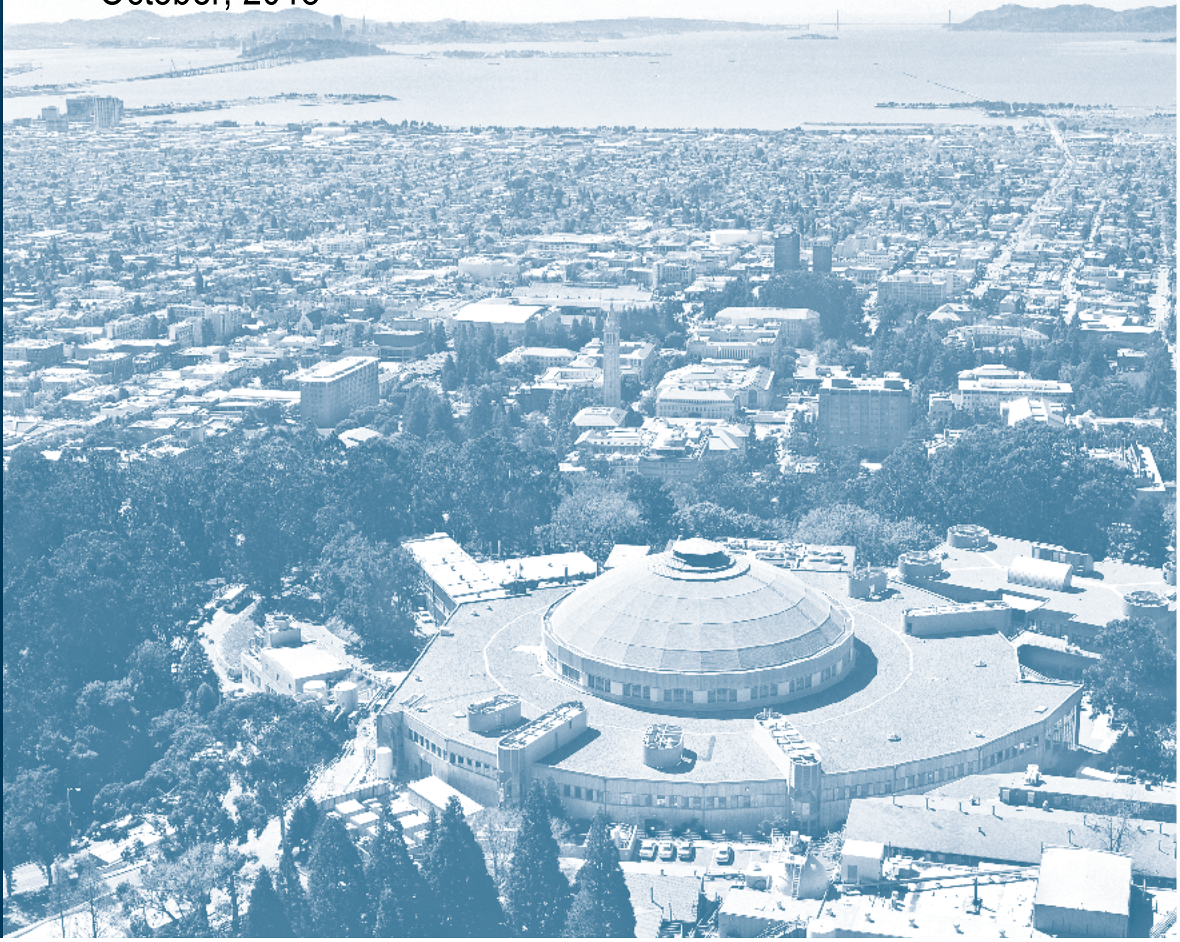
BERKELEY LAB

Lawrence Berkeley National Laboratory

Energy Cost Savings of Systems-Based Building Retrofits: A Study of Three Integrated Lighting Systems in Comparison with Component Based Retrofits

Cindy Regnier, Paul Mathew, Alastair Robinson,
Peter Schwartz, Jordan Shackelford, and Travis Walter

Energy Technologies Area
October, 2018



Energy and Cost Savings of Systems-Based Building Retrofits: A Study of Three Integrated Lighting Systems

Cindy Regnier, Paul Mathew, Alastair Robinson, Peter Schwartz,
Jordan Shackelford, Travis Walter

Lawrence Berkeley National Laboratory

October 2018

Acknowledgement

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Building Technologies Program, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

The authors would like to thank ComEd, California Publicly Owned utilities and Xcel for their participation in this project. The authors also thank Amy Jiron and Jason Hartke in the DOE Building Technologies office for their support and guidance.

Disclaimer

Table of Contents

Executive Summary

Most building retrofit projects are still component-based in that they typically address only one piece or type of equipment at a time. Systems-based retrofits that seek to address multiple components in an integrated manner have the potential to provide significantly greater energy savings.

Lawrence Berkeley National Laboratory (LBNL) partnered with several utilities to develop and evaluate three different integrated retrofit packages involving lighting systems: automated shading with daylight dimming controls, workstation-specific lighting with daylight controls, and task/ambient lighting with plug load occupancy controls. Specifically, our analysis sought to quantify the marginal benefits of these systems (energy savings as well as lighting performance and visual comfort) relative to component-based approaches. The analysis was based on a combination of measured performance data from LBNL's FLEXLAB® test facility and energy simulations. All three systems were compared to a simple fluorescent-to-LED retrofit, which represents the component-based approach. While the simple LED upgrade provides significant lighting energy savings of 63%, the systems yielded energy savings of 81-93%, which equates to *additional* savings of 49-82% over the simple LED upgrade (Table A-1).[1] All systems tested provided satisfactory visual comfort as well, indicating good potential for market acceptance.

Table A-1. Comparison of component- vs. systems-based energy savings for three integrated lighting systems.

Option	Lighting EUI (kWh/sf/yr)	Lighting Energy Savings relative to Baseline	Lighting Energy Savings relative to Component-based Retrofit
Baseline (Fluorescent, scheduled control)	4.02	_	_
Component-based Retrofit (simple LED)	1.48	63.1%	_
Automated Shading and Daylighting	0.61	84.8%	58.8%
Workstation-Specific and Daylighting	0.27	93.3%	81.9%
Task/Ambient and Occupancy	0.75	81.3%	49.3%

While the savings from systems are significant, the cost effectiveness (limited to simple payback analysis here) of a systems approach can vary considerably based on the retrofit scenario, installation costs and utility prices. Project economics were evaluated for pure retrofit scenarios (replacement of functioning equipment in an existing building space) where the full material and labor costs associated with

---

[1] Whole building energy savings for the integrated lighting systems are detailed in the report section for each system and are based on the FLEXLAB results compared to DOE reference building simulations. Savings range from 5% - 20% and are highly dependent on assumptions regarding impacted floor area, ratio of perimeter area to total floor area (for daylighting), building type, and HVAC system type.

replacing existing equipment with the evaluated technologies are considered, as well as incremental cost scenarios where only the cost differences between the evaluated technologies and standard alternatives are considered. This approach is applicable to major renovations and tenant improvements, and replace on burnout (ROB) projects in existing buildings, and new construction projects.

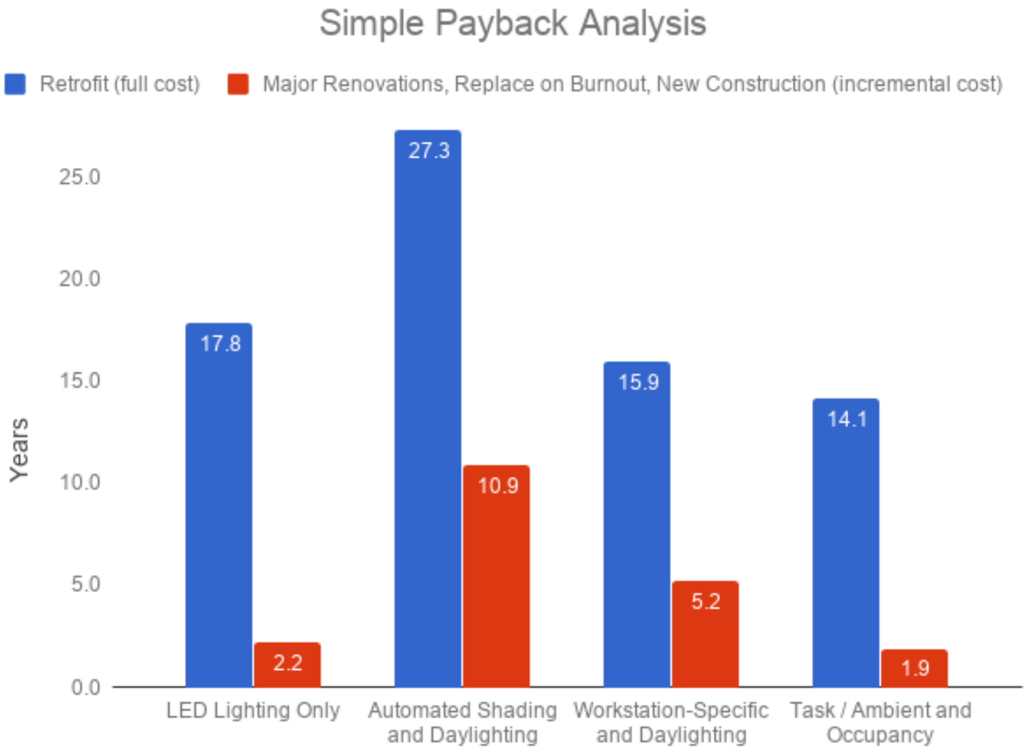


Figure A-1. Comparison of component- vs. systems-based simple paybacks

For pure retrofit scenarios, cost effectiveness for the integrated lighting systems was challenging, with paybacks ranging from 14 to 27 years. Paybacks were shown to improve at higher utility prices that increase the value of the energy savings. In pure retrofit cases, the task/ambient system and the workstation-specific system achieved better paybacks than the component-based LED retrofit. The systems were much more cost-effective in major renovations, replace on burnout, and new construction scenarios, with simple payback ranging from 1.9 years for the task/ambient system to 5.2 years for the workstation-specific lighting system, and 10.9 years for the automated shading and daylighting system, assuming an average utility price of $0.11/kWh (time-of-use rates and other complex tariffs were not evaluated). Additionally, cost effectiveness was actually found to be better for the task/ambient system than for a component-based approach (simply installing new LED fixtures instead of new fluorescent fixtures) at a payback of 2.2 years at the same utility rate.

Some technology innovations are available on the market today, such as LED replacement lamps and LED retrofit kits with onboard controls and sensing, either of which avoid the installation of entirely new fixtures, that could improve the pure retrofit cost effectiveness of the systems studied. It is also important to recognize that there may be significant non-energy benefits from integrated systems technologies such as the lighting - focused packages evaluated here (occupant visual comfort, glare control, access to views) and the value of these benefits (e.g. improved workplace satisfaction and/or productivity). The value of these benefits is less clearly quantified and has not been factored into the cost effectiveness analysis presented here.

The cost effectiveness result perhaps underscores the potential value of utility incentive programs targeting these integrated lighting system packages, to help support implementation and buy down retrofit project costs. A key challenge is to reduce the transaction costs of designing, installing and operating integrated lighting systems. One way to reduce these costs, especially for utility incentive programs, is to develop quasi-standardized validated systems ‘packages’ where guidance can be given to streamline implementation. This can include the utility programs providing standardized specifications, design and installation guidance (such as tuning levels for commissioning), operation procedures, and standardized M&V protocols.

Introduction

What is a System?

For the purposes of this white paper, we define a system as one of the following:

1. Building End Use System: *The set of equipment, supporting devices, distribution, sensors and controls used to maintain a desired service level, such as environmental conditions, in a space for a given end use.*

This may be further described by end use system within a building, such as:
- HVAC System - The set of equipment, distribution, sensors and controls technologies used to maintain a desired environmental condition in a space.
- Lighting System - The set of light fixtures, fixture distribution, sensors and controls technologies, as well as interior design elements and daylighting sources (e.g. windows, skylights), used to maintain a desired light level condition in a space.
- Domestic Hot Water System - The set of equipment, distribution, sensors and controls technologies used to maintain a desired hot water service condition to a space.

Envelope components can become Building End Use Systems once there is a degree of automation or controls involved, and they become energy consumers. The combination of a building's miscellaneous plug loads can also be thought of as an end use system.

2. Interactive Building Systems - *A Building End Use System or envelope component(s), the performance of which impacts the energy use or performance of a different Building End Use System.*

There is a strong connection between building envelope design, construction, and retrofits, and building end use system energy use. For example, a well-designed building envelope can significantly decrease heating or cooling loads on the HVAC system. Other systems that produce internal heat loads such as lighting systems and plug load devices also contribute to HVAC system energy use. 'Widget' based equipment replacements typically replace equipment at the same location (e.g. light fixtures), at the same capacity or larger for the replacement (e.g. HVAC equipment), and are not coordinated to take into account the potential impacts of other retrofit strategies. A coordinated (systems) approach enables broader changes – e.g. installation of different system types or smaller capacity equipment – that yield larger energy savings. Examples of Interactive Building Systems retrofits include:
- Envelope retrofits enabling increased lighting savings
    - Daylight redirecting retrofits, enabling daylighting and dimming controls deeper into a building's floorplate
    - Facade solar control strategies that enable consistent daylighting (e.g. upper window designed for daylighting, with solar controls in lower window area)
- Envelope retrofits enabling smaller load or capacity HVAC systems, or enabling the retrofit of a new inherently low capacity HVAC system (e.g. radiant cooling)
    - Envelope insulation and/or glazing improvements

    - Cool roofs or cool walls
    - Exterior shading applications
- Lighting or plug load retrofits lowering internal heat gains, enabling smaller load or capacity cooling systems, or enabling a new inherently lower capacity cooling system to be installed (e.g. radiant cooling)
    - Light fixture and controls retrofits
    - Office equipment improvements
    - Process equipment improvements

3. Integrated Building Systems - *Two or more Building End Use Systems actively controlled together to produce collective behaviors or services, typically resulting in greater value than the performance of the Systems in isolation.*

A defining characteristic of Integrated Building Systems is active controls engagement across the End Use Systems, typically with a goal to provide more energy savings or greater services (such as peak demand reduction) than the system elements in isolation. Examples of Integrated Building Systems approaches include:

- Automated envelope retrofits (e.g. dynamic facades, shading) actively combined with HVAC system strategies
- Automated envelope retrofits (e.g. dynamic facades, shading) actively combined with lighting system strategies
- HVAC system strategies actively combined with domestic hot water system strategies
- Lighting system strategies actively combined with plug load system strategies

Other integrated system strategies include integration with Distributed Energy Resources systems technologies.

