancy, daylight levels, solar radiation, HVAC status, etc., to maximize comfort and energy efficiency.

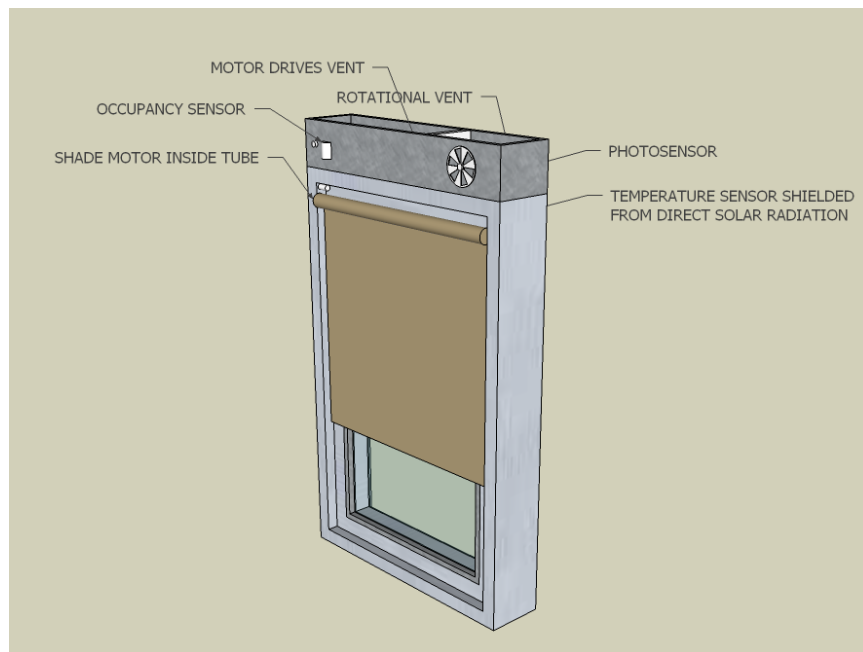
Adaptive envelope operation is completely automated focusing on comfort and energy efficiency, and also supports occupant override. The main control strategy gives priority to comfort during occupancy and to energy efficiency during vacancy. Developing and commercializing these systems will be an important step in continued efforts to reduce commercial building energy use by taking full advantage of the daylight harvesting strategy.

2.2.1.1 Smart Windows and Skylights

Smart windows and skylights are automated systems that actively monitor the changing characteristics (i.e. temperature, light levels, occupancy, and/or glare levels) of a space and are capable of implementing changes to their dynamic components (i.e. vents, louvers, electrochromic glazings, and blinds) to modulate the amount of daylight entering the space. These systems can also be expanded to integrate other systems such as electric lighting and HVAC. Through proper control, these systems are able to optimize occupant comfort and energy. Advances in Smart Windows and Skylights have the potential to be highly beneficial and assist in California's continued efforts to reduce energy use while providing high quality indoor lighting through the use of daylight.

In concept, a Smart Window contains multiple environmental sensors, shading components, vents and integrated electronics. A basic design concept is shown in Figure 12. One of the key system elements is an occupancy sensor, which allows the system to use different control strategies during occupied and unoccupied times. Smart Windows may be integrated with building energy management systems to coordinate its functions with electric lighting and HVAC. Detailed information on smart window and skylight research is provided in APPENDIX L: Smart Windows and Skylights.

Figure 12: Smart Window - Conceptual Design



Source: CLTC

2.2.1.2 Skylight Optimization

While skylights are great alternatives to electric lighting for illumination during the day, one of the most common obstacles to their implementation is glare created by the bright skylight when adjacent to darker ceilings. This type of glare is mainly an occupant comfort issue, but is accompanied by unnecessary solar heat gain, which lowers a building's energy efficiency by increasing its cooling requirements. This can offset all or part of the lighting energy savings.

There are several mechanical and electrochemical technologies available to mitigate glare and solar heat gain. Non-mechanical methods such as films or electrochromic glass rely on calibrating the material's transmissivity to manage the amount of solar radiation it will pass. The majority of active skylight daylighting control is mechanical, and most often realized as louvers that can block sunlight. The louvers can be actuated in response to incident daylight and building conditions.

A smart skylight has the ability to optimize energy efficiency and occupant comfort through automated, dynamic control of daylight penetration into the space. Automation is achieved through control algorithms that govern the operable elements of the smart skylight system based on sensor inputs. Researchers monitored currently installed skylight control systems, performed technology and building simulations, and developed and tested smart fenestration prototypes to evaluate system components and control algorithm possibilities for future use in commercial facilities. A full description of these activities is provided in APPENDIX M: Daylight Optimization for Skylights.

2.2.2 Core Daylighting

In multi-story buildings, or buildings that are partially shaded by taller surrounding structures, it is difficult to implement daylighting as part of the building's lighting design because daylight can enter only through the building's vertical facade. Several daylighting solutions targeted at illuminating a building's core have received attention for their potential to address the shortcoming of traditional perimeter daylighting.

Researchers at the University of British Columbia (UBC) developed the "Solar Canopy", a combination of moveable and fixed mirrors with a horizontal light-pipe that redirects and distributes direct sunlight into the core of multistory buildings. The light pipe is integrated with electric lighting, which is dimmed based on available daylight.

The Solar Canopy transports daylight up to 50 feet horizontally into the building. Ideally, this technology could provide architects, lighting designers and building managers with a daylighting solution that doesn't require vertical pipes passing through multiple building stories, but allows sunlight to be distributed horizontally down the length of a hallway or across a room using a low profile tube or channel. Such a system has become technically feasible in recent years because of the availability of highly reflective films that can line the light distribution channel.

Figure 13: Core Daylighting System Installed at the CLTC



Source: CLTC

Potential benefits of core daylighting include reduction in use of electric lighting, both overall and during periods of peak electricity usage, and better psychological connection of occupants to exterior conditions. To evaluate these claims, CLTC collaborated with UBC and later SunCentral, performing multiple technological demonstrations at UC Davis to test the feasibility of their core daylighting systems. Detailed information on this research is provided in APPENDIX N: Solar Canopy for Core Daylighting.

CHAPTER 3:

Market Facilitation

CLTC delivered targeted market transformation support for the Public Interest Energy Research (PIER) technology portfolio in order to achieve increased market penetration for PIER lighting, daylighting, and fenestration technologies. Market facilitation objectives included increasing customer awareness of energy-efficient lighting and best practices and educating Californians on existing and emerging high-quality lighting products, design principles, and their associated codes and standards requirements. Activities included teaching seminars, providing daily support for inquiries and requests on general illumination topics; responding to speaking requests to address California stakeholders; promotion of PIER lighting technologies at industry trades shows and conferences; development of application guides, technology fact sheets, case studies, and similar materials for PIER stakeholders; creating, maintaining and enhancing websites that support PIER technology; providing support for the development of new product and building standards; and supporting utility and case study development, market analyses, and other requests as needed. These activities were critical in communicating the benefits PIER research results. Resulting market connections and project partnership activities fall into one of the four primary groups listed below. A full report on all market facilitation activities may be found in APPENDIX P: Market Transformation and Partnership Development.

- Technology transfer to industry / partnership development
- Market transformation through communication to critical audiences
- Policy development
- Workforce development and education

3.1 Workforce Development and Education

CLTC played a pivotal role in development of CALCTP; multiple statewide training programs on Energy Efficiency Standards (California Code of Regulations Title 24) and Appliance Standards (California Code of Regulations Title 20); and numerous technology-specific education and training programs for lighting professionals, contractors, utility customers and consumers. CLTC is widely recognized as the leading institution for lighting energy-efficiency training and policy integration.

Recent legislation including The California Clean Energy Jobs Act (Proposition 39, Tax Treatment for Multistate Businesses. Clean Energy and Energy Efficiency Funding. Initiative Statute.) and various other state mandated efficiency programs have committed a significant amount of resources into relighting California buildings. Unfortunately, knowledge barriers exist relative to both technology and best-practice approaches for achieving optimal energy-efficiency outcomes. Significant potential exists for financial waste and implementation of poor technology with sub-par energy performance. This will result in California failing to meet the ambitious goals associated with many of these state-lead efficiency programs. CLTC and its

utility, industry and state partners understand that lighting education and training for building owners, facility manager's, decision-makers and other energy program personnel is one of the most effective, long-term approaches for ensuring California's investment in energy efficiency produces tangible results that help achieve state goals.

3.2 Policy Development

A key component of the program focused on supporting and promoting advanced regulatory activity to encourage the most efficient technologies and design approaches for long-term public investment. These activities were highly effective in uniting industry, the Energy Commission and California utilities in a roundtable format to accelerate the most effective strategies for the future. Program activities ensured that the best technologies and design approaches were developed and promoted for inclusion in California energy codes and appliance standards. Policy and outreach activities provide long-term support to better ensure full realization of California's energy-efficiency goals.

3.2.1 Building Codes and Appliance Standards

CLTC has provided long-term continuity and a lighting/daylighting knowledge base to the Energy Commission. Since its inception in 2004, CLTC has actively supported the Energy Commission by providing industry intelligence and market projections; assessing the feasibility of new lighting and daylighting measures; proposing and developing new lighting and daylighting codes and standards; hosting state and industry stakeholder workshops; and providing rapid response and support on lighting and daylighting topics and activities. Success stories include:

- Development support for the 2018 Title 20 lamp standards
- Development support for the 2013 Title 24, Part 6 standards addressing automatic shut-off controls (occupancy and schedule based control during night time hours) for outdoor commercial luminaires
- Refinement and development support for the 2013 Title 24, Part 6 Automatic Daylighting requirements for commercial buildings
- Development of the 2012 California Voluntary LED Lamp Standard
- Development of the 2007 Lighting Electricity Use Baseline to support implementation of the Lighting Efficiency and Toxins Reduction Act (AB 1109, Statutes of 2007)
- Development support for the 2005 Title 24, Part 6 Residential Lighting Standards

3.2.2 California's Lighting Electricity Use Baseline to Support AB 1109

The California legislature mandated that lighting electrical energy use in the state's commercial and residential building sectors must be reduced. Assembly Bill 1109, Lighting Efficiency and Toxins Reduction Act (Huffman, Chapter 534, Statutes of 2007), signed in 2007, requires that between 2007 and 2018 electricity use reductions must reach 50 percent for residential interior

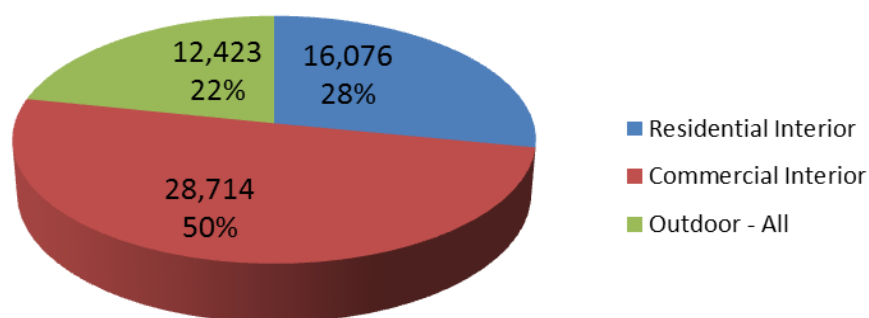
lighting and 25 percent for commercial interior and outdoor lighting. To measure progress against these goals, a 2007 lighting energy use baseline must first be determined.

Historical data from existing lighting surveys and studies was used to conduct trend analysis estimating California's 2007 lighting electricity use. The analysis contained in this report is based on a collection of secondary data sources and publications produced between 1995 and 2010; it does not use new primary data such as building audits or owner surveys. Existing data was used to create a timeline of lighting electricity use between 1995 and 2010 for each sector affected by AB 1109. Some regional data, collected by the DOE, was included to supplement the information when California data was not available.

Lighting electricity use, for this analysis, was compared in an absolute and normalized manner. Normalization adjusts values to a common scale eliminating unwanted influences. For this work, normalization isolates energy-use fluctuations resulting from non-efficiency measures, and allows for a true comparison of savings. California's electricity use, in whole, typically grows over time due to growth in the state's population and building stock. The lighting electricity savings expected by 2018 cannot only be compared to a 2007 baseline in an absolute manner. A normalized quantity is required to isolate potential savings from energy-use increases attributable to changes in population or building stock. For commercial lighting use, absolute values were normalized to commercial floor space. Residential and outdoor lighting use was normalized to occupied California households. Both values are provided in this report.