Background and Motivation

Systems thinking around energy efficiency in buildings is not new. Research efforts on the topic go back many years (Elliot et al. 2012). Nonetheless building retrofit projects still typically address one equipment piece (chiller) or type (light fixtures) at a time, in a component by component fashion. As increasingly efficient products meet technological and cost-effective limits, component-level savings may eventually only achieve marginal returns. With component-based retrofits pushing up against practical limits, additional improvements in operational efficiency will increasingly require more integrated systems-level approaches. According to an ASHRAE study on whole building retrofits for climate stabilization, "[m]ore than simply upgrading systems, we can analyze and optimize the coordinated energy savings benefits deduced from interactions between systems, such as daylighting systems, alternative mechanical layouts, envelope measures and other load reduction improvements" (Olgyay 2010).

The Systems Efficiency Initiative (SEI) of the Alliance to Save Energy contrasts an integrated systems approach with traditional prescriptive approaches to energy efficiency, which involve either a) individual equipment component upgrades and performance prescriptions or b) whole building performance requirements through codes and benchmarking. SEI describes building systems as the "combination of equipment, operations, controls, accessories, and means of interconnection that use energy to perform a specific function"; a systems approach considers the interactions of components within and among various building systems (e.g., heating and cooling systems, lighting systems, miscellaneous electric loads), as well as interactions among multiple buildings, and between the building and the electric grid (ASE 2016, 2017). ACEEE proposes the concept of *intelligent efficiency* which further connects the systems-based approach to building energy efficiency to the modern technologies that enable smart interactions among systems. Intelligent efficiency "optimizes the performance of systems overall – components, their relationships to one another, and their relationship to human operators," propelled by increasingly affordable and ubiquitous information and communication technologies (sensors and networks) that allow systems to react dynamically to conditions (Elliot et al. 2012).

Utility incentive programs have been an important market force in driving building retrofit projects for energy efficiency, reducing project costs and providing support to a broad customer base. However, as noted above, the traditional utility program model that focuses on component (or "widget")-based solutions with deemed rebates and energy savings per piece of equipment faces natural limitations in energy savings potential. Simplified, deemed incentive programs are appealing for their streamlined implementation (incentive dollars per widget to customer, energy savings per widget to regulators) but have tended not to emphasize interactions between building systems (e.g. lighting and facade elements, lighting and HVAC). Integrated systems approaches have been neglected, or left to more complicated "custom" programs that can include complex analysis and higher program administration and implementation costs that are only feasible for larger utilities and/or facilities. There is then still a large swath of the market that could benefit from integrated-systems incentive programs that are simplified and streamlined in the model of the deemed program but that are able to address multiple systems elements together.

Recognizing this opportunity, LBNL partnered with several utilities to develop and evaluate three different integrated systems retrofit packages that could potentially be deployed through incentive programs. The research effort culminated in a package of information, technology specifications, validated data, design and implementation guidance, and savings estimation methods. These resources are intended to support retrofit programs that are similar to the deemed model, but that tap into the deeper energy savings possible from integrated systems projects, without the complexity and cost associated with custom programs. This would reduce transaction costs for incentivizing integrated systems in utility programs. Results of the lab evaluations for the following three systems packages are detailed later in this study:

- Automated shading with lighting daylight dimming control
- Workstation specific lighting with daylight control
- Task/ambient lighting with plug-load occupancy controls

In this study, we compare the integrated systems savings for the three technology packages as measured from lab test periods to a widget-based alternative, where only one system or component is addressed, such as an LED retrofit to existing lighting system that does not include advanced sensors and controls (e.g. for daylighting) or other design changes (e.g. task/ambient strategy, or workstation - specific layout). All three systems that we studied involved lighting and the next section provides more detail on systems approaches for lighting.

Lighting Systems

Lighting retrofit projects in commercial buildings have traditionally focused on replacing individual components. Light fixtures are specified within prescribed equipment efficacy limits (minimum lumens per watt) and power density requirements set in building energy codes (maximum watts per square foot). Within these limits, the fixture power and light output are specified with the intent of achieving target illuminance levels. With traditional non-dimmable, on/off light sources like fluorescent lamps on static ballasts, equipment has often been over-specified to guarantee that minimum light levels at the task plane are met regardless of space configuration (in contrast to dimmable fixtures that are "tuned" to hit design illuminance targets). During new construction a lighting designer may be involved to specify and even model the selected lighting system in the building to ensure that it meets code requirements and design criteria such as average maintained illuminance, contrast ratios, etc. In a retrofit project, a lighting designer may or may not be involved, with the result that furniture layout and other interior design elements that affect office lighting environment (surface colors and reflectances, partition heights and orientations, locations relative to fixtures) may or may not influence fixture selection and layout. Similarly, façade elements such as windows, films, blinds and shades, all affecting the interior lighting environment, as well as building heat gain/loss, often are not considered or modified during a lighting retrofit. For controls, circuit-based scheduling may be implemented along with occupancy sensors and daylight sensors in different zones, per building code requirements. In summary, in the standard practice for lighting retrofits, these systems and elements are not integrated.

Integrated systems approaches to lighting include building design to allow optimal daylight penetration, glazing, light shelves and films to project daylight further into buildings, along with workstation specific lighting where fixtures are strategically located above work areas where illumination is needed, task lighting, integrated control of lighting and blinds, and interior design to maximize daylight and minimize glare and contrast. All the individual design and equipment elements are interactive parts of one system, including hardware - e.g. luminaires, sensors, control units, windows, skylights, and shading devices - and soft components including software and algorithms that implement schedules and operational behavior, networking, and interior design elements affecting lighting usage, including furniture, partition, luminaire arrangement and layout, and colors and textures or surfaces and user interfaces (ASE 2016).[2]

The premise of the systems-based lighting and controls retrofit packages studied by LBNL was to capture the larger benefits of integrated, intelligent lighting upgrades that include multiple systems (lighting fixtures, lighting design, sensors and controls, shading elements) working together. There is precedence in research and field demonstrations for this approach, with several documented successes. An often-cited project at the New York Times Building included simultaneous implementation of an advanced dimmable lighting system with daylight dimming and set point tuning, and automated roller shades that managed glare and visual comfort while providing natural light, along with an underfloor air distribution system for thermal comfort. The project resulted in 24% annual electricity savings, 51% heating energy savings and 22% peak load reduction, compared to an EnergyPlus model for the same space calibrated to meet ASHRAE 90.1 (Lee et al. 2013). An earlier project at the Empire State Building used advanced glazing to reduce heat gain, along with improved lighting and office equipment, reduced peak cooling load by one third and achieved 38% whole building energy savings. An important additional benefit and big cost saving from the integrated project was eliminating the need to up-size the building's chiller due to increasing cooling loads in the building from more densely utilized spaces, additional server room usage, and increased plug loads and occupants (Harrington and Carmichael 2009). A more recent real-world study from the Commercial Building Partnership (Regnier et al. 2017) found 83.7% energy savings potential building-wide for Kuykendall Hall in Hawaii, from an integrated systems retrofit compared to a baseline energy model of the existing building. The integrated system scenario included HVAC system changes, decreased lighting power density and daylight dimming, and improved thermal properties of glazing, shading system upgrade, and thermal mass increases for interior walls. The integrated systems savings compared to 12.5% and 32.7% energy savings, respectively, for standard and improved efficiency widget-based retrofit scenarios.

Building performance simulations and modeling have also underscored the benefits of integrated lighting systems retrofits (see, for example, Chan and Tzempelikos 2013). A study simulating control of dimmable lights and electrochromic windows to optimize daylight transmittance to improve daylight dimming, integrated with the HVAC system to optimize solar heat gains while maintaining illuminance set points (keeping windows in clearest transmittance for heating months and lowering transmittance in cooling months), found the potential to save 64% - 84% of perimeter zone lighting energy use. This translated to 26-34% lighting energy savings for the whole building (with perimeter zones around 40% of total floor area). HVAC energy savings were 4% to 43% depending on climate zone and window-to-wall ratio (Shen and Hong 2009).

---

[2] Standards organizations are getting beyond the widget-based mode for commercial lighting too. The NEMA ASC 137 Lighting Systems Committee, formed in 2014, is developing standards and recommendations that treat lighting sources, services, and methods as a system rather than as components. The committee is addressing human health and comfort, security, energy usage and daylighting in its working groups, including the interconnection of the components for control and monitoring. https://www.nema.org/Technical/Pages/ANSI-C137-Lighting-Systems-Committee.aspx

The following sections describe the three integrated system packages developed, tested and validated for three sets of utilities across the U.S. utilizing the reference baseline for each utility as dictated by their regulatory requirements (e.g. energy code, or existing building conditions). Following these sections, these test results are normalized to a common baseline condition for comparison to the component based retrofit.

Automated Shades with Daylight Dimming Controls System

System Description

ComEd considered several systems and selected automated shading integrated with dimmable lighting. The key features of this system are:

- Automated Shading: The system consists of motorized roller shades, control system and sensors. The functional requirement is for the shades to control glare while maximizing daylight availability, based on use characteristics and user preferences. Optionally, in unoccupied perimeter areas, the shades may be deployed according to the prevailing HVAC mode of operation (e.g. deployed in cooling mode, retracted in heating mode).
- Lighting Controls: The lighting control is in response to occupancy and illuminance levels. Occupancy-driven control switches lights on/off or dim to minimum background levels. Illuminance-driven control dims lights continuously based on daylight availability.

ComEd identified two target market segments for this system package: offices and schools. For offices, the focus was on medium and large size buildings. The package targets both retrofit and new construction. The baseline was existing conditions (not minimum code requirements).

System Potential for Energy Savings

Daylight-based dimming is a proven but underutilized energy-efficiency technology, particularly within the context of utility programs. An LBNL meta-analysis study (Williams et al. 2011) showed that daylighting alone yielded an average lighting energy savings of 27% (N=18 projects) for offices and 29% (N=7 projects) for education. A post-occupancy study of the New York Times headquarters building (Lee et al. 2013) showed 38% lighting energy savings compared to code, with a simple payback of 4.1 years.

A key driver of savings in this system is automated control of shading, compared to manual operation of blinds. Blinds, when down, can reduce solar gain by 50%, and daylight by 80%, according to Newsham (1994). Reduced daylight availability due to blinds usage, compared to a building with no blinds, increased lighting energy by 66%. A study in Japan found that blind occlusion was proportional to sunlight penetration depth if a threshold sunlight intensity was reached (Inoue 1988). Some studies have tried to examine blinds' opening and closing relationship to illuminance and luminance, with limited data indicating manual blinds closing triggered at 40,000 - 50,000 lux in one study and another finding a 50% likelihood of blind closure at 4,466 cd/m2 (Van Den Wymelenberg 2012). Generally, blinds usage clearly affects the quantity and distribution of daylight in a building. How manual blinds are used will affect how daylight dimming systems operate. Van Den Wymelenberg (2012) provides a comprehensive look at research on occupant interactions with window blinds. Consistently, orientation and sky condition have been found to be important factors in blind occlusion. The strongest observed effect has been on the low occlusion rates for north facades, typically 15 - 25%, but high occlusion rates for south facades at 40% - 70%, across multiple climate zones. This follows logically for the northern hemisphere buildings studied, where direct sun is incident on the south facade and must be managed for comfort. The lighting energy benefit therefore offered by automated shading systems that control for visual comfort while maximizing daylight availability is to increase daylight dimming opportunities relative to manual blinds that may often block useful daylight.

LBNL commissioned a market analysis to estimate the savings in the two market segments. The total technical potential for these segments was 519-633 GWh of savings. The Total Resource Cost (TRC) criterion for the utility service territory was 0.25-0.28 for a retrofit scenario and 0.44-0.53 for a Replace on Burnout (ROB) scenario[3]. Using these TRC criteria, this system is cost-effective only in the incremental system costs analysis (ROB scenario). This is primarily due to the low avoided energy cost rates in Illinois, which are about $0.04/kWh. However, from a customer perspective these systems are life-cycle cost effective with the average rates of about $0.10/kWh.

System Testing Results

Test Description

The automated shading integrated with lighting was tested at FLEXLAB®, LBNL's building technologies test facility (FLEXLAB.lbl.gov). The main objectives of the testing for this system were to: 1) analyze lighting and HVAC energy savings from automated shading integrated with lighting controls, for Chicago climate conditions; and 2) evaluate visual comfort parameters. The test case (i.e. automated shading integrated with lighting controls) and the baseline case (i.e. manually operated venetian blinds and no daylight-based dimming) were tested at the same time under identical conditions using the two cells of the FLEXLAB rotating testbed. Figures 1,2 and 3 show the floor plan, external view, and internal views respectively of the rotating testbed. Each test cell is approximately 20' wide and 30' deep.

---

[3] A system is normally considered cost-effective if the TRC ratio is greater than or equal to 1.0 but a utility may offer a program to "jump start" market adoption with a goal of transforming how integrated systems are marketed and priced, as in the case of the utility's TRC criteria listed here for determining the economic potential of systems. (DNV GL / KEMA, Inc., 2015)

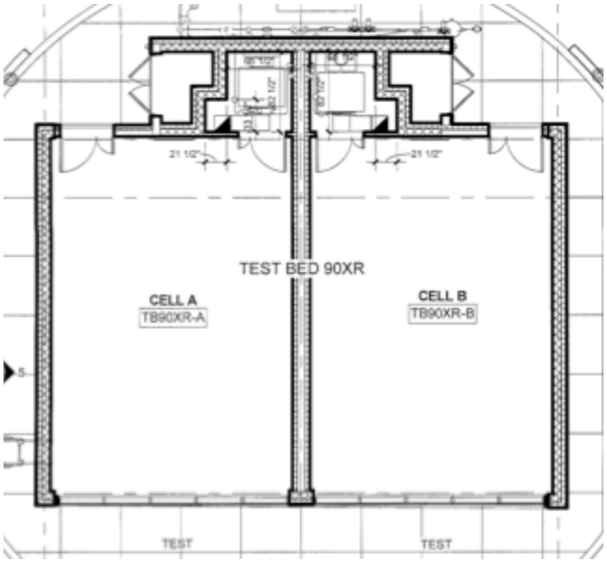


Figure 1. Floor plan of the FLEXLAB rotating testbed showing two test cells used for the test case (Cell B) and baseline case (cell A).

Figure 2. External view of the FLEXLAB rotating testbed

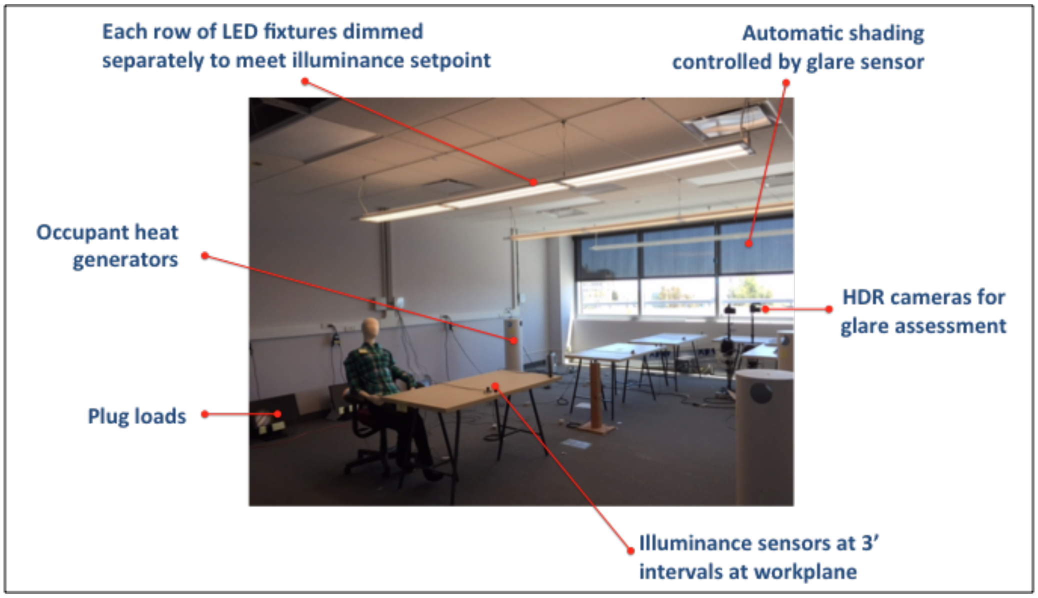


Figure 3. Internal view of FLEXLAB test cell set up for automated shading and daylighting.

Testing was conducted in two stages: the first three-month period was from May 9 to August 10, 2016; the second was from October 3, 2016 to January 4, 2017. The following four parameters were varied to evaluate their impact on the results. A total of 16 different configurations (representing various combinations of these parameters) were tested. Each configuration was tested repeatedly for short periods of several days across the 6 month testing period.

- *Orientation*: south and west. This was accomplished by rotating the testbed.
- *Window-to-wall ratio*: 0.4 (default) and 0.3. The smaller WWR was accomplished by placing foamcore panels in the window.
- *Daylight-dimming zone*: Three depths were tested. A 10' zone that would represent a smaller single occupant perimeter closed office; a 15' zone that would represent a larger multi-occupant perimeter office; and a 25' zone that would represent an open office extending to the perimeter. Moveable walls were used to change the zone size.
- *Lighting type:* Two Lighting types were tested: LED (default) and T-8. Both lighting types were pendant mounted, with three rows located parallel to the window wall. The spacing between fixtures was 8 feet on center. Light levels were tuned to meet 500 lux (~50 fc) workplane illuminance. The lights were turned off during unoccupied hours (7pm to 7am). For this test, which is designed to be broadly applicable, the dimming controls were set to represent a 'standard' application without aggressive dimming strategies. For the 25' zone, the default control setting only dimmed the first and second row of lights from the window wall. LBNL also tested a more aggressive control setting which also dimmed the third row of lights.

In order to obtain an assessment of HVAC loads in Chicago climate, the internal temperature setpoints were adjusted in real time to match the indoor-outdoor temperature difference in Chicago (solar heat gains for the two climates were found to be similar in terms of annual average). Two visual environment parameters evaluated: workplane illuminance using a row of illuminance sensors at 3' increments from the window; and daylight glare probability (DGP) using two high dynamic range (HDR) cameras, with views parallel and perpendicular to the window plane.

A complete description of the test conditions and test plan is available in the program manual developed for this system on the project's website (cbs.lbl.gov/beyond-widgets-for-utilities).

Test results

First, we analyzed lighting energy savings for each configuration. For example, Figures 4 and 5 show the savings percentage for each hour (blue), day (green) and multi-day period (red) for the south and west orientation for the basic configuration. Table 6 provides a summary of the savings for each configuration.

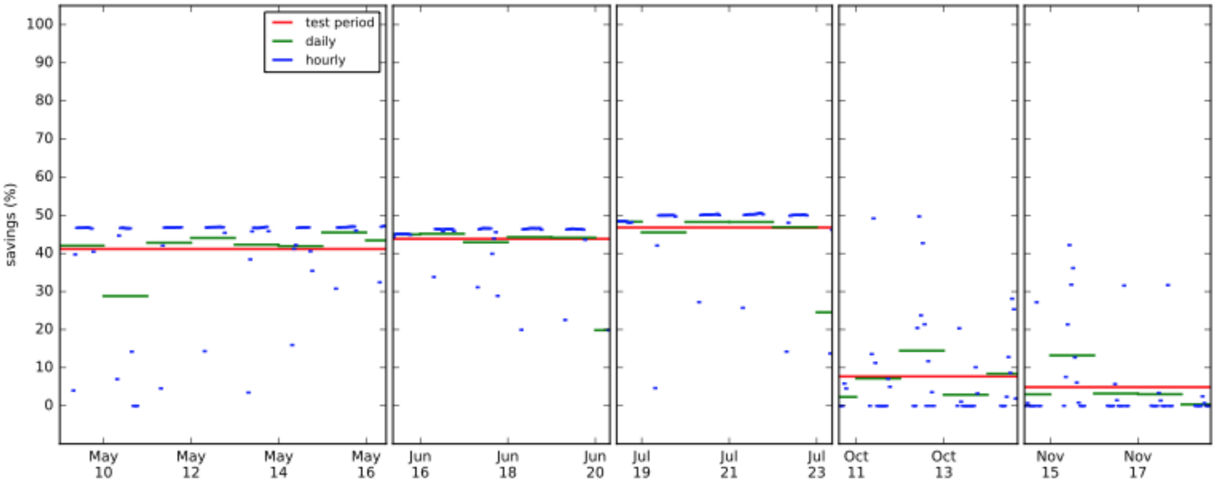


Figure 4. Lighting energy savings for configuration 1S (south, 25' daylight zone, 0.4 WWR)

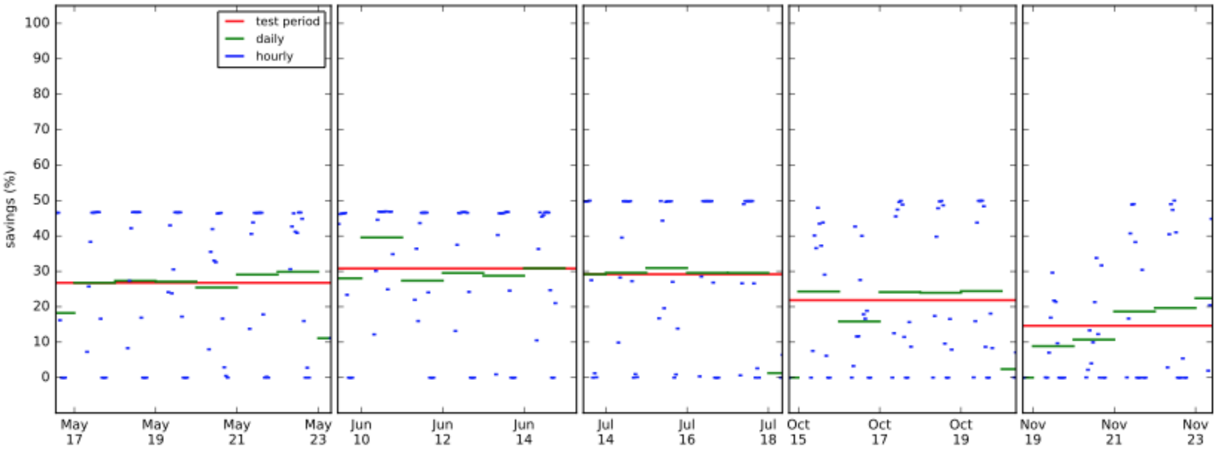


Figure 5. Lighting energy savings for configuration 1W (west, 25' daylight zone, 0.4 WWR)

Annualized lighting savings

Next, test period lighting savings were extrapolated to annual savings using regression models of the test period data. We analyzed the relationship between lighting savings and global horizontal illuminance, global horizontal radiation, vertical illuminance, solar azimuth and solar altitude. We also explored the impact of using different time steps – 5 minutes, 10 minutes, 60 minutes, and 24 hours – for the analysis. We explored various forms for the regression equation. The regression model which provided the best fit computes lighting savings on any given day as a function of solar altitude and horizontal radiation. Details of the model are documented in the systems program manual (ref).

We then calculated annual savings by calculating savings for each day of the year driving the regression equation with TMY (Typical Meteorological Year) data for the dependent variables for each day.

Figure 6 shows the daily and annual lighting savings for Chicago for configurations 1S and 1W respectively. The figures also show the savings range for the 95% confidence level.

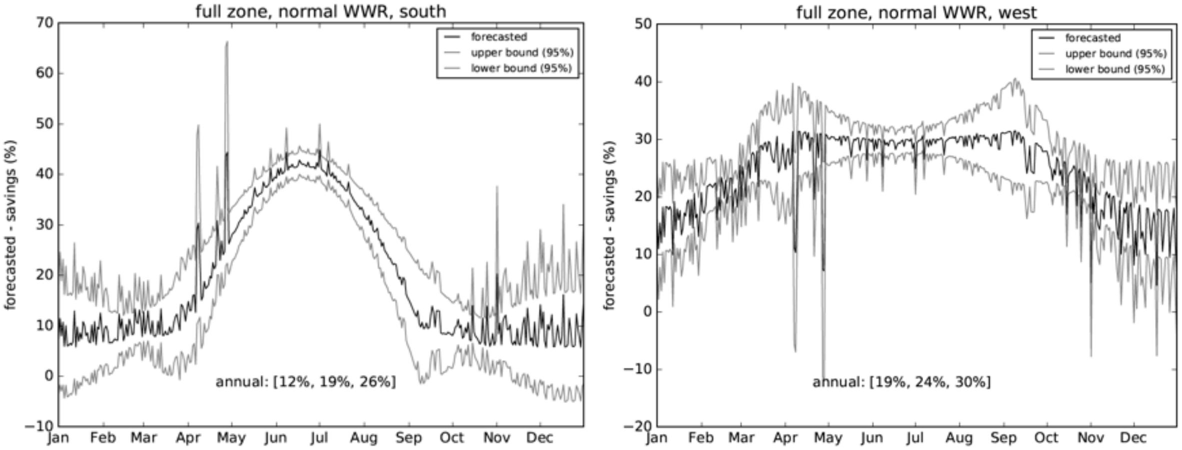


Figure 6. Annual lighting savings for Chicago for south (left) and west (right) configurations

South orientation shows a mean of 19% annual lighting energy savings, with a range of 12-26% (at 95% confidence). West orientation shows a mean of 24% annual lighting savings, with a range of 19-30% (at 95% confidence). Savings can vary widely over the course of the year, due to change in sun angles and associated deployment of shades. In summer, savings are higher for south facing configurations than west-facing configurations all other parameters being equal. Analysis of the shade operation and solar conditions indicate that the shades are deployed for longer periods in the west facing orientation in the afternoons to minimize direct solar radiation, resulting in the lights being turned on for longer periods. Also, the west orientation has less dimming in the morning. In winter, savings in the south facing configurations are generally very low because low sun angles cause the shades to be deployed during most daylight hours. Savings for the west orientation in winter are not as low as the south because there is no direct sun on the façade during the morning hours, allowing shades to be retracted during those hours.

It is important to reiterate that these savings are exclusively attributable to automated shading and dimming and will be additional to savings from lighting upgrades. In particular, these savings do not include the savings from tuning. It should also be noted that more aggressive dimming strategies would result in higher savings. As noted earlier, we intentionally used 'standard practice' settings for the shades and dimming, in order to reflect broad deployment in the context of a utility program.