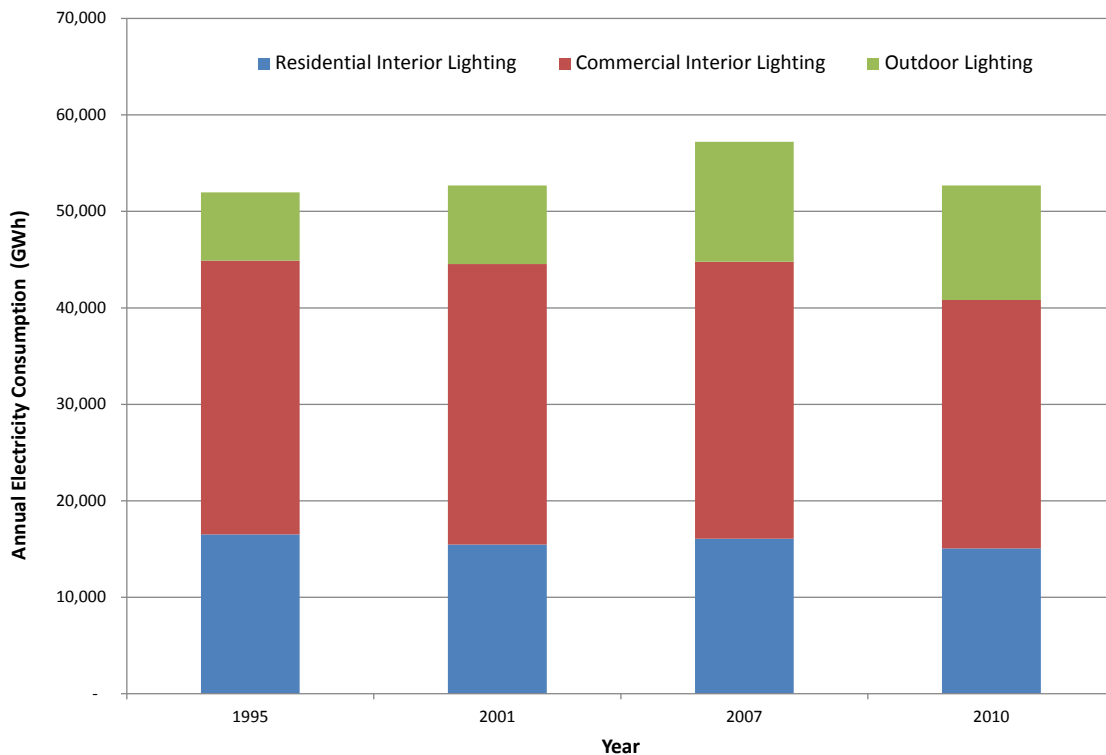
Based on trend analysis of historical data, in 2007 California is estimated to have consumed a total of 57,213 gigawatt-hours (GWh) of electricity for residential interior, commercial interior and outdoor lighting. Commercial interior lighting consumed approximately 50 percent of this total at 28,714 GWh, while outdoor lighting and residential interior lighting accounted for 12,423 GWh and 16,076 GWh, respectively.

Figure 14: California Lighting Electricity Use (GWh) – 2007



Trends show that lighting electricity consumption of these sectors peaked between 2006 and 2008. Between 2004 and 2005, new residential construction hit a 15-year high, increasing demand for residential electricity (Department of Finance 2011). In 2006, following these record-high construction years, residential interior lighting use peaked at 16,429 GWh. Commercial interior lighting peaked that same year at 28,876 GWh. Overall, exterior lighting shows a slow yet steady increase throughout much of the analysis period, peaking in 2008 at 12,776 GWh.

Figure 15: California Lighting Electricity Consumption, All Sectors, Select Years



Following this period of aggressive growth, lighting electricity use in all sectors appears to be dropping. Between 2008 and 2010, electricity use, across the commercial and residential sectors declined, resulting in a similar decline in lighting electricity use. Lighting electricity reductions between 2007 and 2010 are estimated at 4,525 GW. Residential lighting electricity use per occupied California household is down by more than 7 percent during this period. Commercial interior lighting electricity use is down by approximately 13 percent and outdoor lighting electricity use has declined by nearly 6 percent.

The combination of total reduced electricity use and lighting consumption contributed to the decline in residential lighting electricity use, even though the population increased during the analysis period. Similarly, even though commercial building floor stock increased, total electricity use and the portion attributed to lighting declined since its peak in 2003. These estimates were based on absolute reductions normalized to account for growth in population and building stock. These results are encouraging, and they demonstrate that California may be on its way to meeting its lighting energy reduction goals mandated by Assembly Bill 1109. The full report may be found in APPENDIX O: California's Lighting Electricity Use.

3.3 Market Transformation through Communication to Critical Audiences

Throughout the program, CLTC served as a resource to California and beyond by increasing awareness to PIER-funded energy efficient lighting technologies and strategies. Information was distributed through a range of published tools, including the CLTC website, the Lighting

Link newsletter, events, and standard communication modalities such as email exchanges, phone conversations and small meetings. Select publications are detailed below. More information may be found in APPENDIX P: Market Transformation and Partnership Development.

3.3.1 Case Studies

Case studies provide proof of technology viability. By sharing results from the Program and other PIER-sponsored research, CLTC encouraged the implementation of these strategies for wide variety of indoor and outdoor applications. PIER resources were used to develop, demonstrate and support the market adoption of new energy-efficiency lighting products brought to market by CLTC and Program partners. The research, development, outreach and technology transfer activities were completed in collaboration with the Energy Commission, utilities, industry and other academic and professional institutions.

CLTC played a leading role in incorporating adaptive lighting controls into the 2013 Title 24 Building Energy Efficiency Standards. The lighting portion of Title 24 incorporates many technologies developed through CLTC's work with PIER. The demonstrations, conducted through the State Partnership for Energy Efficiency Demonstrations (SPEED), provided data about the effectiveness, affordability and feasibility of adaptive lighting technologies. The publication, education, and training efforts for adaptive controls for outdoor applications helped UC Davis and University of California Irvine adopt smart lighting measures.

These case studies were included as examples in a range of training materials, presentations, and guides, including the Title 24, Part 6 lighting guides. Case studies are archived online at <http://cltc.ucdavis.edu/publication-type/case-studies>. Significant case studies featuring the implementation of PIER technologies are listed below.

- Adaptive Exterior Lighting at University of California Santa Barbara
- Adaptive Corridor Lighting at University of California San Francisco
- Campus-wide Networked Adaptive LED Lighting, UC Davis
- Adaptive LED Wall Packs at UC Davis
- Curfew Dimming Parking and Area Luminaires at California State University Long Beach
- Adaptive Corridors at UC Davis
- Adaptive Corridors at Latham Square
- Integrated Classroom Lighting System at Laney College
- Adaptive LED Post-top Luminaires at Los Angeles
- SPEED Business Case: Adaptive Corridor Lighting
- SPEED Business Case: Adaptive Street and Area Lighting

3.3.2 Design Guides

CLTC has been a critical resource for lighting education and training since its inception. The center has provided codes and standards resources and training for lighting industry professionals across every market sector. Over the last year, CLTC has positioned itself as a statewide educational resource for the lighting portions of the 2013 Title 24, Part 6 Building Energy Efficiency Standards.

CLTC's education and outreach efforts have included numerous publications, in-person and web-based training sessions for a variety of projects partners, utility-sponsored full-day training courses, and lighting design guides and presentation-based curriculum materials.

The Title 24, Part 6 design guides assist lighting and building industry professionals become more familiar with the standards and increase compliance throughout California. The guides complement the Energy Commission's compliance manuals by focusing on specific applications and providing additional resources where needs for supplemental materials have been identified. They provided information on current lighting technologies, lighting design terms and principles, and best-practice recommendations. The guides complemented lighting courses developed through CLTC and funded in part by this contract. Funding was also provided from Pacific Gas and Electric Company and Southern California Edison, through the Energy Education programs, and from CLTC's affiliate gift funding. Select CLTC affiliates consider codes and standards education for employees, product distributors, and customers a valued component of their relationship with CLTC. These manufacturing partners have requested trainings on the topics covered in the guides and are interested in distributing them.

CLTC assessed market sectors and target audiences for the guides to determine which had the greatest potential to reduce statewide energy use through standards compliance. CLTC identified applications with the greatest lighting energy use or the highest lighting power density in California, providing the greatest opportunities for energy savings. The decision was made to develop guides for residential, office, retail, and non-residential outdoor applications.

CLTC's affiliates assisted with the guides by providing insights on the current lighting market and emerging product categories. Manufacturer affiliates submitted case studies and product briefs. They also provided examples of commercially-available solutions and illustrated concepts for specific applications. More information and links to all publications produced as part of the Program may be found in APPENDIX P: Market Transformation and Partnership Development.

Table 2: Design Guides published under the Program

What's New in the Title 24 2013 Code?	Title 24, Part 6 Residential Lighting Guide
Title 24, Part 6 Outdoor Lighting Guide	High-Efficacy Residential Lighting Guide
Retail Lighting Guide	Lighting For Office Applications
Advanced Lighting Guidelines (ALG)	LED Retrofit Options for Linear Fluorescent Luminaire
Lighting Retrofit Strategies for California Schools	

3.4 Technology Transfer to Industry / Partnership Development

Throughout this project, CLTC strengthened its relationships with a variety of stakeholders including manufacturers, utility companies; representatives from professional lighting associations, educational and nonprofit organizations focused on training; and large end-users from the public and private sectors. These partnerships form an evolving network of lighting stakeholders. CLTC collaborates with these partners research lighting energy use patterns; develop improved products, systems and components; establish demonstration projects; and support educational programs for students and professionals. CLTC works with these partners to effectively increase the number and variety of innovative, energy-saving products and practices brought to market and applied through more widespread use.

Some of these stakeholders are members of the CLTC affiliate annual gift program. These affiliates, which include utilities and lighting technology manufacturers, fulfill the role of the stakeholder task force by commercializing next-generation lamps, fixtures, controls, and other lighting components and technologies this contract was designed to bring to market. CLTC has strong relationships with these organizations. Each member gives an annual gift of \$10,000 or more to UC Davis to sustain the center. This funding mechanism creates a community of invested stakeholders. The annual gift fosters ownership of CLTC's project process and outcomes. The center works with affiliates to advance goals related to strategic planning, research and development, demonstrations, policy development, and outreach. The affiliate program is the backbone of the partnership development efforts that took place as part of the Program. The current member list is located at: <http://cltc.ucdavis.edu/affiliates>.

Figure 16: Past and Current CLTC Affiliate Members



Source: CLTC

3.4.1 Partnership Development with State and Federal Agencies

Public organizations represent a significant opportunity for reducing energy use in public facilities. CLTC has strengthened or initiated relationships with California state agencies and academic institutions including the University of California; California State University; California Community College Districts; School Facilities Planning Division of the California Department of Education; municipal departments in cities across California; the Governor's Office of Planning and Research; California Department of Public Health; California Department of Parks and Recreation; California Department of Corrections and Rehabilitation; and other state agencies. Additionally, CLTC has used resources from this contract to reach state agencies by interacting with the investor-owned and municipal utilities that provide electricity to their facilities.

Interactions with the organizations occurred through a variety of methods. CLTC leadership, technical staff and outreach staff scheduled conference calls, answered emails, hosted small meetings, and conducted outreach at conferences at forums hosted by CLTC or others. CLTC provided publications to share PIER-funded research results.

To effective in encouraging the adoption of energy-efficient lighting technologies in California's public buildings, CLTC became known as an approachable resource willing to take the time to understand requests and provide the needed information or support. Using the CLTC website and e-newsletter as information distribution points, CLTC staff provided access to project results in a timely and efficient manner. Groups addressed as part of the Program are listed below.

- California Department of General Services
- California Public Utilities Commission
- California Department of Corrections
- California Department of Transportation
- California Department of Education
- California Investor Owned Utilities
- California Cities and Municipalities
- U.S Department of Defense
- U.S. Department of Labor
- U.S. Department of Energy
- U.S. Environmental Protection Agency

CHAPTER 4:

Program Outcomes

The program resulted in a myriad of outcomes including commercialization and increased market adoption of its advance lighting and daylighting solutions resulting in positive energy savings for California. Indirect benefits resulting from education and outreach activities will continue to deliver savings well into the future.

Table 3: Estimated Electricity Savings of Key Program Technologies and Strategies

Program Focus	Estimated Savings	Baseline
Adaptive Outdoor Lighting	40% - 90%	Static HID luminaires
Smart Fenestration	5% - 25%	Static windows and skylights
Adaptive Indoor Lighting	40% - 80%	Fluorescent lighting, Title 24 – 3013 compliant
Residential LED Lighting	50% - 80%	Incandescent and Fluorescent screw-base lamps
Novel Office Lighting Design	35% - 45%	Title 24 – 2013 LPD for offices

4.1 Adaptive Outdoor Lighting

Adaptive lighting is clearly shown to be an effective strategy to mitigate energy waste and light pollution during long periods of inactivity generally associated with illuminated outdoor environments. The research repeatedly and consistently demonstrated 50 percent to 60 percent energy savings with the use of occupancy-controlled, adaptive lighting for parking lots, parking garages, building perimeters and other related outdoor lighting applications. This approach was integrated into Title 24 – 2013 regulations for certain parking and outdoor illuminated areas. Most outdoor areas with luminaires mounted 24 feet or less above grade must now utilize occupancy sensors to reduce light levels when areas are vacant. This represents one of the larger energy-efficiency success stories in the Codes and Standards Enhancement (CASE) partnership program among Energy Commission, the California IOUs, and CLTC.

Industry sources, lighting standards, best-practice lighting guides and an increasing number of nationwide case studies indicate adaptive lighting is increasing in use for parking and area applications. Efforts are now beginning to address the use of adaptive control systems in roadway applications, and multiple stakeholder groups are working on development of systems to meet these goals. Both domestic and international standards are moving towards adoption of new LED sources with adaptive controls for their high efficacy, even illumination and ability to accommodate adaptive control strategies.

However, feedback from system owners belonging to the Municipal Solid-State Street Lighting Consortium (MSSLC), a national consortium funded by the DOE, shows that many owners are

still delaying implementation of advanced controls because project payback periods exceed the typical ‘acceptable’ range, which is generally around seven years. Utilities creating a dimmable street light tariff, however, would address this issue by allowing system owners to benefit monetarily from the dimmable capabilities enabled by advanced controls. Financial incentives and tools to support implementation of new systems can be instrumental for early adoption of new systems and will help to synergize development processes for better sensors and controls. Payment systems that are not based on a flat tariff but tailored towards metered and logged actual energy use will incentivize use of the new technologies. This will help lower system loads with a high level of demand control and benefit from maintenance alerts with opportunity to prevent system outages.

4.1.1 Energy Impacts

Because of the high efficacy and increasing penetration of LED products, significant energy savings are predicted for the buildings sector, with a 36 percent decrease in energy consumption compared to a no-LED scenario by 2030⁸. The biggest barrier for widespread use of certain types of adaptive LED lighting is the associated high cost per luminaire and the resulting time interval to recover the cost through annual savings depending on the local energy prices. When adding a wireless control system to the adaptive luminaire, the price of the components adds a significant amount of 10 to 30 percent to the luminaire price. In depth financial analysis of the gained energy savings through advanced scheduling, logging, maintenance and facility management amenities is necessary to gauge validity of the added system components on a case by case basis.

Studies have shown that when implementing multi-level adaptive controls with LED luminaires, as much as 89 percent energy savings was achieved, depending on the differences of incumbent and new luminaires, area of use and occupancy levels in the space. Longer light source lifetime and less maintenance are additional factors that help to reduce associated costs. Incentives and rebate programs will help early adopters in regards of financing and to lower the payback time.

4.1.2 Market Impacts

Parallel to program efforts, the lighting industry made significant progress towards highly energy-efficient light sources, controllable drivers, reliable and affordable communication systems. For example, the American National Standards Institute (ANSI) C136.41-2013 standard was introduced to standardize outdoor luminaire receptacles. Outdoor sensor technology appears to be slowly catching up with this development trend.

Commissioning routines and hardware installation specifications throughout the industry show the trend for cross-platform compatibility. New components such as the ANSI C136.41-2013 receptacle, now adopted by luminaire manufacturers, demonstrate this fact. Component compatibility makes for easier “plug-and-play” solutions, which can drive down product cost. Subsequently, market acceptance will progress faster and result in higher energy savings for many outdoor market segments.

Figure 17: Original ANSI 136.10-2006 Receptacle (left); Manufacturer Specific Receptacle (right)



Source: CLTC

Key drivers behind the sales of more energy-efficient lighting and control systems have been utility rebates, incentives and standards mandated by national and state energy codes such as Title 24 when adding, conducting alterations or retrofitting luminaires. In the case of specific sensor use such as directional, long range or specialty occupancy sensors, and when using RF system components, retailers and specifiers are the go-to source for help implementing ideal solutions for specific sites and applications.

4.1.3 Research Needs and Next Steps

Using and implementing available lighting standards and guides by competent designers is a key concern, especially since the market is still evolving fast and new technologies may not be captured in recent design guides. When planning an adaptive lighting system, lighting policies should be implemented and confirmed with local authorities, emergency responders, police and other stakeholders, alongside with a risk assessment for each design and concise records of design decisions.

To maximize market penetration of networked lighting control systems, the lighting industry must recognize the needs of system owners, such as interoperability between system components from all manufacturers. For example, municipalities have requested that if hardware components from various manufacturers are installed in their city, the components should be able to be incorporated into one user interface provided by the system owner's manufacturer of choice – as opposed to being required to control the lights via multiple interfaces. The components do need to be interchangeable, or in other words need to be able to replace each other in the field.

However, valid manufacturer concerns surrounding issues such as intellectual property and sensor and RF system proprietary algorithms must be resolved before system owners will see a shift in the market. It is noteworthy that many large manufacturers are beginning to offer their own, integrated multilevel and RF controlled system solutions with their luminaires, such as

Philips (CityTouch, AmpLight, Starsense, and MultiOne)⁴, Eaton Cooper (LumaWatt)⁵, Kenall (Smartsense)⁶, Eye Lighting (Cimcon)⁷, Hubbell (wiHUBB, wiSCAPE)⁸ and GE (LightGrid)⁹.

These systems offer features such as scheduling, trimming, energy logging and maintenance reports, but not all include sensor integration for local adaptive control. If sensor solutions are offered, typically passive infrared (PIR) sensors with limited range are the standard solution. Inclusion of long range sensors such as microwave sensors or other signal inputs such as road loops or video feed systems are extremely rare. Ability to use any other system components or to combine control system software from competitors is not advertised to date. This is an area for future research and development. The combination of reliable local sensors with networked control systems proofed a valid way to optimize energy savings through fully adaptive solutions based on local conditions and occupant's needs. Expanded use of these technologies and strategies will help bring more affordable solutions to the California and subsequent United States market.

Current networked lighting control systems, occupancy and especially environmental sensors are in various stages of maturity. For example, control systems that utilize environmental sensors to detect changes in pavement reflectivity or weather, are still in early stages and will need careful development and implementation for reliable future use. Research conducted on the eight luminaire types discussed indicates that the amount of physical customization is, to some degree, bound rather to luminaire type than manufacturer. All roadway luminaires with prepared photocell receptacle socket were relatively simple customizations compared to dedicated area lighting fixtures with no prepared socket. The specific physical build of the luminaire including housing details such as wall thickness of castings; prepared punch out markings; the internal arrangement of electrical components such as driver, surge protector and terminal block; and remaining cavities to allow for sensor and RF node integration made a significant difference in the time and effort needed for each luminaire type to include all necessary customization components.

⁴ Information on Philips lighting products may be accessed at http://www.lighting.philips.com/main/products/controls/outdoor_products.wpd

⁵ Information on Eaton Cooper lighting products may be accessed at <http://www.cooperindustries.com/content/public/en/solutions/wireless.html>

⁶ Information on Kenall lighting products may be accessed at <http://www.kenall.com/Products/Product-Categories/Controls.htm>

⁷ Information on Eye Lighting products may be accessed at <http://www.eyelighting.com/products/lighting-controls/>

⁸ Information on Hubbell Lighting Products may be accessed at http://www.hubbell-automation.com/products/wireless_lighting_controls/

⁹ Information on GE lighting products may be accessed at <http://www.gelighting.com/LightingWeb/na/solutions/control-systems/lightgrid-outdoor-wireless-control-system.jsp>.

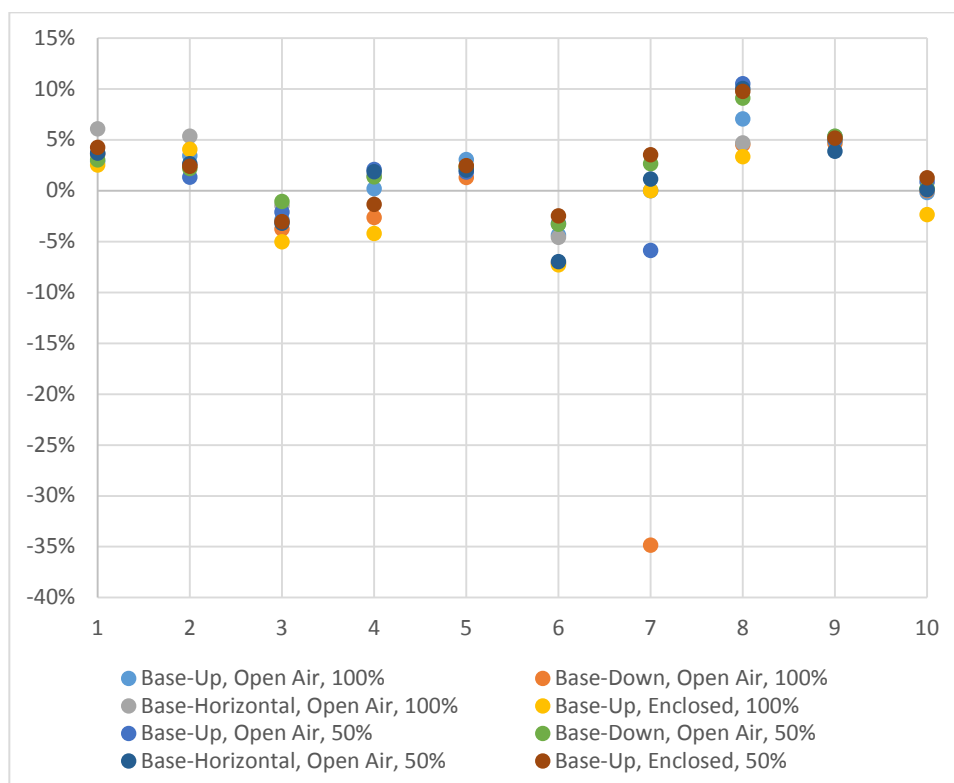
Ongoing developments and communications with market leaders and manufacturers will help to promote changes in future luminaire designs to prepare or factory-include sensors and RF nodes and in general to support the trend for cross-platform compatibility. Even though no flicker issues have been noted by CLTC or reported from the various test sites, a preemptive flicker control specification for dimming settings similar to Title 20 Section 1605.3.1.F.2 is recommended for future development of adaptive systems, specifically with interchangeability in mind.

4.2 Indoor Lighting Solutions and Strategies

4.2.1 LED Replacement Lamps

Today, the majority of LED replacement lamps are marketed as having lifetimes of 25,000 hours. At the time of this report, the lamps in this study operated in the testing environment for 5,000 hours. Overarching correlations between performance and time have not been determined based on the testing timeframe. Figure 18 shows the mean difference in lumens for each operating conditions group between the baseline measurements and the 5,000 hour measurements. To date, the expected downward trend of lumen output is negligible for all operating conditions.

Figure 18: Difference in Luminous Flux over Time for Tested Products, Grouped by Operating Conditions



Source: CLTC

The mean difference between baseline and 5,000-hour performance for tested products in varying operating conditions is also provided for correlated color temperature (CCT), D_{uv} ¹⁰, color rendering index (CRI), power, power factor, and percent flicker metrics. Plots of different performance metrics are segmented into the different operating conditions to illustrate how those conditions affect the performance metrics. Lamp failures are indicated with a large circle around the last data taken before the lamp failed. All results are contained in APPENDIX C: Directional LED Replacement Lamps.