Whole building savings estimates

Finally, we estimated whole building savings for four building types using the DOE reference building EnergyPlus simulation models (REF) in combination with the FLEXLAB lighting savings results, adjusted to account for savings from institutional tuning. Table 1 shows the whole building savings estimates for the reference buildings. Whole building (WB) savings estimates include lighting energy savings as well as HVAC energy savings (or penalties). It is difficult to generalize WB savings because they are highly dependent on two key building features: impacted area (i.e. the % of total floor area that is impacted by shading and dimming) and HVAC system type. Buildings with smaller impacted areas will naturally have smaller WB savings all other things being equal. HVAC energy savings can vary quite differently for different HVAC system types and efficiencies for the same reduction in thermal load.

Table 1. Savings for automated shading from lighting dimming and tuning

Reference Building	**Retrofit Zone Savings**		**Whole Building Annual Energy Savings**		
	Lighting Annual Energy (%)	**Lighting EUI Savings (kWh/sqft/yr)**	**Lighting Saving %**	**Total Elec Saving %**	**Site Energy Saving %**
Large Office	36%	1.13	16%	5.0%	2.6%
Medium Office	36%	1.13	22%	4.5%	3.5%
Primary School	30%	1.57	20%	9.0%	4.8%
Secondary School	30%	1.56	14%	6.2%	2.7%

Visual comfort analysis

The visual comfort analysis showed that the system maintained workplane illuminance and daylight glare probability at satisfactory levels throughout the test period. Detailed results are documented in the system program manual (Mathew et al. 2017); we present a few representative results below. Figure

7 shows the show the range of illuminance at different depths from the window during the measurement period, for configuration 1S. As expected, sensors closer to the window show higher illuminance values. The plot shows that the test system maintained illuminance at or above 500 lux throughout the measurement period, as intended.

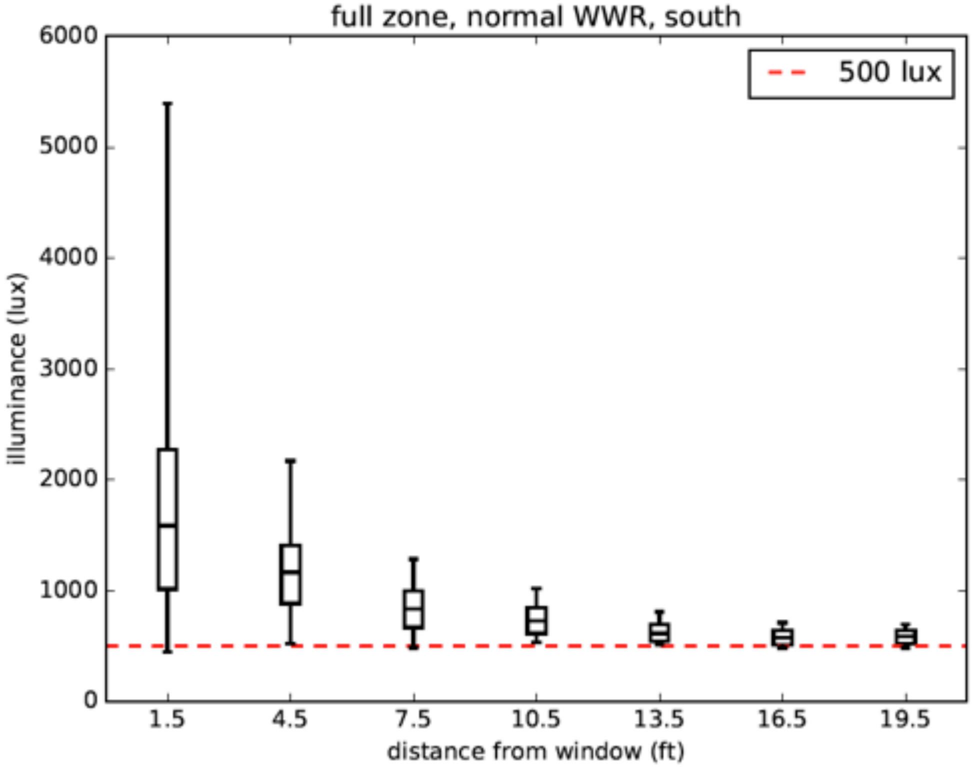


Figure 7. Illuminance ranges for configuration 1S. Box plot markers are for 5th, 25th, 50th, 75th and 95th percentiles.

Figure 8 shows the DGP for configuration 1S. The data show that the test system (cell B) maintained daylight glare probability (DGP) within acceptable levels and did so more effectively than the manual blinds left at a fixed position.[4] In the test cell, for the view parallel to the window plane, DGP was imperceptible almost all the time and for the view perpendicular to the window plane, DGP was occasionally in the perceptible range and very rarely in the disturbing or intolerable range. For the baseline case (cell A) there were significant periods where DGP was in the disturbing or intolerable

---

[4] It should be noted that occupant overrides could affect automated blind effects on daylighting. For example, tenants in Class A real estate may pay a premium for views and may not want those views obstructed. However, one of primary features of the technology is to automatically lower blinds to control for glare, with the premise being to prioritize occupant comfort during glare conditions. The analysis here presumes occupant comfort, in terms of glare mitigation, would take priority over view through the window and occupants would not override this control.

range because the venetian blinds were in a fixed horizontal position that sometimes allowed for direct sunlight in the field of view at lower sun angles.

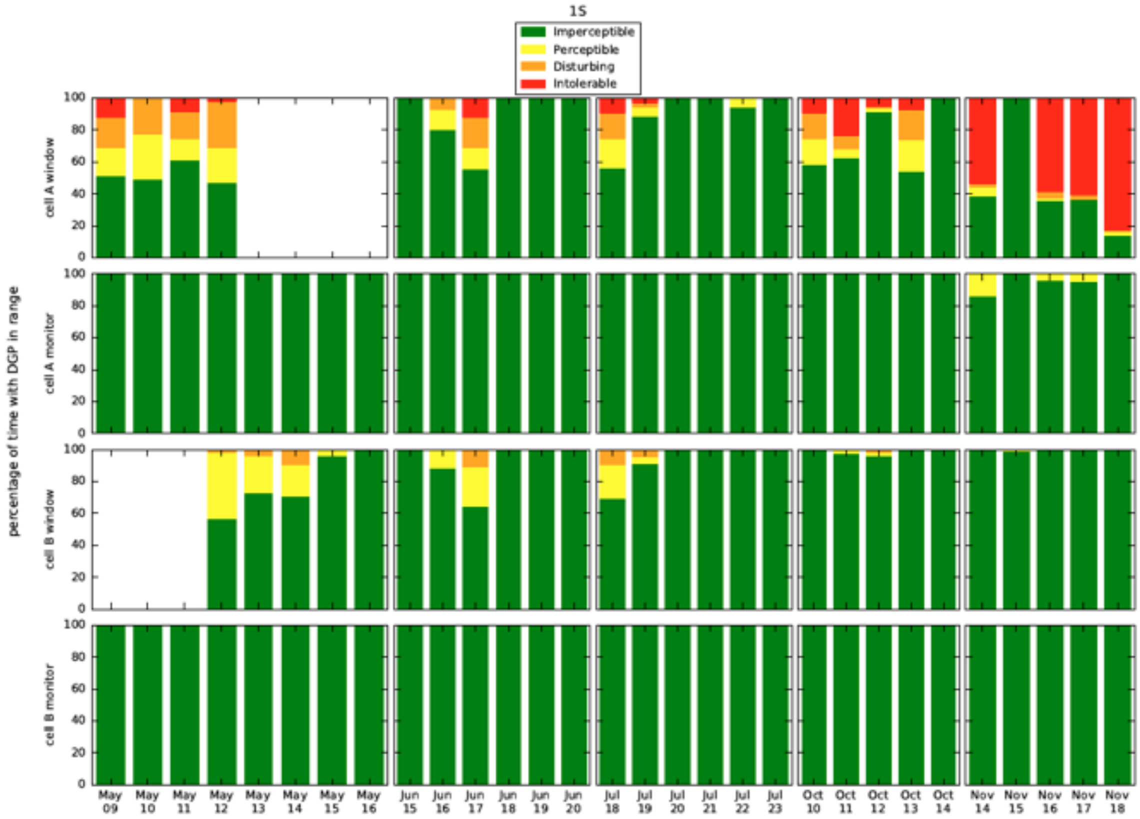


Figure 8. DGP ranges for configuration 1S. Cell A is baseline cell. Cell B is test cell. Window refers to camera facing window. Monitor refers to camera facing parallel to window plane.

Workstation Specific Lighting System with Daylight Dimming Control System

System Description

This project worked with Xcel Energy in Colorado and Minnesota to select an integrated system and develop a streamlined approach to its deployment for small and large commercial offices. The system that was selected consisted of a workstation specific lighting system with daylight dimming controls, applied as a retrofit in commercial office spaces.

This integrated workstation specific lighting system contrasts with a component based lighting upgrade for this application, which is considered to be an LED light fixture replacement, with light fixture quantity and locations congruent with a standard zonal approach to lighting. In this condition, there would be generally speaking either a higher quantity of light fixtures in the space, or more light fixture linear footage, in either case resulting in a higher Lighting Power Density (LPD) than in the workstation specific case. Such lighting systems are specified to deliver the same minimum light levels throughout the space (e.g. 500 lux), rather than delivering that level just to the workplane (where it is needed).

Xcel also had a desire to incorporate light fixture replacement in their integrated system package, and as a result annual energy lighting savings are expected to be higher. The key technology features of this integrated system are:

- Occupant/Workstation Specific Lighting — Revising lighting system layout during retrofit to provide one individual light fixture per occupant workstation. Lighting is designed to provide a reasonable light output at the occupant's workplane (i.e. 300 or 500 lux). Light fixtures were specified as LED, and were tested as pendant fixtures with direct/indirect light distribution.
- Daylight Dimming Lighting Controls— Enterprise-level or local, intelligent granular workstation specific control through local photosensors tied to the lighting control system. Each light fixture has its own local photosensor and independent dimming ability, in contrast to the typical zonal lighting approach which groups light fixtures together and controls from one common photosensor. Lighting control responds to available daylight illuminance levels. Illuminance--driven control will dim lights continuously based on daylight availability, down to a zero lux light output at full dimming.

For most existing building open plan office configurations, especially those where spaces are reconfigured over time due to tenant changes, light fixtures are not arranged directly above each workstation or cubicle. Intentional alignment of each workstation with a designated light source for the workstation occupant is a "leading-edge" practice requiring precise design and arrangement of fixtures and desks, which is often not practical to implement in existing buildings without a major renovation (Wen and Agogino 2011).

The applied system was tuned to provide the light output levels indicated above at the work plane, but also to dim to a zero lux light output. This tuning effort is important to achieve the overall energy savings demonstrated. For retrofit applications, this system was tested against a baseline that consisted of 3-lamp T8 2x4 recessed troffers.

System Potential for Energy Savings

Substantial energy savings are possible with a high-resolution sensor network combined with workstation specific LED lighting in open-plan offices. LED packages with inherent dimmability have enabled sensor co-location at the fixture, and with declining prices for sensor and networking technology, real-time, high-resolution feedback from all fixtures and sensors is increasingly viable (Dikel et al. 2018). Compared to using a single sensor for an entire daylighting zone, localized daylight harvesting to tune individual lights to meet task plane illuminance target has been found to deliver 35% additional energy savings and improved delivery of setpoint levels throughout a space. In this study, multiple small LED spotlights were dedicated to each workstation, controlled to provide 400 lux at the desk, achieving 79% energy savings compared to a code baseline with this lighting model.

Even a decade ago, prior to the proliferation of quality LED fixtures for office lighting, workstation - specific lighting layouts with fluorescent fixtures were found to reduce lighting power density necessary to provide appropriate illumination. A field installation of workstation specific direct/indirect 2-lamp fluorescent in a deep open-plan office to replace conventional recessed fluorescent 2-lamp troffers was able to cut lighting power density by around 42% (Anka, et a. 2007). When fixture-based daylight sensing and dimming was added, the energy savings increased to 54% compared to the conventional baseline (Anka, et al. 2007, p.19). Adding fixture-based occupancy sensing and daylight dimming increased savings to 70% for the workstation-specific scenario (Galasiu et al. 2007).

More recent studies indicated a potential lighting annual energy savings of 28 - 63% for workstation specific lighting systems (Wei et al. 2012), with an average of 47% (Robinson and Regnier 2015), due to reduced fixture LPD and controls only, not including a full fixture replacement from a condition such as T8 to LED.

A study deploying workstation-specific dimming controls even for a lighting layout that was not workstation specific (desks were not completely aligned under fixtures in a one-to-one relationship), found that implementing dynamic tuning of overhead lights to deliver the light level setpoint at each desk (350 lux, including daylight sensing) could save over 60% lighting energy (Wen and Agogino 2011).

System Testing Results

Test Description

The workstation specific LED lighting system with daylight dimming controls was tested at FLEXLAB. FLEXLAB testing provided savings data based on controlled side-by-side testing compared to the utility baseline over a range of seasonal and test conditions. FLEXLAB testing covered various configurations of lighting system types (LED pendant and troffer), light level output (300 lux and 500 lux) and shading configurations (no shades, and shades mounted and positioned at various seasonally-determined angles).

The major objectives of the FLEXLAB testing for this system were to:

- Analyze the energy savings impact of the workstation specific lighting system with daylight dimming controls as compared to the base case condition.
- Evaluate the visual comfort and illuminance provided in the workplane and surrounding areas of the workstation specific lighting system with daylight dimming controls as compared to the base case condition.

The test case (i.e., workstations specific LED lighting fixtures, sensors and daylight dimming controls, and manually operated venetian blinds) and the base case (i.e., T8 lighting with manually operated venetian blinds, recessed fluorescent troffers and no daylight-based dimming) were tested at the same time under identical conditions using the two FLEXLAB testbed cells. Figure 9 shows the external view of the testbed. Each test cell is approximately 20’ wide and 30’ deep (see again Figure 2).

Figure 9: FLEXLAB Test Cells, Proposed (Cell A) & Basecase (Cell B).

A complete description of the test conditions and test plan is available in the program manual developed for this system on the project’s website (cbs.lbl.gov/beyond-widgets-for-utilities).