4.2.1.1 Energy Impacts

Replacing existing incandescent downlights with dedicated LED downlights or retrofit kits containing LED replacement lamps delivers energy savings of approximately 80 percent (Pacific Northwest National Lab and California Energy Commission 2010). Replacing fluorescent downlights with LED options can reduce lighting energy use by 50 percent (California Energy Commission 2010, Emergy Technology Associates 2010). Conversion of existing residential recessed downlights to LED alternatives could save 4,950 GWh annually, according to a 2012 report supporting California's statewide lighting market transformation program (Cadmus Group 2012). In California's commercial sector, where incandescent and CFLs predominate in pin and screw-base applications at approximately 90 percent or more utilization, savings from conversion to LED alternatives could be significant. Approximately 85 percent of all California commercial businesses utilize some form of pin or screw-lamp¹¹. Nationwide, total potential savings could be as high as 48,000 GWh, according to a 2008 DOE study.

4.2.1.2 Market Impacts

Since the start of the program, many manufacturers have released multiple varieties of LED replacement lamps and dedicated luminaires giving consumers many viable options to choose from. Many of these products are sold with rebates to entice and reduce costs for potential buyers.

4.2.1.3 Research Needs and Next Steps

Independent lamp testing and validation is still needed to ensure high-quality LED lamps are identified, promoted and incentivized in the California market. The Voluntary California LED Quality Specification has made great strides in promotion of some types of high-quality LED replacement lamps; however this specification relies heavily on ENERGY STAR™ Lamp Product Specification (V 1.0) for many of its metrics and associated compliance testing procedures. This creates a problem for manufacturers, utilities, and other stakeholders because the ENERGY STAR™ compliance requirements are not yet fully defined and standardized. In addition, lamps installed in some California applications may experience a more difficult set of operating environments, yet federal lamp standards and test procedures do not account for the challenges associated with operation in the California building sector.

¹⁰ D_{uv} is defined as the distance from the chromaticity coordinate of the test light source to the closest point on the Planckian locus on the CIE coordinates.

¹¹ California Commercial Saturation Survey, Itron, August 2014.

To remedy these gaps and ensure true, California-quality lamps are brought to market, testing is needed to understand and document precommercial and commercially available LED lamp performance over time and under installed conditions representative of the California building sector.

4.2.2 Residential LED Luminaires

Current Title 24 building code requirements call for use of high-efficacy lighting in a limited number of residential space types. Builders are allowed to install low efficacy lighting if they also install dimming controls. However, significant load reduction and energy savings over current code-compliant designs can be achieved through the use of All High-Efficacy (AHE) lighting design practices. Currently, AHE lighting design practice utilizes application appropriate controls paired with high-quality, dimmable LED luminaires, or GU-24 socketed fixtures paired with GU-24 base LED replacement lamps. By current code definition GU-24 base lamps are the only replacement lamps considered high-efficacy, while traditional Edison screw-base sockets are considered low-efficacy. In addition to limiting the source type to LED only, AHE lighting requires a minimum quality standard for interior LED sources, requiring a CRI rating of at least 90 and a CCT between 2,700 Kelvin (K) and 4,000 K.

CLTC contacted Wathen Castanos, a residential builder, to install a demonstration of AHE commercial products. Wathen Castanos is a green focused builder whose mission is to provide homes that allow for an energy usage reduction by at 71 percent compared to new homes built to standard requirements, without compromising design or comfort. CLTC performed iterative photometric modeling of high performing products for a select floorplan and compared the simulation results against target light levels and uniformity ratios recommended by the IES Handbook standards. The AHE design resulted in a lighting power density of .38 Watts per square foot (W/sf) for the kitchen and dining areas. Work was proceeded with field demonstration, including energy and performance monitoring to quantify performance in real-world conditions. More information on residential LED luminaires developed as part of the Program may be found in APPENDIX B: Indoor, Residential LED Luminaires.

4.2.2.1 Energy and Market Impacts

Energy impacts are similar to those described for LED replacement lamps. Since the start of the project, many manufacturers have released LED downlights, giving consumers many viable options to choose from. Many of these products are sold with rebates to entice and reduce costs for potential buyers. AHE products offer higher efficacy when compared to other incumbent technologies, such as incandescent or CFL.

Figure 19: High-Efficacy LED Downlight Demonstration Home



Photo credit: CLTC

Figure 20: LED Task Lamp Developed by CLTC and Commercialized by Full Spectrum Solutions



Photo credit: CLTC

4.2.3 Plasma Lighting

Light-emitting plasma luminaires have the potential to be a dimmable, high efficacy light source, reducing the energy required to illuminate commercial areas, providing energy savings to building owners, and an additional option for architects to meet building lighting requirements. In addition, they have the potential to change the paradigm of ceiling-mounted luminaires that occupy a large fraction of the ceiling area, because a single plasma source can potentially replace multiple fluorescent fixtures. This implies significant reduction in materials, transportation, storage, and maintenance costs. Their dimming ability, and potentially high color quality and system efficacy make plasma sources very attractive from a conceptual point of view.

4.2.3.1 Energy and Market Impacts

As a result of this research, in 2011, plasma manufactures brought high and low bay fixtures to the market. Manufacturer product literature (circa 2011) indicates that their light engines are capable of achieving greater than 80 CRI in a fixture that has a system efficacy of 86 lumens per Watt (lm/W). In laboratory tests, the luminaire produced off-white light with a CRI of 80.7 and system efficacy of 63.5 lm/W. Evaluation of a second manufacturer's product showed it produced light with a significantly higher CRI, but at a much lower efficacy. A comparison of these results to 2011 literature indicates that the technology has not significantly progressed in the last five years.

Table 4: Commercial High Bay Luminaires – Measured Performance Data

	Product A	Product B	Metal Halide High-bay	LED High-bay
System Power (W)	230	275	475	234
Total Initial Lumens (lm)	14597	13220	29,520	25,000
System Efficacy – Full Output (lm/W)	63.5	48.1	62.1	107
CCT (K)	4400	5400	3900-4500	4000
CRI	80.7	92.5	65-70	80+

Source: CLTC

4.2.3.2 Research Needs and Next Steps

A major technical gap exists with respect to dimming and color consistency. Both of the commercial plasma lamps evaluated by CLTC were marketed as having 100 percent to 30 percent dimming; however, the color of the light shifted by more than 10,000 K within this range. This color shift is the result of the different metal ions comprising the plasma having different excitation energies, and so altering the magnetic field reducing the flow of energy into the plasma will dim the various elements differently, shifting the observed color. This is potentially correctable or limitable, as solutions were found for metal halide lamps (which

operate on a similar principle) that reduced the color shift to less than 500 K. Research is needed on manipulation of the magnetic field that energizes the lamp in order to reduce color shift to within a more reasonable range. Additionally, there is the potential for further research into improving lamp stability and reducing infant failures. If improvements in dimming and color shift are made, as well, reevaluation of the technology for more commercial applications may be appropriate.

Potential host sites were interested in energy savings and high-quality, high-intensity light. Neither plasma high-bay product was capable of producing light that was significantly more efficacious than that provided by metal halide lamps. Additionally, light emitting plasma technology did not appear to improve over the duration of the project, despite significant research and development by multiple companies. This, coupled with high mortality rates documented in IOU studies, such as Pacific Gas and Electric's (PG&E) emerging technology study on plasma street lighting in 2013 (PG&E Field Assessment 2012), lead researchers to defer product demonstrations until a competitive product was available.

4.2.4 Novel Office Lighting Design Strategies

While several publications are available for layered approaches to lighting use in office settings and analysis of discomforting glare perception in interior working environments¹², not a lot of specific material and research is available for the evaluation of these areas based on near and far field contrast ratios through carefully orchestrated layered ambient and task lighting. The layered lighting approach, using a mix of overhead lighting, wall wash luminaires, task lighting, under cabinet luminaires and eventual accent lighting, are each unique from a formal industrial design approach. This result in unique engineering needs based on the intended use and correlated light levels per luminaire type (from low/ambient to high/task).

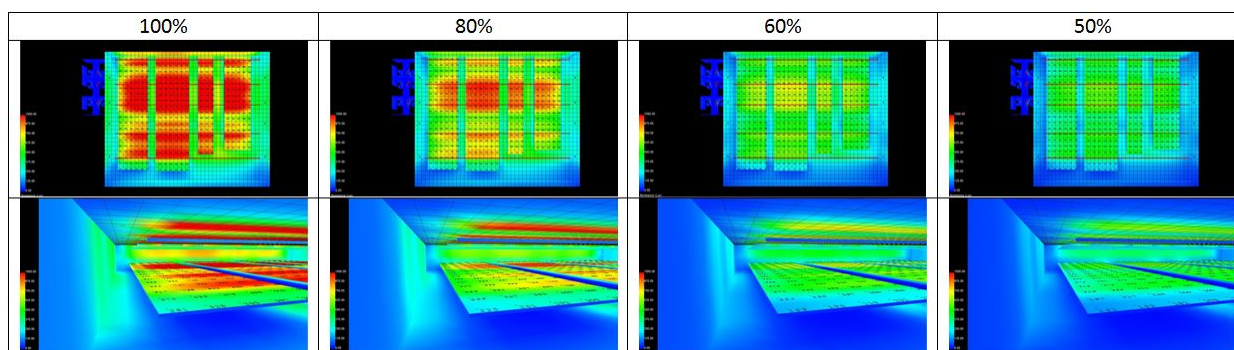
The optical capabilities of each luminaire for amicable ambient or task lighting, as well as the quality of lighting in regards to color temperature and color rendering of the SSL components used, are of high importance and have considerable variation within the luminaire types available. Intuitive user interfaces for operation and flicker free dimmable drivers should be considered a standard user expectation, but interoperability between system components is not guaranteed. Advanced controls currently involve a plethora of parameters such as occupancy sensors, multilevel switching, manual dimming, daylight harvesting, advanced lighting control systems (ALCS) use with time clock and advanced scheduling, energy management systems (EMS), preset scene controls, workstation specific controls or institutional tuning rules.

While the named controls offer many amenities and great energy saving potentials (DiLouie 2013), a combination of any of the named luminaires with their inherent capabilities and any of the various controls make it a challenge for site owners and specifiers to achieve optimized lighting settings for all possible iterations. These challenges support the need and potential for advanced training materials and knowledge transfer programs, such as CALCTP.

¹² For instance, LRP Article: "Discomfort Glare Perception of Non-Uniform Light Sources in an Office Setting" by L. M. Geerdinck, J. R. Van Gheluwe and M.C.J.M. Vissenberg (September 2018).

It is noteworthy that relatively simple lighting considerations such as color temperature, control over discomforting glare (optimized for the intended site and anticipated users), smooth ramp-up and ramp-down dimming controls or, for instance, a well-executed commissioning procedure with user training can make a significant difference in the subjective user experience and amiability of mentioned hard- and software system components. Advanced controls, including remote options through smart phones or tablets, are emerging in the recent past and are gaining traction on the market. Future embedding of demand response system features appears to be in close reach through software solutions that make use of current remote control systems and sophisticated EMS building automation solutions.

Figure 21: Illuminance Model of Open Office and Table Top at Four Different Dimming Levels



Source: CLTC

4.2.4.1 Energy and Market Impacts

Computer modeling indicates that choosing specific luminaire types and distribution patterns, three dimensional placement in the specific environment, and the ability to seamlessly dim high-efficacy luminaires can radically lower lighting power density (LPD) while minimizing contrast ratios. Simulation of high efficacy wall wash luminaires, under-cabinet and task lighting further indicates reduced LPD values could exceed T24-2013 recommended values, while being able to minimize contrast ratios to even lower values than recommended by IESNA. Consideration of all mentioned variables, environmental parameters, and luminaire parameters is vital to minimize contrast ratios and achieve ultra-low LPD without a sacrifice in overall lighting quality or levels.

Demonstrations show this approach truly saves energy. Through careful site-optimized planning, calculations of anticipated light power density values and modeling of expected contrast ratios, demonstrated systems achieved 0.39 W/sf using general ambient lighting at 100 percent power and wall wash at 50 percent power. When including the emergency pendants of the office space that operate continuously throughout the day and night, the LPD increased to 0.45 W/sf, which is 40 percent less than the recommended values of Title 24-13 with 0.75 W/sf.

Table 5: LPD Comparison for Incumbent and Demonstrated Lighting Systems

CDPH-P-IB, LPD results	unit key	PRE	POST	Savings
Duration of energy logging	days	1	60	
load measured on site, circuit 7, 9, 11; all 100 %	Watt	5047		
60 days average logged load	Watt		2013	3034
Area size	square foot	5100	5100	0
resulting LPD	W / sf	0.99	0.39	0.59
including 6x emergency lamps, 24/7 (not logged)	Watt	5735	2277	3458
Resulting LPD	W / sf	1.12	0.45	0.68

Source: CLTC

Research Needs and Next Steps

While latest linear pendant and task light LED products achieve over 100 lm/W, overall efficacy levels of LED wall wash luminaires are still comparatively low. There seem to be a distinct lag between the fast-paced development speed of new SSL chip generations with higher efficacy and associated higher prices for the bulk of linear pendants, and established niche wall wash product developments whereas a high efficacy LED source may also trigger secondary changes to the luminaire design such as thermal management, optics and possibly other related hardware issues. Foresight of development trends and quicker integration of latest SSL generations will help to continuously increase total luminaire efficacy.

Further developments of standardized lighting engine components such as Zhaga consortium books, innovative mounting solutions for LED and optics, and advanced materials will help to minimize the efforts to develop new luminaires and insure faster and more widespread adoption of qualitative, efficient and easily maintained LED luminaires. The Zhaga “books” for instance are well defined, standardized sections and lend themselves for future code and standards approaches on state and federal level.

Computer-aided drafting (CAD)-modelling for an optimized mix of several LED luminaires to achieve low contrast ratios in office applications proofed to be a laborious and time consuming task. With a specific goal LPD value in mind, each of the mix of area lighting pendants, wall wash luminaires, task lights and under-cabinet luminaires in various dimming levels, some also equipped with daylighting features, affect the whole site and the resulting contrast ratios, and therefore made it very difficult to find ideal system settings. When comparing CAD model simulated photometrics with real life at site collected Illuminance and Luminance values, results can vary significantly based on the accuracy and level of detail of the CAD model. Future work related to this project will benefit from higher detailed CAD models and ongoing planning expertise towards holistic understanding of contrast ratios of multi-variable feed-back systems.

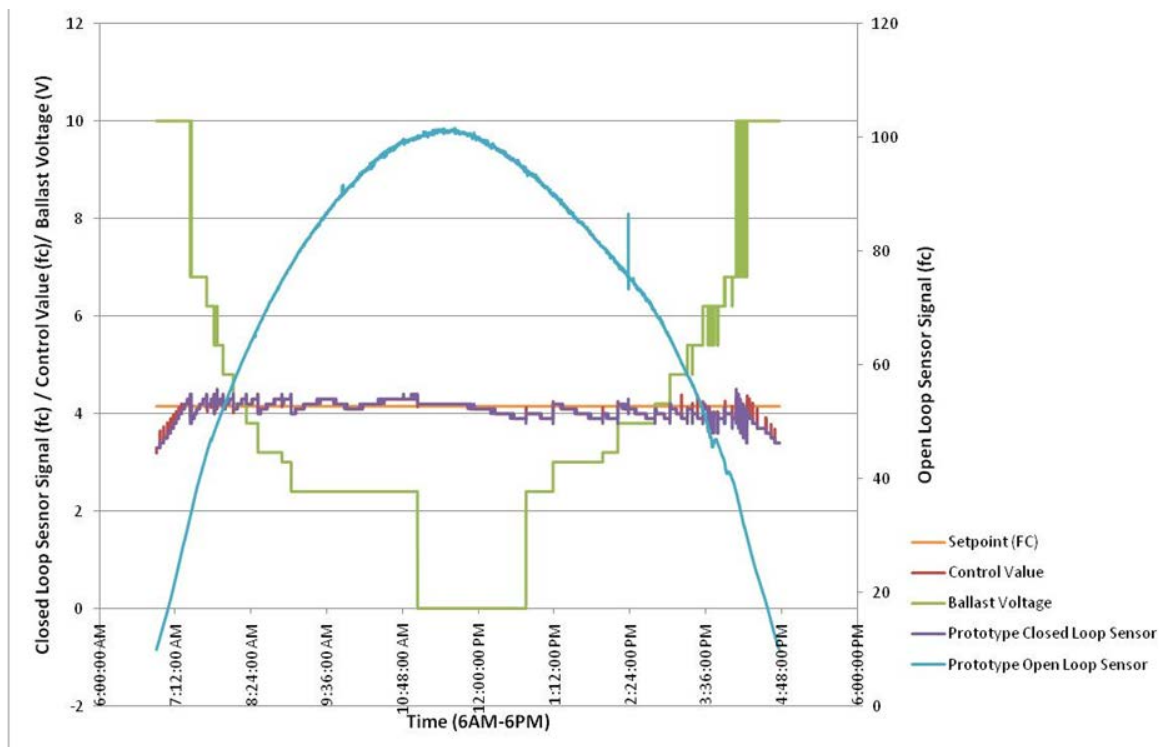
4.2.5 Dual-Loop Controls for Daylight Harvesting

Researchers evaluated a precommercial dual-loop prototype for its ability control the electric lighting appropriately and its ability to self-calibrate as part of fully functional lighting system. Laboratory tests included dimming electric light based on daylight changes, as well as detecting changes in the building environment. Researchers also examined sensor location dependencies and other environmental issues impacting the transition of the dual-loop approach to side-lit spaces. An overview of these project outcomes is provided below. More details this work may be found in APPENDIX G: Dual-Loop Daylighting Controls.

4.2.5.1 Top-Lit Applications

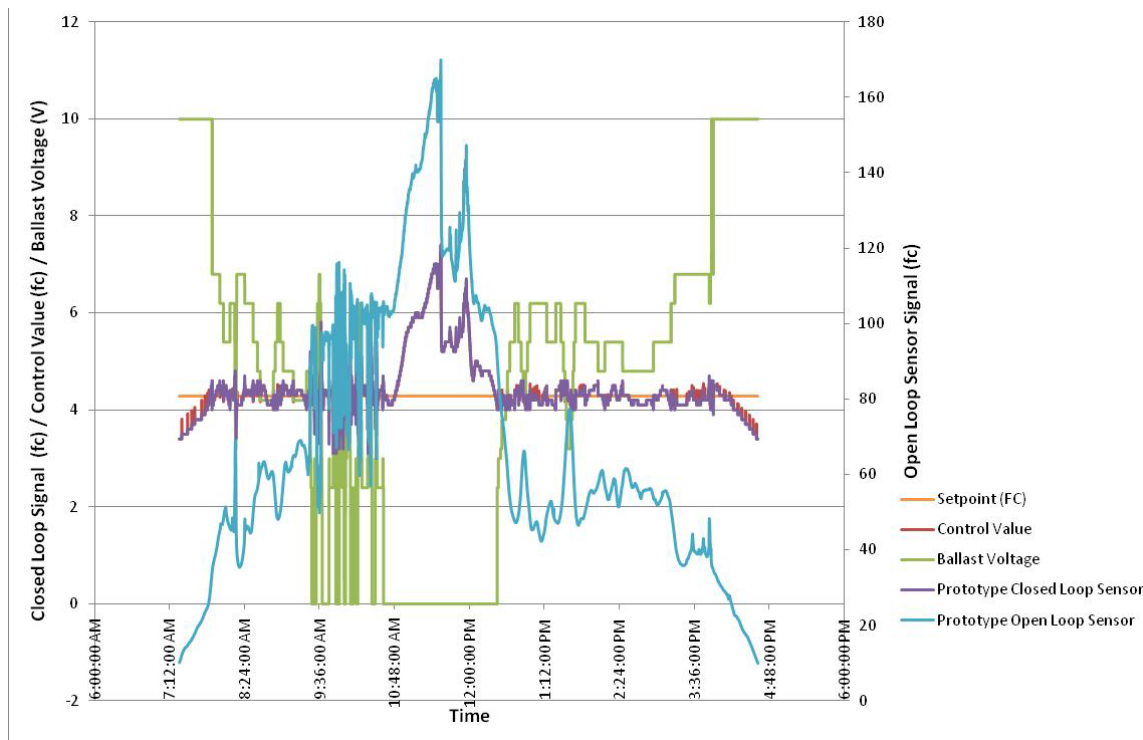
A fully functional, dual loop sensor will provide accurate open and closed loop signals to the lighting control system. The lighting control system will use the dual loop signals and the dual loop algorithm to dim the electric light as daylight rises past the set point dictated by the user. Figure 22 and Figure 23 illustrate the operation of the prototype over several winter days. In both cases, the prototype reduced the ballast voltage (green line) to maintain the light levels (purple line) at the set point (orange line). Even with the rapidly changing daylight conditions, light levels were reliably maintained until daylight conditions provided enough light to turn off the electric light completely.

Figure 22: Dual-Loop Sensor data collected over a winter day



Source: CLTC

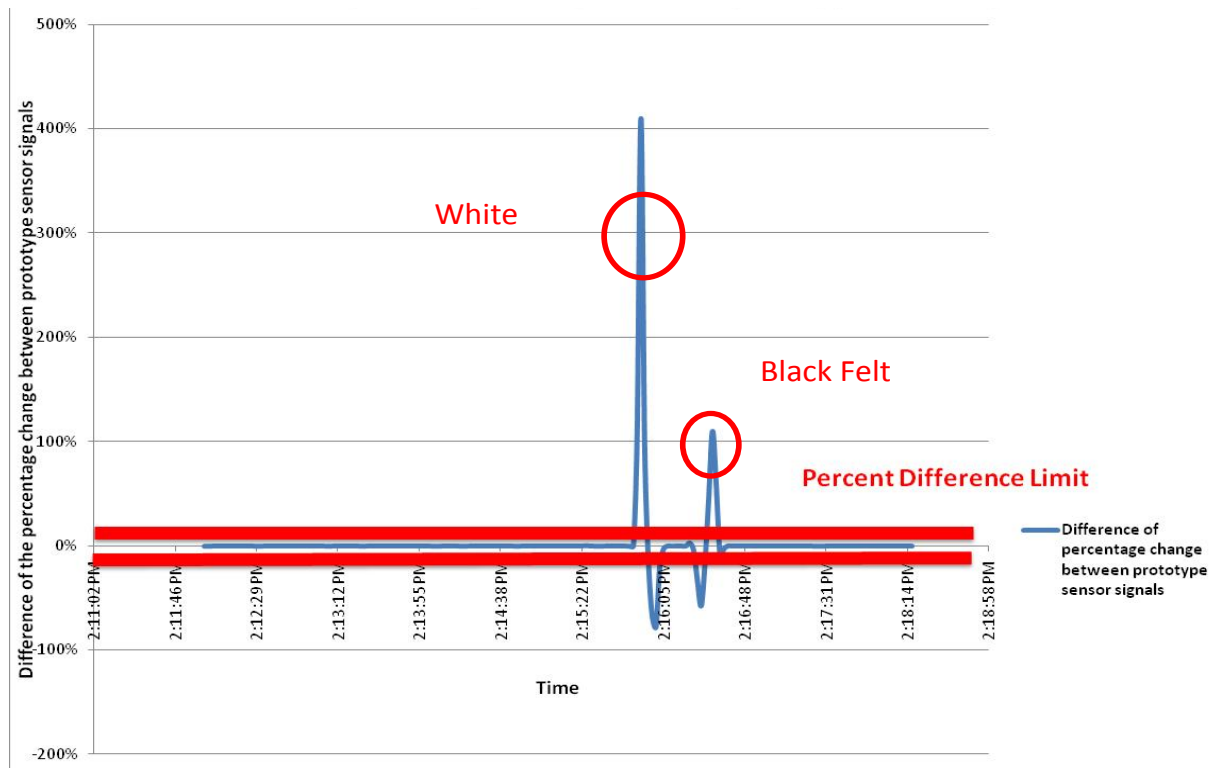
Figure 23: Dual-loop sensor test on a cloudy day



Source: CLTC

Researchers also carried out two occupant interference events to test the precommercial prototype and its ability to recognize changes in its environment. These events consisted of the introduction of a 3 foot by 3 foot piece of black felt and then of white paper approximately 10 feet away from the sensor. These events were chosen as the most extreme reflectance changes in an environment that the sensor would encounter. Each occupant event caused an increase in the signal change rate between the open and closed loop signals by approximately 100 percent and 300 percent, i.e. when the occupant interference was introduced, the closed loop sensor signal value changed 100 percent and 300 percent compared to the amount that the open loop sensor signal value changed (Figure 24). These events triggered the recalibration mode of the system.