Table 2. FLEXLAB test parameters

Feature	**Base Case Description**	**Test Case Description**
Lighting Fixtures	(6) 2'x4', 3-lamp T8 fluorescent, recessed, parabolic troffers	(6) 4' pendant-mounted, LED direct-indirect luminaires with integral occupancy/photosensors
Light Fixture Layout	8' x 8' spacing between fixture center lines (see Figure 10)	(6) 4' workstation-specific fixtures centered above the workstation task areas.
Light Output Level	[Fixed output fixtures, not tunable]	Light levels were tuned to meet: A) ~ 300 lux min. (~30 fc) B) ~ 500 lux min. (~50 fc) only at the workplane, with lower light levels in peripheral areas being acceptable, within recommended practice for ingress/egress lighting .
Lighting Controls	Scheduled on/off control	Scheduled on/off control; as well as dimming all lights throughout day based on available daylight measured by on-board photosensors.
Lighting Schedule	The lights were turned off during unoccupied hours (7pm to 7am).	The lights were turned off during unoccupied hours (7pm to 7am).
Shading	Venetian blinds were in the deployed horizontal position for all test configurations. Blade angle was adjusted seasonally to a direct-sun blocking angle.	Venetian blinds were in the deployed horizontal position for all test configurations. Blade angle was adjusted seasonally to a direct-sun blocking angle.

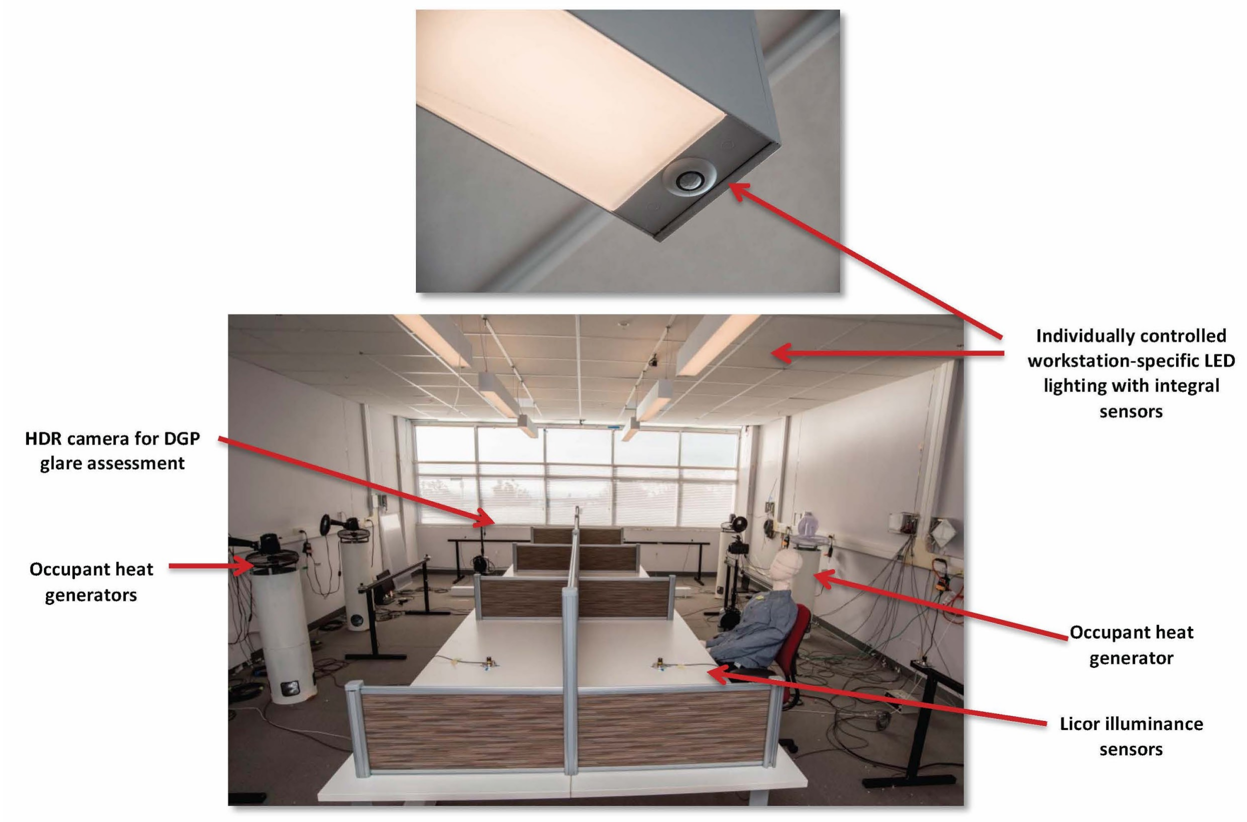


Figure 10: FLEXLAB Internal Test Cell View with Key Features

Test Results

The lighting energy savings for workstation specific lighting were substantial, varying depending upon available daylight and seasonally, with energy savings FLEXLAB test results ranging from 71-96% daily over the occupied hours in the fall and winter periods. Summer periods were projected at higher savings, in the range of 86 - 96%. Overall, equivalent annual lighting energy savings for the FLEXLAB testing for 500 lux minimum output conditions translated into a 94% annual energy savings for this system [as applied to TMY conditions in Denver]. When applied to the DOE reference buildings however, this annual energy savings drops to 82% due to lighting usage during unoccupied hours which predominantly do not have daylight harvesting opportunities. Equivalent whole building annual energy savings using the DOE reference buildings are illustrated in Table 3.

Table 3. Workstation Specific Lighting System Whole Building Savings (500lux Case)

Reference Building	**Retrofit Zone Savings**		**Whole Building Site Energy Savings %**
	Lighting Annual Energy Savings %	Lighting EUI Savings (kWh/sqft/yr)	
Large Office	82%	3.57	6-15%
Medium Office	82%	3.66	13%

The whole building energy savings range for the large commercial offices is presented for the cases with and without an onsite data center (server room) present in the reference model.

Visual comfort was measured in these tests through the use of a grid of Licor photosensors located throughout the test cells, and through the use of two High Dynamic Range (HDR) cameras set up in each cell. Photosensor data was captured to document light levels at the work surfaces and in egress pathways, and HDR cameras provided the imagery of key perspectives in the space to capture data for analysis related to Discomfort Glare Probability (DGP).

Figure 11 provides representative, detailed images and measurements from the HDR cameras of the DGP for the reference basecase test cell (X1B) and proposed test cell (X1A) for workstation-specific lighting combined with the Film 2 with the mini-blinds at partial height.

In summary, in all cases, it was seen that the illuminance levels throughout each test case met or exceeded the minimum illuminance levels as set by IES for egress purposes (i.e. 100 lux), or for the minimum levels desired at the workplane (i.e. 300 or 500 lux). As expected, increased light levels occur closer to the window, and at significant levels that may cause glare issues at times. Figure 12 provides a representative result of the illuminance distribution for a given test configuration. The data shown are for photosensor readings taken from set distances from the window.

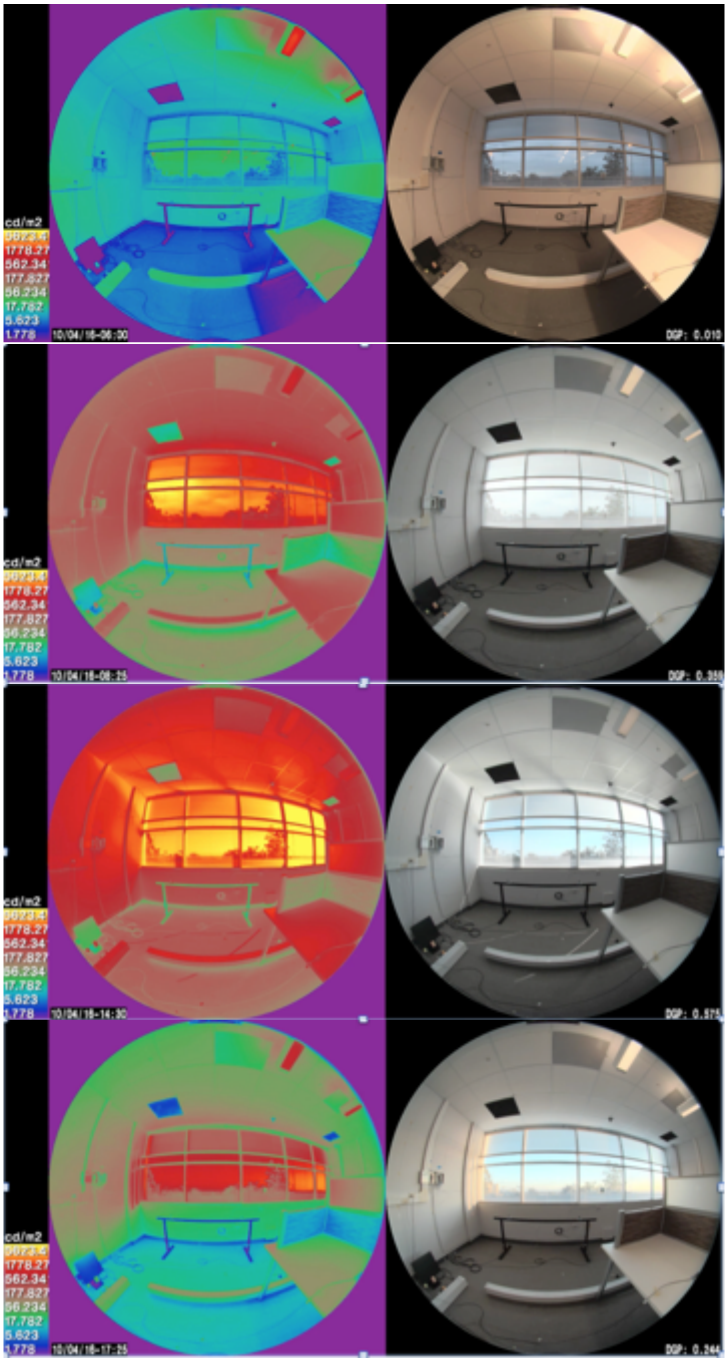


Figure 11. Representative HDR Camera Images for Film 2 plus Workstation-Specific Lighting Showing Discomfort Glare Probability throughout the Day; Blinds Partial Height (10/04/16)

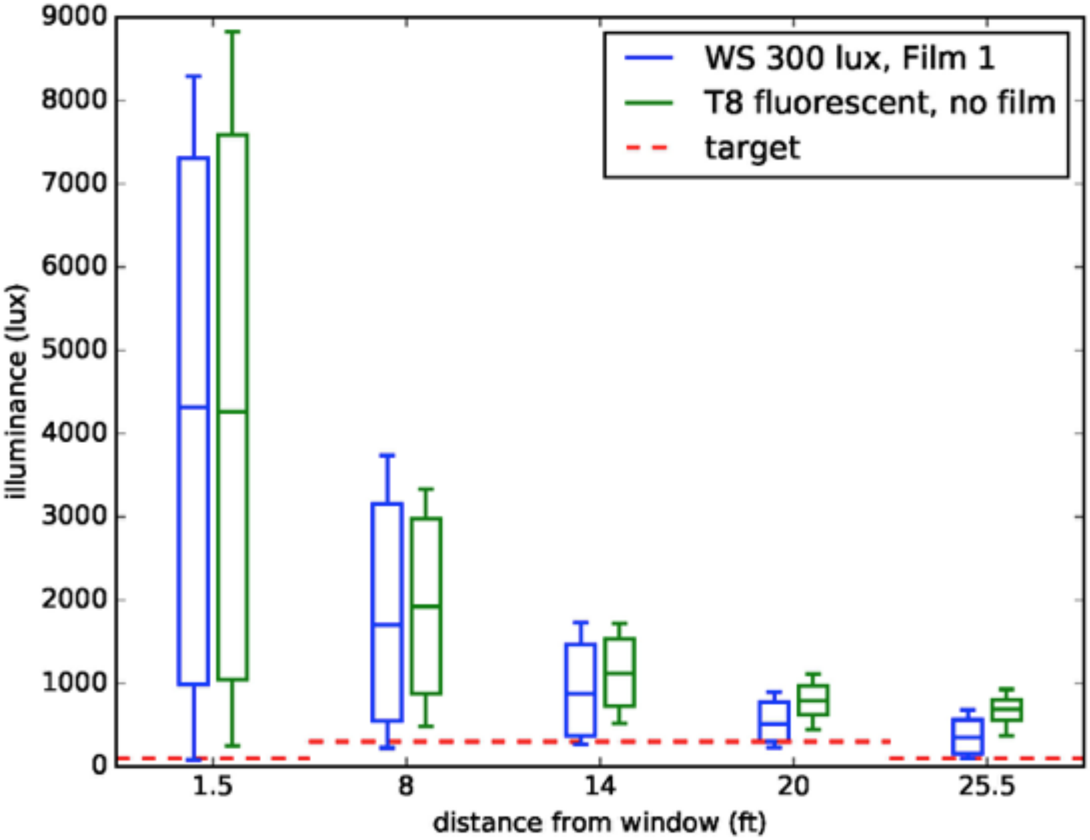


Figure 12. Workstation Specific Lighting System, Illuminance Distribution, 300lux minimum workplane case with Film 1.

Task/Ambient Lighting with Plug Load Occupancy Controls System

System Description

Following discussions with California Public Owned Utilities (CA POU) representatives, and taking into consideration results of their market analysis, the technology package selected consists of a task / ambient lighting retrofit combined with occupancy-based plug load control. This package was selected because of its applicability to all utilities regardless of location or building size, and its flexibility according to a variety of building conditions and existing overhead lighting fixture types.