Figure 24: Percent difference change between open-loop and closed-loop sensor signals.



Rate change due to occupant interference, collected as changes in indoor surface reflectance were made.

4.2.5.2 Side-Lit Applications

With respect to side-lit applications, results indicate that the best location for the closed-loop photo sensor is on the ceiling, with the sensor facing the space that the electric lighting is illuminating. The open-loop sensor needs to be carefully configured so that only the window is within its field of view; at the same time, the open-loop sensor must be positioned at a sufficient distance from the window and window treatments such as Venetian blinds, to minimize the contrast gradient across the window. On a bright day, horizontal blinds can result in high-contrast lines of dark and light across a window; if the open-loop sensor is positioned too close to the window and at the wrong angle, this contrast can interfere with the sensor's ability to accurately register outdoor daylight conditions.

4.2.5.3 Energy and Market Impacts

The WattStopper Dual-Loop sensor became commercially available in March 2013 as the LMLS-600 Dual-Loop sensor. Philips Lighting has also secured a license from UC Davis to incorporate the dual-loop technology into their lighting controls offerings.

4.2.5.4 Research Needs and Next Steps

While the dual-loop photosensor for skylight applications focuses on daylighting controls for electrical lights, it does not incorporate any sky lighting controls such as louvers, suspended

particle devices (“smart glass”), or shade systems. Incorporating sky lighting controls into the dual-loop daylighting control system would allow for maintenance of desired light levels in cases of desired low design light levels (applications such as museums and galleries, for example). The system would be able to allow for a high daylighting level during desired periods, while maintaining a lower design light level during other periods. This would allow for a larger range of light levels in a space, maximizing daylighting utilization and occupant comfort. Further research into incorporating the dual-loop self-commissioning algorithm with sky lighting controls should be targeted towards suspended particle device developers, or shade control system manufacturers.

In addition, when properly configured, the dual-loop implementation for side-lit spaces seems to handle daylight and space changes very effectively; however, proper configuration requires installation by knowledgeable and experienced installers, especially for the position of the open-loop photo sensor, i.e., the photo sensor positioned with only the window(s) of the space in its field of view. However, due to commissioning complexity, the dual-loop approach for side-lit applications was deemed too costly for field trials as of the time of the Program. Elements of this research were transitioned to new work on networked, intelligent lighting systems utilizing a distributed intelligence approach. Details on outcomes of this work may be found below and in APPENDIX K: Ultra Smart Indoor Lighting Systems.

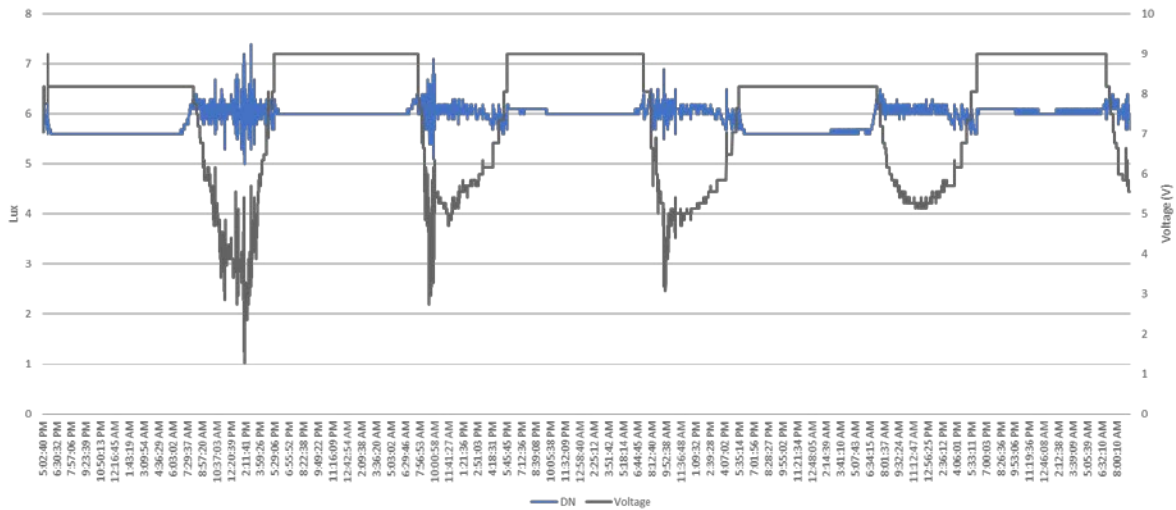
4.2.6 UltraSmart Indoor Lighting Systems

Researchers completed testing of the UltraSmart Luminaire System for both single fixture and multi-fixture configurations. The tests monitored the performance of the system in maintaining the light level within a specified light level range. The system’s maintained, target light level range is determined during the auto-commissioning phase of the system. Single-fixture activities provided researchers information on system performance at the individual luminaire level, which could then be replicated across a multi-unit configuration.

4.2.6.1 Single Fixture Operation

Single-fixture testing was carried out at CLTC’s Daylight Harvesting Laboratory. Laboratory testing took place over a five-day period, during which researchers collected data pertaining to UltraSmart luminaire photosensor readings, control algorithm inputs and outputs, and output voltage to the fixture’s dimming ballast. Figure 25 shows the comparison of the monitored light level of one downward facing photosensor on the UltraSmart luminaire to the voltage output to the dimming driver. Results demonstrated that the UltraSmart system behaved as expected, increasing and decreasing the voltage output to the dimming driver to maintain desired light levels within the space.

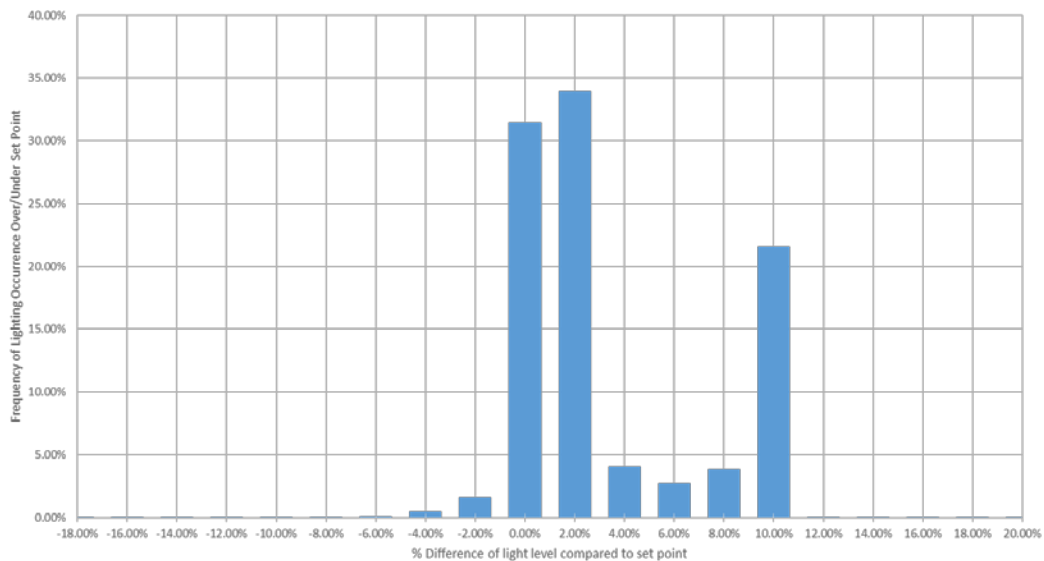
Figure 25: Comparison of Light Level Signal to the Voltage output to the UltraSmart Luminaire's Dimming Driver



Source: CLTC

Figure 26 and Table 5, which are based on the data displayed graphically in Figure 25, show the percentage of light level readings that deviate from the target light level range. This analysis represents the system's ability to consistently maintain light levels within a specified range. The results from this analysis shows strong support for the system's ability to maintain a consistent light level within close proximity to the desired light level range for the space. More than two thirds of the readings are within two percent of the desired light level range and less than one percent of the light level readings deviate more than ten percent from the desired range.

Figure 26: Light Level Consistency for Ultra Smart Fixture



February 18-25, 2015

Source: CLTC

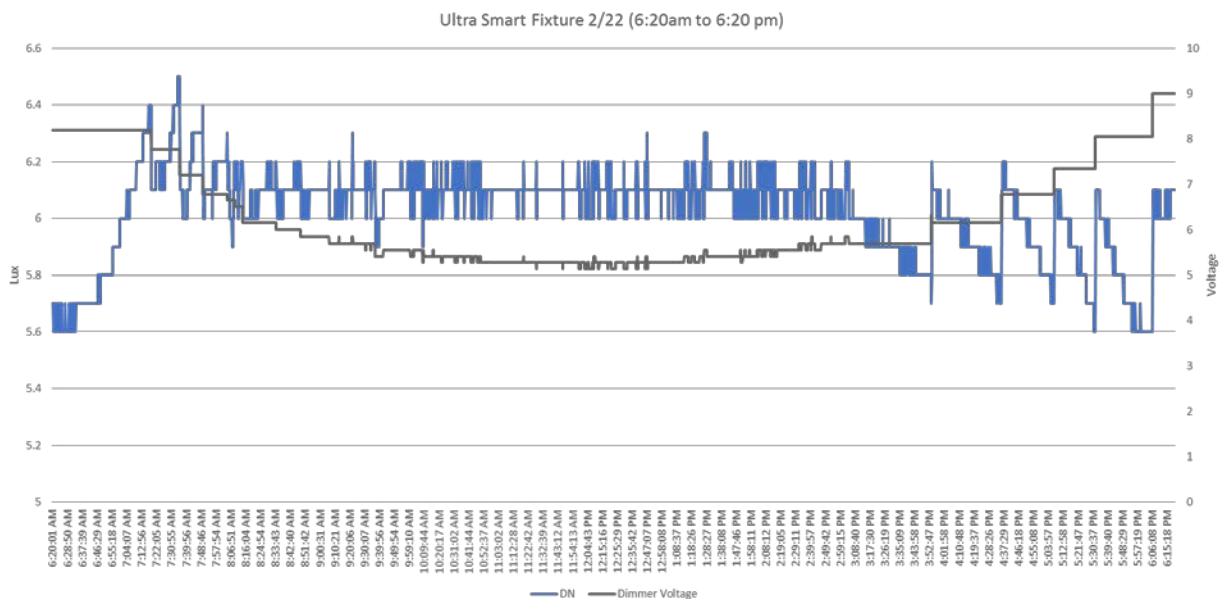
Table 6: Histogram Chart Values

Bin	Frequency	% Occurrence	Bin	Frequency	% Occurrence
-18.00%	1	0.00%	2.00%	20740	33.99%
-16.00%	1	0.00%	4.00%	2476	4.06%
-14.00%	3	0.00%	6.00%	1673	2.74%
-12.00%	6	0.01%	8.00%	2338	3.83%
-10.00%	5	0.01%	10.00%	13182	21.61%
-8.00%	14	0.02%	12.00%	15	0.02%
-6.00%	67	0.11%	14.00%	5	0.01%
-4.00%	289	0.47%	16.00%	6	0.01%
-2.00%	1000	1.64%	18.00%	1	0.00%
0.00%	19188	31.45%	20.00%	2	0.00%

Figure 27, Figure 28 and Table 7 provide further analysis of the UltraSmart luminaire's ability to maintain a consistent light level. The data shown above represents all measurements taken over five days. The data presented below condenses this time frame to just one day's daylight hours. This provides a more focused looked at the system's operation.

Results confirm the findings from the analysis of the whole five-day testing period. The UltraSmart luminaire is capable of maintaining light levels consistently within a desired target light level range. The accuracy of the system even increased, with almost 75 percent of the light level readings being within two percent of the target light level range and none of the readings deviating more than ten percent.

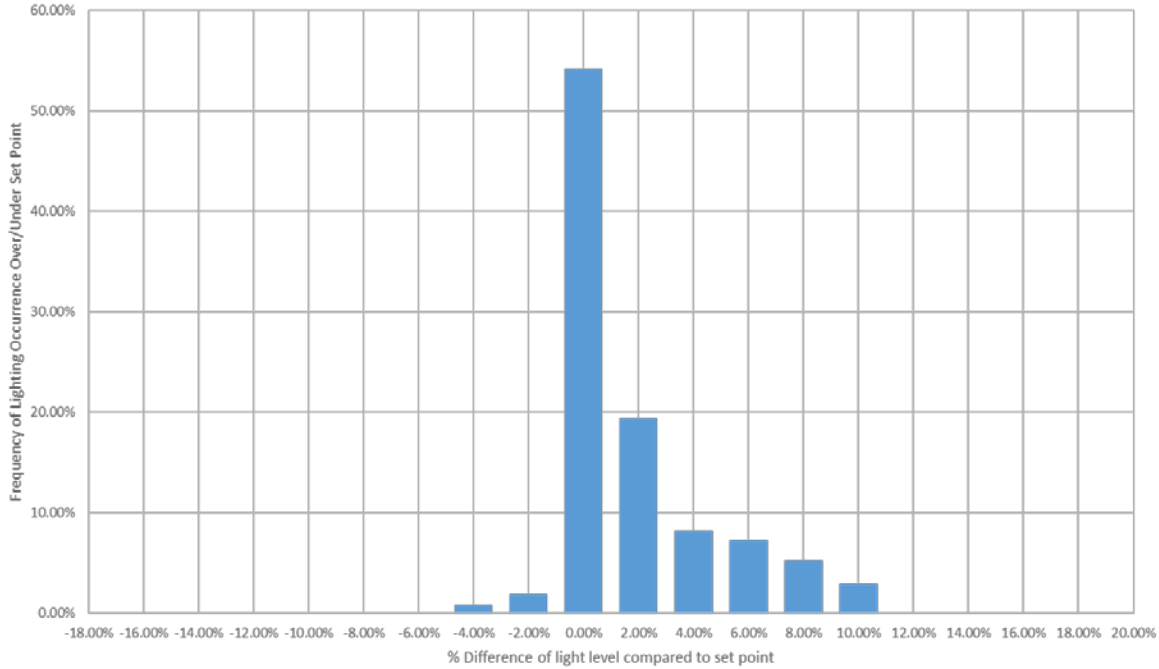
Figure 27: Comparison of Light Level Signal to Voltage to Dimmer Diver – Daylight Hours



Feb. 22, 2015 6:20 am to 6:20 pm

Source: CLTC

Figure 28: Light Level Consistency - Daylight Hours



Feb. 22, 2015 6:20 am to 6:20 pm

Source: CLTC

Table 7: Histogram Chart Values (Feb. 22 “Daylight Hours” 6:20 am to 6:20 pm)

Bin	Frequency	% Occurrence	Bin	Frequency	% Occurrence
-18.00%	0	0.00%	2.00%	1219	19.44%
-16.00%	0	0.00%	4.00%	513	8.18%
-14.00%	0	0.00%	6.00%	456	7.27%
-12.00%	0	0.00%	8.00%	327	5.21%
-10.00%	0	0.00%	10.00%	185	2.95%
-8.00%	0	0.00%	12.00%	0	0.00%
-6.00%	3	0.05%	14.00%	0	0.00%
-4.00%	51	0.81%	16.00%	0	0.00%
-2.00%	119	1.90%	18.00%	0	0.00%
0.00%	3398	54.19%	20.00%	0	0.00%

4.2.6.2 Future Research, Development & Demonstration Opportunities

Intelligent, automated luminaire networks are an area with clear needs for further research, development and demonstration. The Ultra Smart Luminaire system developed herein demonstrated the potential and capabilities of adaptive luminaire technologies for reducing building energy use. Initial research returned positive results, but obstacles remain to bring a fully functional and economically feasible smart system to the commercial market. Further

development is needed on control algorithm design and hardware selection. While initial ground work was completed in terms of development and testing of control algorithms, further work is needed to provide a ready to install system for use in field demonstrations and commercial use. Existing prototypes still require increased integration of other lighting control technologies, such as occupancy controls and timers, to maximize the energy savings potential of the system beyond just daylight harvesting.

Caring out future field testing demonstrations of the UltraSmart luminaire system is vital in developing the system towards being commercially viable. The testing and monitoring of preliminary technologies and research in authentic commercial environments (i.e. office spaces or retail stores) allows researchers to gain critical information and insight into the development of the product that might possibly not be obtained within a controlled lab setting. While the processes of specifying, purchasing, installing, commissioning, and monitoring the system can assist with determining commercial feasibility of the system.

4.3 Adaptive Envelope Systems

Adaptive envelopes are an emerging technology, however, there are many commercially available products that can be used in development of an optimized, adaptive envelope system. In most current applications, these technologies are manually operated. Operation requires occupant involvement, which has been shown to be very unreliable. Studies show that occupants adjust dynamic fenestration systems only in response to needs such as privacy and comfort. For example, occupants will adjust dynamic systems to block direct solar penetration but will not adjust them again for energy efficiency when direct solar penetration is not an issue. Automation of dynamic fenestration is the most effective way to realize the full potential for energy efficiency and peak demand reduction, while maintaining comfort through “comfort-based” operation and occupant override.

The key to effective, automated, dynamic envelope systems is reliable sensing of environmental conditions such as occupancy and daylight combined with the ability to recognize and act on the status of the electric lighting and HVAC systems. Reliable sensing depends on robust sensor technology and the algorithms embedded in logic controllers. The logic controller must accept inputs from the sensors, astronomical clocks, and occupants, then provide output to actuators, such as motors, to adjust the dynamic components of window and skylight systems to appropriate states for comfort and energy efficiency.

To better understand the energy impacts of dynamic fenestration, researchers completed a set of parametric simulations for a big box retail space, comparing the performance of adaptive and static skylight systems to a baseline building without skylights. The building geometry and skylight layout were based on building plans of a recently renovated retail supermarket.

The operation of adaptive skylights was simulated using a predefined “switchable glazing” system in the simulation software, which allows glazing properties to be altered from/to predefined “clear” and “tinted” states. This is equivalent to an electrochromic glazing with full control along the entire range of its solar-optical properties. Currently available systems offer

operation only in terms of four states, including the maximum and minimum settings, which are approximately 1 percent and 60 percent in terms of visible transmittance.

In the simulation, the switchable glazing was controlled based on daylight work plane illuminance and the status of the electric lighting. The model assumed a minimum requirement of 500 lux at the work plane, 30 inches from the floor. The skylight system was operated for maximum daylight contribution at the beginning of the day. As the daylight levels increased, the electric lighting was dimmed accordingly, aiming at maintaining the 500 lux requirement. When daylight alone was meeting the 500 lux requirement, electric lighting was switched off. From that point on, the switchable glazing system was operated to maintain the 500 lux requirement, i.e., continuously reducing transmittance as daylight levels continued to rise and then increasing transmittance following the daylight decrease at the end of the day.

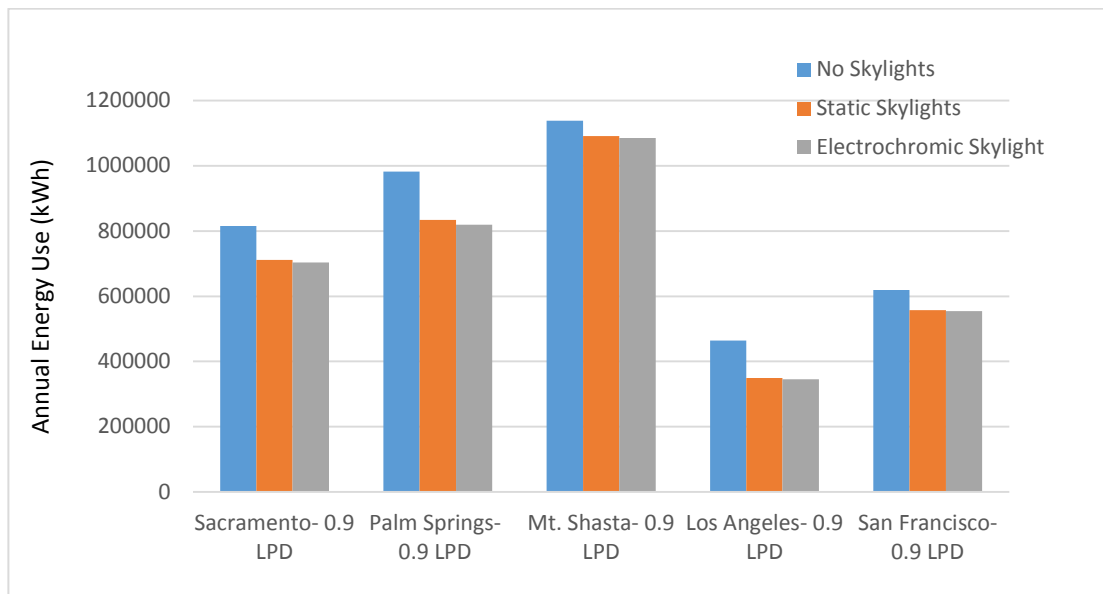
4.3.1 Energy and Market Impacts

Potential energy savings were computed by comparing the energy use of the base case model without skylights, a model that included static skylights and a model that included adaptive skylights. Simulations were performed for five different California locations representing a cross section of climate zones: Sacramento, San Francisco, Los Angeles, Mt. Shasta, and Palm Springs. Simulations included consideration of two different LPD = 0.9 W/sf and 0.7 W/sf. The higher LPD represents a lighting system linear fluorescent lighting and the lower a system composed of LED lighting.

Simulation results showed a variance in the level of energy savings across individual climate zones. Energy savings were found to range between approximately five and 25 percent. The savings range was similar for static skylights, however the savings were greater in each of the five zones for the dynamic skylights in comparison to the static skylights. Potential savings are found to be highest in moderate climate areas, such as Los Angeles, where heating and cooling play a lesser role in energy use within a building. Locales with more extreme climates experience reduced savings, especially where heating energy usage is high.

Skylights are shown to reduce energy use of both electric lighting and cooling, while increasing heating energy use. The main source of potential savings comes from the reduction in electric lighting energy use. The savings associated with cooling through reduction of daylight penetration has far less of an impact. In this “minimal” adaptive operation, reduction in heating loads played the largest role after electric lighting reduction in potential energy savings variance across climate zones. Figure 29 show total building energy use, by climate zone.

Figure 29: Comparison of Building's Total Annual Energy Use for 0.9 W/sf



Source: CLTC

4.3.2 Research Needs and Next Steps

Current simulation software does not support modeling of optically complex skylights, which represents the majority of skylights used in retail buildings. The preceding skylight simulation results, as is the case with most results from most building simulation software, are based on a flat glass skylight model. The errors from this simplification can be large, as the shape of most commercial skylights has been considered for best performance in terms of daylight and solar heat gain. Software also did not support modeling of dynamic shading systems beyond the electrochromic glazing option.

The characterization of these optically complex systems has been a major barrier in performance simulations for a very long time. The most promising approach to overcoming this barrier is through the combination of experimental and computational means, i.e., measure the directional output of optically complex systems for each and every incoming direction of radiation, and then treat the optically complex system as a “black box” in the energy simulation software, i.e., treating the fenestration system as a luminaire of varying candle power distribution, which is computed at each time step of the energy simulation process.

While measuring the directional transmittance of small material samples (2 inches by 2 inches) is possible with commercially available goniophotometers, it is not yet possible to use this approach for large systems such as a full window or skylight. This can only happen with through research and development of measurement methods and, while the need has been recognized for a long time, the issue has not yet been addressed successfully.

The next characterization level of optically complex systems is measuring of their directional hemispherical transmittance, i.e., the total (rather than directional) light transmitted for each

and every incoming direction of radiation. This characterization could be successfully realized using integrating spheres. During its establishment, CLTC saw this next potential step and developed an integrating sphere that is designed to measure the directional hemispherical transmittance of windows and skylights as large as 4 feet by 4 feet.