The design and operating principle of this system is that by providing desktop task lighting, it is possible to reduce the lighting output from (and therefore the electrical power to) overhead light fixtures. To supplement light levels in the work area, office occupants can place their desktop light in the appropriate location for their work tasks. Simultaneously, all non-critical desktop equipment (including the desktop lighting) will be operated via occupancy-based controls, and so will operate on an as-needed basis. As such, night time loads for occupancy-controlled equipment will be zero, as power will cease to be provided following a prescribed period of office / cubicle vacancy (known as timeout). For system testing, overhead lighting output was reduced to achieve a measurement of approximately 200 lux at the floor level. [5]

Two distinct technology packages – Technology Package 1 (TP1) and Technology Package 2 (TP2) - were specified for testing according to two separate market needs – a 'basic', minimally intrusive system that would not trigger California's Title 24 Energy Code and its corresponding prescriptive feature requirements, and an 'advanced' system that requires electrical work and therefore necessitates compliance with the 2016 version of Title 24 (latest version as of publication).

Energy savings were assessed against the existing building condition, represented by DOE reference models for California in EnergyPlus. Test results are presented with comparisons of system energy performance against these same baselines. The test methodology for TP2 is identical to that for TP1.

System Potential for Energy Savings

The literature indicates substantial energy savings are available from overhead lighting retrofits (Wei et al. 2015; Shackelford et al. 2015) as a result of reduction in lighting power density (via a change in light source from fluorescent to LED or implementation of controls), further tuning of fixtures to meet a target illuminance and occupancy-based operation. Daylight dimming in perimeter zones offers further potential gains, although results of the daylight dimming strategy are not included in the results presented here. For plug load control, results across sites are more varied (Metzger et al. 2012) and

---

[5] IES specifications for corridors and egress, assuming over 65 age group

comprise observations on performance of controlled plug strips, a different technology to that proposed for technologies packages presented here.

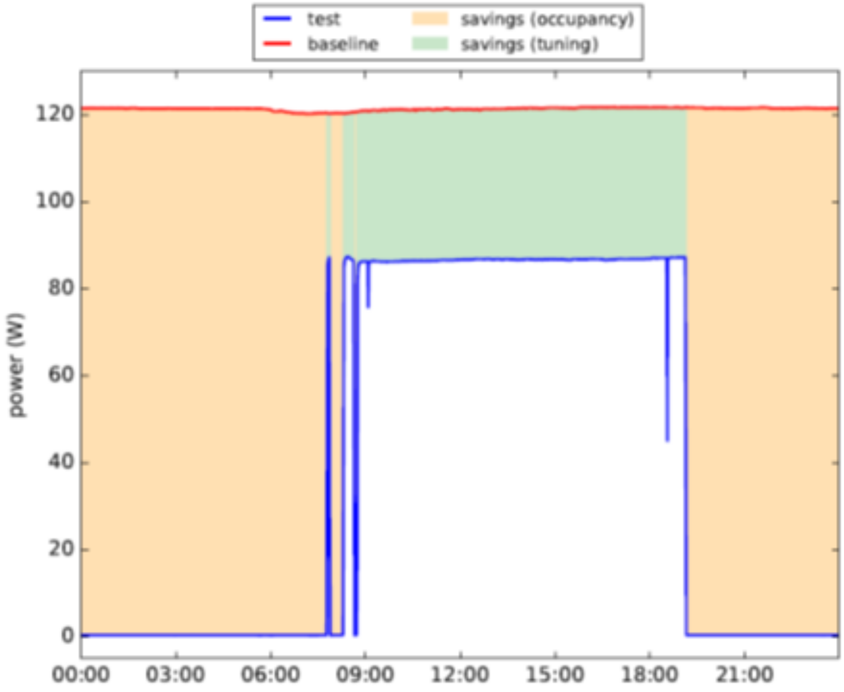


Figure 13: Overhead Lighting Energy Savings by Strategy

Energy performance of the proposed systems packages and cost effectiveness of the proposed systems was estimated on the basis of energy performance of the separate system elements (lighting and plug loads respectively) seen in field testing, and evaluating potential energy savings and energy cost savings for relevant DOE Reference Building models for California. From those results, LBNL derived some estimates for simple payback, to confirm that the systems as specified were worth proceeding with in principle.

Table 4: Original Estimates for Task Ambient Lighting and Plug Load Control Energy Savings

Technology Package	Reference building	Whole Building Lighting Svg %	Whole Building Plug Load Svg %	Whole Building Total Elec Svg %	Whole Building Site Energy Svg %
TP1 - Basic	Small Office	50%	22%	21%	17%
	Large Office	46%	16%	14%	12%
TP2 - Advanced	Small Office	84%	31%	34%	28%
	Large Office	78%	23%	22%	20%

The Technology Package 1 (TP1) and Technology Package 2 (TP2) systems were intended to satisfy two distinct California market needs.

TP1 was specified such that the plug-and-play nature of the overhead lighting retrofit does not trigger Title 24 Code. As such the intention is that energy savings claimed for the incentive be based on a comparison with an existing building baseline condition. Given the range of possible existing building conditions that relate to vintage size, climate zone etc., the baseline used here was defined as the average small and large office energy consumption for California-based DOE reference models for small and large commercial offices respectively.

A recent study found that task lighting control combined with dimmable general lighting was able to reduce lighting energy usage 59%. The lighting strategy involved achieving a task plane illuminance setpoint of 300 lux by a combination of a lower general lighting level, providing around 150 lux at the floor plan, made up with task lights (5W/desk) as necessary throughout the day to reach 300 lux at the desk (Xu et al. 2017).

For the purposes of deriving a potential energy savings estimate, the baseline building type for our energy performance estimates are the DOE reference buildings.

Based on published results of field testing, LBNL applied the sum total energy savings from the two discreet subsystems – a) lighting and b) plug load control - that make up the proposed system, to the model baseline to provide an estimate for overall system savings and energy savings at the whole building level. These field test results comprise work completed under a previous project conducted for the U.S. Department of Defenses' ESTCP program and the U.S. General Services Administration's Green Proving Ground program, and were thought to be conservative assumptions given the deep dimming of the overhead lighting to ambient levels.

System Testing Results

Test Description

Results reflect comparison of installed test conditions for each of the technology packages compared with the energy savings at end-use, system level, and whole building savings for the DOE Reference Building baseline for small and large commercial office respectively.

Each system was tested at pilot scale prior to rolling out the full-scale test in FLEXLAB's occupied testbed. This allowed a period of familiarization with the software (graphic user interface, programming, process of controls activation and commissioning techniques) and testing of hardware and installation techniques.

The period for testing each TP option was 2 months, doing 'before-and-after' analysis (baseline condition is measured, followed installation and measurement of the multiple test conditions). The 2-

month period reflected the full schedule of testing for the various TP options and the degree of baselining required in order to provide confidence in the results. It is worth noting that the shorter 2 month period is considered an appropriate sample considering there are no seasonal variations affecting potential energy performance, since daylight dimming controls are not included.

When compared to the alternative of side-by-side testing (running test and baseline conditions concurrently) this proved to be important as it means that the same occupant cohort is assessed in test and baseline cases, and therefore user behavior can be assumed to be relatively constant. It also supports a greater sample size for both test and baseline conditions and so provides greater confidence in the results.

On the plug load side, it was necessary to normalize the data for occupancy for a fair comparison. This normalization process necessarily led to a reduced sample cubicle size (versus the maximum available within the baseline and test) due to observations of inconsistent occupancy and to some extent, inexplicable load differences within individual cubicles between baseline and test or inexplicable load deviations within the test period.

Figure 14 illustrates the FLEXLAB test bed space, indicating the locations of cubicles (walls annotated on drawing, shaded blue areas indicate some of the work area locations) relative to the baseline condition pendant lighting fixtures. The testbed is bounded on the two long sides by private offices and office cubicles that were not included in the test and as such does not fall within the 'traditional' definition of the daylit zone. It can be seen from the results of test 3 however, that due to the prominent location of the building, and the office wall design which incorporates glazing in the top-most section, that there is significant daylighting potential in the testbed space during occupied hours especially via the southwest exposure. As the specified systems are intended or open offices in general, we have removed the impact of daylight dimming from the results (particular to test 3), and suggest that daylight dimming offers energy savings over and above those presented here, with the precise amount being a function of the perimeter-to-core ratio of the space in which systems are implemented.

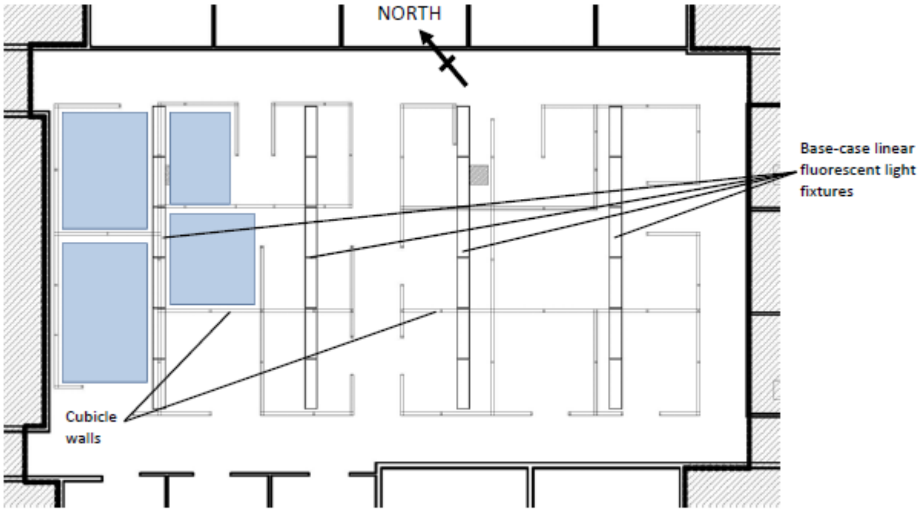


Figure 14: Plan View of Testbed, showing all 18 open office cubicles

Table 5: FLEXLAB Technology Packages and Testing Program

	Test	**Baseline Condition #1**	**Baseline Condition #2**	**Tested Technology Package**
1a	*Technology Package 1 – [Existing bldg. baseline]* Existing fixtures with LED lamp replacement only to reduce overhead LPD, existing switch/time clock lighting controls only, occupancy plug load control Applicable for troffers and pendant fixtures	Overhead Lighting: Existing overhead lighting in FLEXLAB® testbed space (T5), manual control switches Plug loads: Manual operation / switching of desktop plug loads, existing task lighting	Overhead Lighting Fixture type, quantity and operating hours determined to represent the LPD of empirical existing CA office building data – (e.g. CEUS or GPG measured). No additional controls. Plug loads: Same as baseline #1	Overhead Lighting: Linear LED lamp replacement (including integrated driver) in existing fixtures, no additional controls Plug loads: Scheduled operation, occupancy sensor-based control, task lighting throughout. Occupancy sensor-based control of all non-computer (desktop or laptop) loads.
1b	*Technology Package 1 – [Existing bldg. baseline]* Existing fixture with LED lamp replacement only to reduce overhead LPD, existing occupancy controls on overhead lighting, occupancy plug load control Applicable for troffers and pendant fixtures	Overhead Lighting: Same as 1a Plug loads: Same as 1a	Overhead Lighting Same as 1a Plug loads: Same as 1a	Overhead Lighting: Linear LED lamp replacement (including integrated driver) in existing fixtures, scheduling and occupancy controls Plug loads: Same as 1a

	Test	Baseline Condition #1	Baseline Condition #2	Tested Technology Package
2a	*Technology Package 2a –* *[Title 24 baseline]* Existing fixture adding tuning / occupancy controls, occupancy plug load control Applicable for troffers and pendant fixtures.	Overhead Lighting Title 24 compliant (LPD-based) overhead lighting with: ● Manual on/off ● Scheduling ● Occupancy controls ● Tuning Plug loads: Same as 1a.	N/A	Overhead Lighting: Addition of controls to existing (T5 pendant) fixtures: ● Manual on/off ● Scheduling ● Tuning ● Occupancy controls ● Daylight dimming in perimeter offices, none in the core Comparison against both baseline conditions. Test bench results will allow for T8 lamp-based fixtures evaluation as well Plug loads: Same as 1a

	Test	**Baseline Condition #1**	**Baseline Condition #2**	**Tested Technology Package**
2b	*Technology Package 2b –* *[Title 24 baseline]* Existing fixture reduced LPD via LED lamp retrofit and adding scheduling / tuning / occupancy controls, plug load control. Applicable for troffer and pendant fixtures.	Overhead Lighting Same as 2a Plug loads: Same as 1a	N/A	Overhead Lighting: Retrofit of T5 with LED replacement tubes: ● Manual on/off ● Scheduling ● Tuning ● Occupancy controls ● Daylight dimming in perimeter offices, none in the core Comparison against both baseline conditions Plug loads: Same as 1a

	Test	Baseline Condition #1	Baseline Condition #2	Tested Technology Package
3	*Technology Package 2b –* *[Title 24 baseline]* Light fixture replacement with reduced LPD, scheduling/ occupancy controls/daylight dimming, plug load control. Applicable for troffer and pendant fixtures.	Overhead Lighting: Same as 2b Plug loads: Same as 1a	Overhead Lighting Same as 2a Plug loads: Same as 1a	Overhead Lighting: LED fixture replacement with: ● Manual on/off ● Scheduling ● Occupancy controls/ ● Tuning ● Daylight dimming in perimeter offices, none in the core Comparison against both baseline conditions. Results also apply to the retrofit kit use-case. Plug loads: Same as 1a

Data gathered for each of the tests comprised of fixed and variable components of the measured space. Fixed values include characteristics inherent to the measured space such as floor area, maximum occupancy and installed lighting power density. Variable values reflect the dynamic use of the space, such as occupancy at any one time, and resultant equipment power use, and the direct impact this has on energy use at any point on time.

Data was measured at a highly granularity – i.e. electricity metered per single light fixture (in this case pairs of 4 foot pendants or single fixture for troffers) or per each single duplex power receptacle.

A complete description of the test conditions and test plan is available in the program manual developed for this system on the project's website (cbs.lbl.gov/beyond-widgets-for-utilities).

Test Results

There were measurable energy savings arising from each of the tested technology packages, and these were extrapolated to represent annual energy saving, are summarized in Table 6 below. These results were broadly in line with the performance expected, and therefore in principle meet the requirements of a prospective rebate program.

The two discrete system elements (overhead lighting and plug load control respectively) however, did not perform as anticipated. Energy savings from plug load control were lower than anticipated, and it is possible that with heavy task light use (i.e. switched on for the entirety of occupied hours), those savings could be reduced to around zero. However, although measured savings on the plug load operations were minor, the integrated nature of the proposed packages meant this unlocked previously un-accessed energy savings from the overhead lighting.

In addition, the test results presented here exclude the incremental additional energy savings of daylight dimming – including these would further support the economic case for both variants of TP2. The whole building energy results stated reflect a situation whereby 100% of a commercial office building is dedicated to office space (i.e. no conference rooms, break rooms etc.) Adjustments to how these estimates are interpreted to real buildings will be necessary on a case by case basis.

While the percent energy savings by combined end uses seems similar across the TP1 and TP2 packages, it is worth reiterating that the energy savings for TP1 were in contrast to an existing building baseline, whereas the savings for TP2 are compared against a more efficient Title 24 minimally compliant baseline.

Table 6. Task / Ambient Lighting with Occupancy Plug Load Control Energy Savings

	Retrofit Zone Savings (Large/Small Commercial)		**Whole Building Energy Savings (Large/Small Commercial)**
	Lighting and Plug Load Annual Energy Savings %	**Lighting and Plug Load EUI (kWh/sqft/yr)**	
Tech Package 1 – Basic	33% / 36%	3.16 / 2.8	14% / 18%
Tech Package 2(a) – Adv	30% / 32%	2.82 / 2.52	12% / 16%
Tech Package 2(b) – Adv	38% / 41%	3.61 / 3.23	16% / 20%

Systems vs. Widgets: Savings and Cost-Benefit Comparison

Retrofitting commercial office lighting to LED, once a cutting-edge efficiency measure, has become increasingly common as LED general lighting performance has advanced and costs have dropped. The DOE's 2015 lighting market characterization found that while less than 2% of lamps used in commercial light sources were LEDs in 2010, that figure had risen to over 10% by 2015 (USDOE 2016). The report attributes this growth to improvements in solid-state lighting technology (improved lighting, increased energy savings) as well as federal regulations pushing adoption and utility support through incentive programs. While 12.6% of lighting installations in 2016 across all common lighting applications involved LEDs, up from only 3% in 2014 (USDOE 2017), LEDs with connected lighting controls (integrated, networked sensors and controllers) were included in less than 0.1% of lighting systems installations. Integrated controls enable responsiveness to dynamically changing conditions such as daylight and occupancy, but appear to be much less far along the adoption curve than simple LED upgrades.

For building owners or lease holders investing in a commercial lighting retrofit, it would be useful to quantify and compare the energy performance of the options and the costs to install them; from a simple component-based retrofit to the systems-level solutions with integrated controls and design elements evaluated in FLEXLAB. In short, do the integrated approaches deliver on the improved energy savings promise and at what additional cost?

Energy savings for the systems in this comparison are based on measured project results applied to a common baseline, defined below. The annual value of the energy savings is calculated for a U.S. average commercial electric rate[6] ($0.1068 / kWh) as well as over a range of electric rates ($0.06 – 0.16 / kWh). Installation costs are based on labor and equipment costs from several sources[7], normalized to building area for the areas where the systems would be installed (not total building square footage). The cost-benefit analysis is carried out for the full costs of retrofit projects and the incremental costs of new construction and replace-on-burnout (ROB) projects (over the costs of systems that would otherwise be installed).

Baseline

Recall that annual energy savings from systems-based FLEXLAB tests reported in previous sections were relative to specific baselines tailored to each utility's respective markets. Because the baseline varied across the systems, savings across the projects are not directly comparable. For cross-project comparisons, energy savings for the lighting retrofits must be calculated from a common baseline.

---

[6] 2017 Average Commercial Electric Rate from U.S. Energy Information Administration; https://www.eia.gov/electricity/data/browser/

[7] Costs for light fixture equipment (fluorescent and LED), labor, and demolition of old equipment where applicable (retrofit case), from RS Means data for U.S. national average (labor – union shop) used, including standard markups on labor and equipment for overhead and profit. https://www.rsmeansonline.com/. Costs for lighting controls from Memorandum for the Northwest Energy Efficiency Alliance: Incremental Cost of Luminaire Level Lighting Controls (LLLC), September 8th, 2017. Prepared by Energy Solutions. Costs for LED task lamps, automated shade systems from vendors.

The baseline lighting system energy performance for this analysis comes from energy modeling of a DOE reference office building[8] relevant to these projects (existing building - large commercial office[9]), for a location and climate zone of one of the project partner utilities.[10] The computed lighting EUI for this baseline model is 4.02 kWh/ft^2-yr (at a 3-lamp T-12 lighting power density of 1.5W/ft^2). The full cost for installing the baseline system, three-lamp 2' by 4' fluorescent troffers, is estimated at \$3.32/ft^2 including material and labor.[11] The fixture density is assumed to be that of the FLEXLAB baseline fluorescent installation; 87 ft^2/fixture, at a fixture grid spacing of 8' by 10' on center (common for commercial applications and the spacing of the baseline fixtures in FLEXLAB) with a small amount of additional peripheral floor area.

LED Lighting Only

The most likely component-based lighting retrofit to the fluorescent baseline would be a simple LED installation. The energy savings from a component-based LED retrofit relative to the baseline fluorescent system is simply a matter of the reduction in lighting power density (LPD) due to the lower-wattage light source (i.e. no changes in operating parameters that affect how often lights are on or off). For a basic LED retrofit LPD, the measured wattage of the LED lighting system used in the FLEXLAB for the automated shading project resulted in an installed LPD of 0.55 W/ft^2 (no tuning or daylight dimming). This is consistent with prior LED LPDs in other FLEXLAB projects as well and represents over 60% reduction in lighting energy relative to the reference model baseline - a large impact, but within the savings range expected for fluorescent-to-LED retrofit,[12] especially in older buildings with less efficient lighting systems (e.g. T12 fluorescent). The retrofit cost of the LED fixtures is \$5.00/ft^2 including material and labor for the fixture installation as well as the demolition labor to remove existing fixtures. The incremental cost of an LED installation over a standard fluorescent is \$0.61/ft^2 which is simply due to the slightly higher cost of the LED fixture, as labor is assumed to be equivalent.

Systems – Based Solutions

Having determined energy usage and costs for the baseline and the basic LED retrofit options, energy and cost parameters for the systems-based retrofit approaches must be defined. Recall that in addition to LED lighting systems, these projects included:

---

[8] https://www.energy.gov/eere/buildings/commercial-reference-buildings

[9] The prescribed lighting system wattage for existing building - large commercial is built on ASHRAE 90.1-1989 requirements for this space type, per U.S. Department of Energy Commercial Reference Building Models of the National Building Stock, Table 26. https://www.nrel.gov/docs/fy11osti/46861.pdf (Deru et. al 2011)

[10] Note that various baseline scenarios could be considered, such as T-12 vs. T-8 fixtures and 2' by 4' fixtures vs. 2' by 2' fixtures; each of which has different energy and cost implications. However, to reduce complexity and variables to consider, this comparative analysis is limited to the one baseline described here.

[11] Costs based on RS Means values for material and labor (national averages).

[12] *DOE Solid State Lighting Technology Fact Sheet*: upgrading fluorescent troffers to LEDs can save over 60% energy. https://www1.eere.energy.gov/buildings/publications/pdfs/ssl/led_troffer-upgrades_fs.pdf LED troffer retrofits range from 20% - 60% savings per Federal Energy Management Program *LED Retrofit Kits, TLEDs, and Lighting Controls: An Application Guide*. DOE/EE 1544, PNNL-SA-123952 March 2017. https://www.energy.gov/sites/prod/files/2017/03/f34/led_troffer_retrofit_guide.pdf

- task-tuning controls to reduce lighting power to achieve an illuminance setpoint (all systems);
- daylight dimming controls (automated shading and workstation-specific systems);
- changes in layout to maximize utility (workstation-specific system);
- facade changes to improve daylight availability (automated shading);
- task/ambient lighting design (task/ambient system).

Installation costs and energy savings are presented below for the three systems-based solutions. Note that the energy performance of each integrated system in the savings comparison here applies only to the portion of the building for which the system performance was characterized: south perimeter lighting zones for the workstation specific system with daylight dimming, all perimeter zones for the automated shading system with daylight dimming, and any open office zone, for task/ambient with occupancy control, though savings potential from daylight dimming in perimeter areas was not evaluated for this system). In other words, the lighting energy figures here are specific to where the systems are implemented, particularly for daylight responsive systems intended for perimeter zones.

Automated Shading with Daylight Dimming Controls

For the automated-shading project with daylight dimming controls, the lighting savings were measured during a 12-hour per day schedule (7AM - 7PM) for FLEXLAB tests. Lighting system operation in the energy model for the baseline case includes some lighting usage outside that 7AM – 7PM window. To standardize energy savings to the baseline, FLEXLAB - measured savings are therefore only applied to the 7AM - 7PM hours of operation. For operation outside of those hours, savings are calculated based simply on the power reduction from fluorescent to LED fixtures tuned to the illuminance setpoint. Combining the tuned LEDs with daylight dimming and automated shading, this system saved almost 85% lighting energy compared to the reference model baseline.

The total retrofit cost, including automated roller shades, LED fixtures and advanced lighting controls for tuning and daylight dimming, is estimated at \$10.18/ft^2. Of that cost, around 40% is due to the automated shades, around 50% is due to the LEDs and the advanced controls, and the remainder is due to demolition of existing fixtures. The incremental cost, which includes the difference in price to install automated shades over manual roller shades, as well as the lighting system incremental cost, is \$4.06/ft^2.

Workstation-Specific LEDs with Daylight Dimming Controls

Similar to the automated shading project, the workstation-specific system was operated on a 7AM - 7PM schedule for FLEXLAB tests. The measured energy savings for this system are therefore only applied to the baseline lighting energy corresponding to that part of each day. For lighting energy from hours outside the 7AM – 7PM window, savings are calculated based simply on the power reduction from fluorescent to LEDs tuned to the illuminance setpoint.

Workstation-specific lighting design provides more targeted lighting of the task plane from overhead lighting (typically one overhead fixture per desk) rather than traditional lighting design that illuminates an entire open work space equally. The workstation-specific model should then lead to a decrease in overall fixture density and lighting power requirements. Consider that occupant density in open offices is typically limited by building code[13] to no less than 100 ft^2 per worker. At one fixture per desk, the fixture density would go from the baseline density of 87 ft^2/fixture to 100 ft^2/fixture. This results in energy and cost savings that were factored into the comparative analysis here.

In total, with the tuned LED fixtures, lower fixture density, and daylight dimming, energy savings were 93% for this system relative to the reference model. The total retrofit cost, including LED pendants and advanced lighting controls for tuning and daylight dimming, is estimated at \$6.52/ft^2 which also includes demolition labor to remove existing fixtures. The incremental cost is \$2.14/ft^2 which includes higher material costs for the LED pendants with controls relative to fluorescent troffers but labor cost savings due to reduced number of fixtures installed.

Task/Ambient with Occupancy Controls

The task/ambient lighting system with occupancy controls was implemented in the building core for FLEXLAB tests so daylight dimming was not a part of the technology package as evaluated, though this system can be implemented in core and perimeter zones alike. In addition to the annualized lighting energy for the tuned, occupant-responsive overhead LED lighting system, additional lighting energy attributable to task lamp operation was calculated based on task lamp wattage, logs of task lamp usage, and assumptions regarding operating hours. The total lighting energy savings for the task/ambient package with occupancy controls was then calculated from to the reference model baseline. The system saved over 80% lighting energy compared to the reference model baseline. The retrofit cost of the project, including occupant responsive LED overhead fixtures, and LED task lamps at each workstation is estimated at \$5.07/ft^2, with an incremental cost of \$0.68/ft^2.

Results

The results in Table 7 and Figure 15 clearly show that while simple LED retrofits provide significant energy savings on their own (63%), the integrated systems lighting retrofits provide significant additional energy savings potential (81% to 93% relative to the baseline). Compared to the simple LED retrofit, integrated systems savings are 49% to 82%.

Table 7. Comparison of component- vs. systems-based savings for three integrated lighting systems.

Option	Lighting EUI (kWh/sf/yr)	Lighting Savings relative to Baseline	Lighting Savings relative to Component-based Retrofit
Baseline (Fluorescent, scheduled control)	4.02	_	_
LED Lighting Only	1.48	63.1%	_

---

[13] 2015 International Building Code, Table 1004.1.2, Maximum Floor Area Allowances per Occupant, one occupant per 100 gross square feet load factor for Class B, business occupancy.