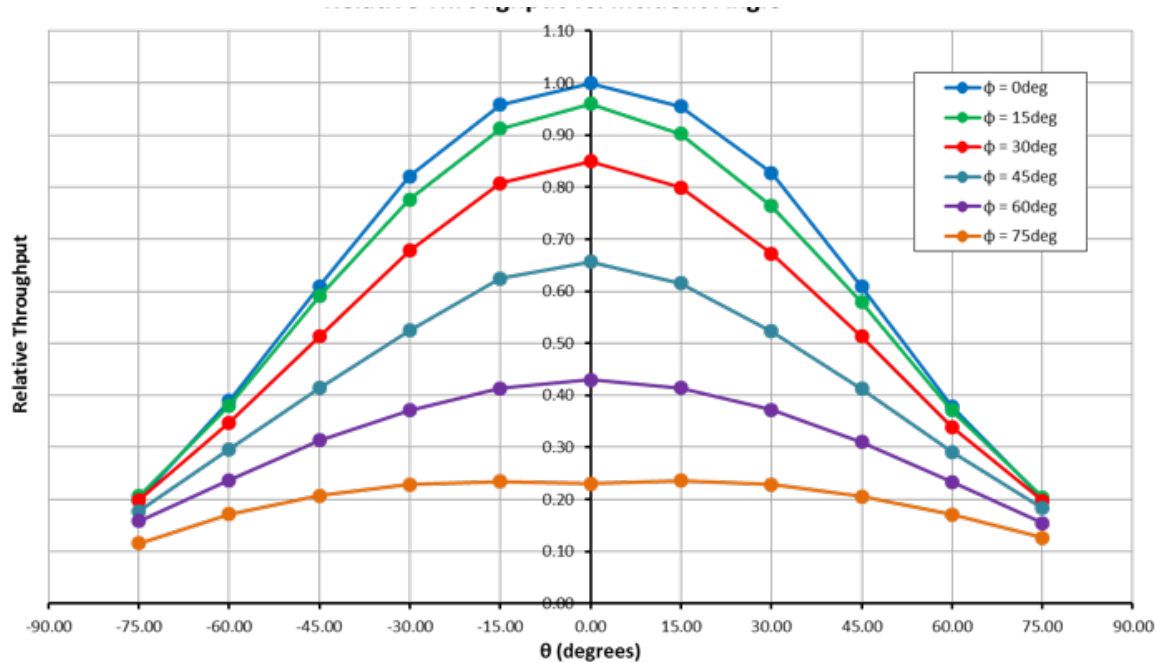
Figure 30: Commercial Skylight with Louvered System Mounted to Custom Integrating Sphere



Photo credit: CLTC

Skylights often use material to diffuse the direct solar radiation, and directional hemispherical transmittance could be used to derive transmitted candlepower distribution considering a theoretically perfect diffuse transmittance. Researchers measured the bidirectional transmittance of a full scale 4 foot by 4 foot commercial skylight. Measurements were taken through a special setup at the CLTC research laboratory that met the requirements for the distance of the light source to uniformly illuminate the sphere opening. Different incident angles were achieved through rotation of the integration sphere, at the end of a long black tunnel set up with black cloth. Measurements were taken for 66 positions in terms of skylight angle, from 0 degrees (fully open) to 75 degrees on the horizontal plane and -90 degrees to +90 degrees on the vertical plane, at 15 degree increments. Results from the measurements are shown in Figure 31 for on azimuthal direction in 15 degree incident angle increments.

Figure 31: Plot of Relative Throughput vs. Incident Angle for Commercially Available Diffuse Skylight



Source: CLTC

Results demonstrate the impact of the solar radiation's incident angle (relative to the skylight surface) on the amount of throughput. Reaffirming the need to take this varying rate into account when modeling skylight systems for performance simulations or when reviewing data from simulations where the varying rate was not able to be taken into consideration. While the experiment was able to give insight into the affect incident angle has on the varying level of visible transmittance, this experiment was not able to show the effect of varying the incident angle has on the thermal characteristics of the system such solar heat gain.

Moving forward, data from future experiments, i.e. skylight with louvers, could be useful in energy performance simulations. It would be beneficial to consider automated positioning of the integrated sphere. This enhancement to the experiment setup would greatly reduce the amount of time currently needed to manually position the integrated sphere for each desired data collection point, since the number of data collection points would greatly increase with the use of complex skylight fenestration controls, i.e. skylight louvers.

Performance simulation is one of the most important fronts to advance, and they can greatly accelerate the development of new technologies. Research and development efforts should be focused on expanding energy simulation software to support consideration of optically complex systems and advanced control strategies based on multiple criteria, such as occupancy, light levels, status of electric and HVAC systems, etc. Such improvements are intimately linked to the characterization of optically complex systems, as the new simulation algorithms should be compatible with what researchers can measure in the laboratory.

4.4 Core Daylighting

Core daylighting systems, like most daylighting technology, are typically more variable in output than electric lighting systems. In the course of this project, weather, dirt build-up, length of day, and sun altitude were identified as major factors effecting the total daily and maximum daylight output of the demonstrated core daylighting system. These in turn affect the potential daily electricity savings and peak reduction provided by the system.

Analysis of the data collected from the CLTC installation showed that the SunBeamer™ requires direct irradiance to transmit light, and does not transmit a significant portion of the diffuse daylight present on overcast days. To provide an estimate for the number of days per year that the SunBeamer could realistically offset electric lighting, CLTC utilized weather data from the National Climate Data Center (NCDC). A key part of this data is an hourly normalization of cloud coverage for the years between 1981 and 2010. This record gives information on the cloud coverage in the area around Sacramento, indicating what percent of the area is in each weather state. Thus for each hour, a probability of the sky being in each of the weather states (cloud designation) is known.

Table 8: Cloud Coverage Description

<i>Cloud Designation</i>	<i>Eighths of Sky Covered</i>	<i>Sunlight Throughput by SunBeamer</i>
Clear	0/8	100%
Few	1-2/8	81.25%
Scattered	3-4/8	56.25%
Broken	5-7/8	25.00%
Overcast	8/8	0%

By using the percent throughput value given in Table 6, the effects of the clouds on the system was predicted for each hour over the course of the year. As shown below, the efficacy of the system is expected to be reduced by an average of eight percent in summer (June 21st to September 23rd) and 50 percent in winter (December 21st to March 20th).

Solar altitude and dirt depreciation also impact overall system efficacy. More details on these and other tests conducted to characterize system performance may be found in APPENDIX N: Solar Canopy for Core Daylighting.

4.4.1 Energy and Market Impacts

Currently, the demonstrated systems do not completely fulfill their potential as a viable replacement for electric lighting in core building areas. Over a five year lifespan, the daylighting portion of the SunCentral System cost approximately \$22 more to clean than is saved in electricity (\$23 savings less \$45 maintenance costs). The system also had much higher installation costs as compared to LED luminaires on a dollar per lumen basis. As such, there is no economic rationale for use of the demonstrated system at this time.

4.4.2 Research Needs and Next Steps

Research is necessary on materials and mechanical design to significantly increase the throughput of light in horizontally reflected, or mirrored core daylighting solutions. Future work should include improvements to increase light collection at low solar angles and minimize losses during transmission. In addition, dirt depreciation must be addressed i to improve overall system performance and cost-effectiveness.

GLOSSARY

Term	Definition
AB	Assembly Bill
AHE	All High Efficacy (lighting)
ALCS	Advanced lighting control system
ANSI	American National Standards Institute
BERG	Building Energy Research Grant
Building Envelope	The physical separators between the conditioned and unconditioned environment of a building resistance to air, water, heat, noise, and light transfer. ¹³
CAD	Computer-aided drafting
Candela	The SI unit of luminous intensity, equal to one lumen per steradian. ¹²
Candlepower	Luminous intensity expressed in candelas. ¹²
CALCTP	California Advanced Lighting Controls Training Program
CASE	Codes And Standards Enhancement
CCT	Correlated color temperature
CFL	Compact Fluorescent Lamp
CLTC	California Lighting Technology Center (Contractor)
CRI	Color rendering index
CT	Current transducer
DALI	Digitally Addressable Lighting Interface
Daylight Harvesting	The use of daylight in the attempt to reduce energy consumption by offsetting the amount of electric lighting used in lighting spaces.
Directional Transmittance	Ratio of incident flux collected over an element of solid angle surrounding the given direction to essentially collimated incident flux. ¹²

¹³ Cleveland, Cutler J., and Christopher G. Morris. "Building envelope (HVAC)". *Dictionary of Energy*. Expanded Edition. Burlington: Elsevier, 2009. Print.

¹² Rea, Mark S. *The IESNA Lighting Handbook: Reference & Application*. 9th Ed. New York, NY: Illuminating Engineering Society of North America, 2000. Print.

DC	Direct Current
DR	Demand Response
DOE	United States Department of Energy
D.O.T	Direction of Travel
Dual Loop	Control method utilizing both open and closed loop control strategies.
ELV	Electronic Low Voltage
EMS	Energy Management System
Energy Commission	California Energy Commission
EO	Executive Order
EPA	Environmental Protection Agency
fc	Foot-candle
Fenestration	Any opening or arrangement of openings for the admission of daylight. ¹²
GHG	Greenhouse gases
Glare	The sensation produced by luminance within the visual field that are sufficiently greater than the luminance to which the eyes are adapted, which causes annoyance, discomfort, or loss in visual performance and visibility. ¹²
Goniophotometer	A photometer for measuring the directional light distribution characteristics of sources, luminaires, media, and surfaces. ¹²
GWh	Gigawatt-hour
HID	High Intensity Discharge (lamp)
HPS	High Pressure Sodium (lamp)
HVAC	Heating, Ventilation, and Air Conditioning
Illuminance	The areal density of the luminous flux incident at a point on a surface. ¹²
IESNA	Illuminating Engineering Society of North America
IOU	Investor-owned utility
K	Kelvin
LED	Light-emitting diode

LPD	Lighting power density. The total load (power) of lighting equipment within a defined area divided by the size of the area. Units are often expressed as Watts Per Square Foot (WSF).
lm	lumens
lm/W	Lumens per Watt
Luminance	The quotient of the luminous flux at an element of the surface surrounding the point, and propagated in directions defined by an elementary cone containing the given the area of the orthogonal projection of the element of the surface on a plane perpendicular to the given direction. The luminous flux can be leaving, passing through, and/or arriving at the surface. ¹²
MLV	Magnetic Low Voltage
MR	Multifaceted reflector (lamp)
MSSL	Municipal Solid-State Street Lighting Consortium
NCDC	National Climate Data Center
NEMA	National Electrical Manufacturer's Association
OLED	Organic Light-Emitting Diode
PAR	Parabolic Aluminized Reflector (lamp)
PG&E	Pacific Gas and Electric
PIER	Public Interest Energy Research
PIR	Passive infrared. A type of sensing technology commonly used with outdoor motion sensors.
PLC	Power line carrier
RD&D	Research, development and demonstration
RF	Radio frequency
SHGC	Solar heat gain coefficient (fraction of incident solar radiation admitted, both directly transmitted and absorbed and subsequently released inward)
SPEED	State Partnership in Energy Efficiency Demonstrations
SSL	Solid-state lighting

TLED	Tubular Light Emitting Diode. A linear LED lamp used to replace linear fluorescent lamps.
UBC	University of British Columbia
UC Davis	University of California Davis
UL	Underwriter's Laboratory
US	Ultrasonic. A type of sensing technology commonly used by indoor occupancy sensors.
VDT	Visible Daylight Transmittance (fraction of incident daylight in the visible light spectrum that passes through a material)
W/sf	Watts per square foot: a measure of lighting power density
WIO	Wireless Input/Output (a method of transmitting information over wireless links)
ZNE	Zero net energy

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APPENDICES

APPENDIX A: Adaptive Outdoor Lighting

APPENDIX B: Indoor, Residential LED Luminaires

APPENDIX C: Directional LED Replacement Lamps

APPENDIX D: Organic LEDs

APPENDIX E: Plasma Lighting

APPENDIX F: Direct-DC Lighting Systems and Microgrids

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APPENDIX H: Novel Office Lighting Design Strategies

APPENDIX I: Adaptive Lighting for Secondary Spaces

APPENDIX J: Smart Lighting for the Agricultural Sector

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APPENDIX L: Smart Windows and Skylights

APPENDIX M: Daylight Optimization for Skylights

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APPENDIX P: Market Transformation and Partnership Development

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