Option	Lighting EUI (kWh/sf/yr)	Lighting Savings relative to Baseline	Lighting Savings relative to Component-based Retrofit
Automated Shading and Daylighting	0.61	84.8%	58.8%
Workstation-Specific and Daylighting	0.27	93.3%	81.9%
Task/Ambient and Occupancy	0.75	81.3%	49.3%

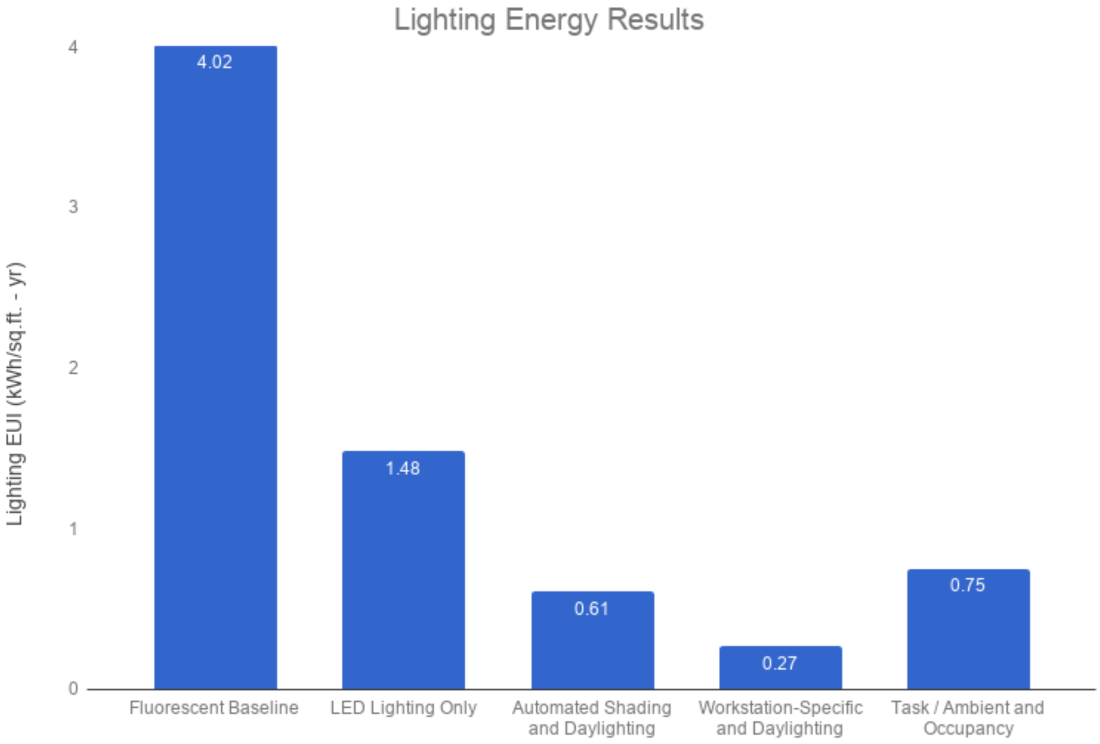


Figure 15. Comparison of component- vs. systems-based lighting EUI for three integrated systems.

While the energy savings are compelling for all cases, the value of the savings compared to the cost of installation determines the cost effectiveness of investing in these systems. Table 8 shows the estimated costs per square foot for the systems in retrofit scenarios, where the full system costs are considered as well as for major renovations, replace on burnout (ROB), and new construction scenarios, where only the incremental costs are considered. Table 8 and Figure 16 shows the simple payback for these systems based on national average electricity price of $0.11/kWh.

There is a significant difference in cost effectiveness between the major renovation, ROB, and new construction scenario (incremental cost) and the retrofit (full cost) scenario. For major renovations, simple paybacks are very favorable for task/ambient and workstation specific systems (just under 2 years and 6 years respectively). For automated shading the simple payback is about 11 years, which may still be acceptable for some organizations and could be brought down with incentives. The primary cost component for this system is the automated shading. It should be noted that there are significant non-energy benefits with automated shading and the value of these benefits has not been factored into the cost effectiveness analysis presented here.

The focus of the integrated lighting systems package development was utility retrofit incentive programs. For the retrofit scenario, the total project cost is considered rather than simply the incremental cost over alternatives, and at this higher total project cost, the value of the lighting energy savings is not sufficient to achieve paybacks under 10 years. For the systems evaluated here, even the most cost effective retrofit option, task/ambient lighting with occupancy controls, results in a retrofit payback over 14 years. Simple LED fixtures pay back in almost 18 years at the cost and savings found here. This analysis result perhaps underscores the value of utility incentive programs targeting these integrated packages, to support implementation and help buy down the project costs. Other options to achieve lighting energy savings at a retrofit cost low enough to get lower simple paybacks include LED replacement lamps that operate on existing ballasts and include onboard sensing and controls (no fixture change out, minimal labor) and LED retrofit kits with onboard sensing and controls (integrate into existing fixtures, more labor).

Table 8. Comparison of component- vs. systems-based costs and paybacks (retrofit and new construction) for three integrated systems.

Option	**Scenario**	**Estimated Installation Cost/ft^2**	**Energy Cost/ ft^2- year (@ $0.1068/ kWh)**	**Cost Savings/ ft^2- year**	**Simple Payback (years)**
Baseline (fluorescent, scheduled control)		$3.32	$0.44	–	–
LED Lighting Only	Retrofit	$5.00	$0.16	$0.28	17.8
	Major Renovation, ROB, New Construction	$0.61	$0.16	$0.28	2.2
Automated Shading and Daylighting	Retrofit	$10.18	$0.07	$0.37	27.3
	Major Renovation, ROB, New Construction	$4.06	$0.07	$0.37	10.9
Workstation-Specific and Daylighting	Retrofit	$6.52	$0.03	$0.41	15.9
	Major Renovation, ROB, New Construction	$2.14	$0.03	$0.41	5.2
Task/Ambient and Occupancy	Retrofit	$5.07	$0.08	$0.36	14.1
	Major Renovation, ROB, New Construction	$0.68	$0.08	$0.36	1.9

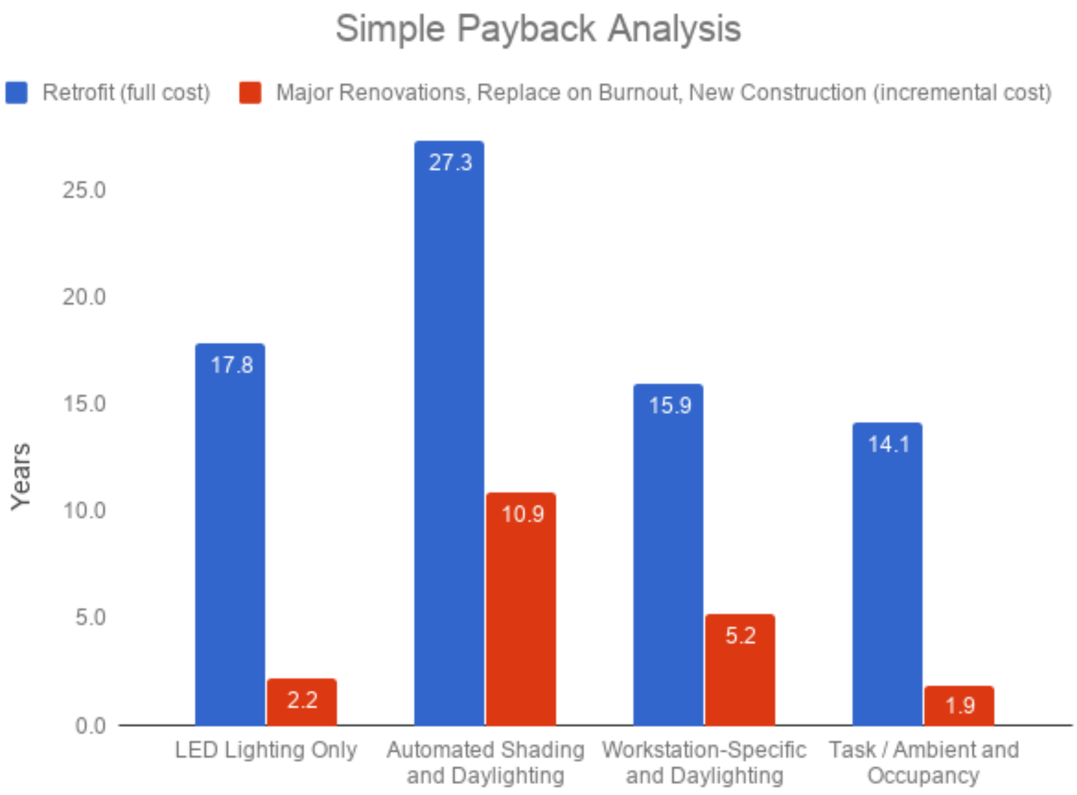
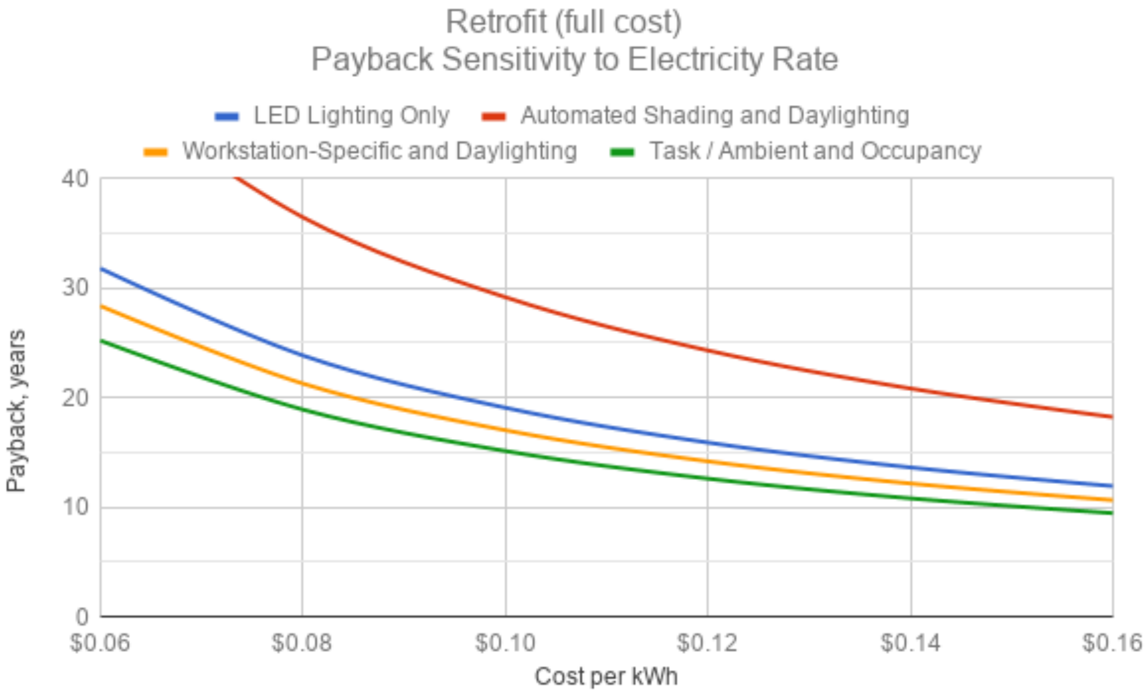
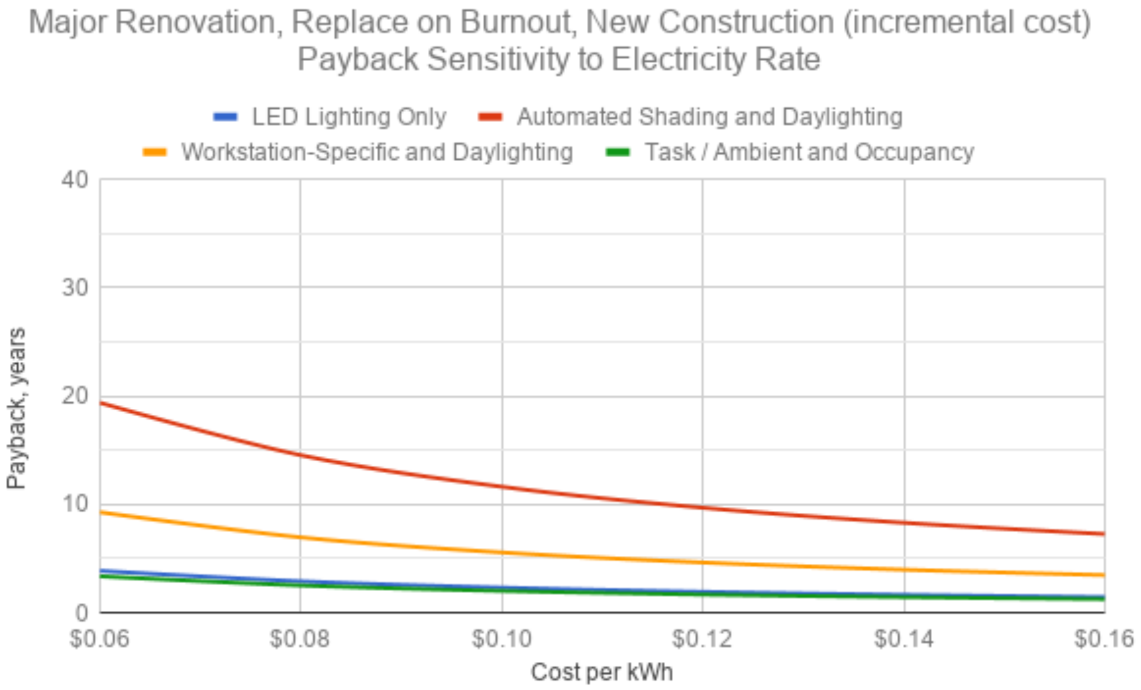


Figure 16. Comparison of component- vs. systems-based simple paybacks (retrofit and major renovation, ROB, new construction).

Given that utility rates for commercial customers vary throughout the country, it is useful to evaluate the sensitivity of payback results to different costs of electricity. Payback results for each system, in retrofit and major renovation, ROB, new construction scenarios, are illustrated in the following figures for a range of utility costs, from $0.06 to $0.16/kWh.

As expected, the results show that higher utility rates lead to higher value of energy saved which in turn improves project cost effectiveness considerably (Figures 17 and 18). Going from the national average rate of 11 cents to 16 cents / kWh, the simple payback for the retrofit scenario drops by around 5 years for task/ambient system (to 9 years) and workstation-specific system (to 11 years), and 9 years for automated shading (to 18 years). For the major renovation scenario, simple payback for task/ambient drops to under 1 year, and workstation specific to less than 2 years, and even automated shading improving to less than 4 years. These results reinforce the case for using incentives to buy down the cost to customer for the added savings from integrated systems.

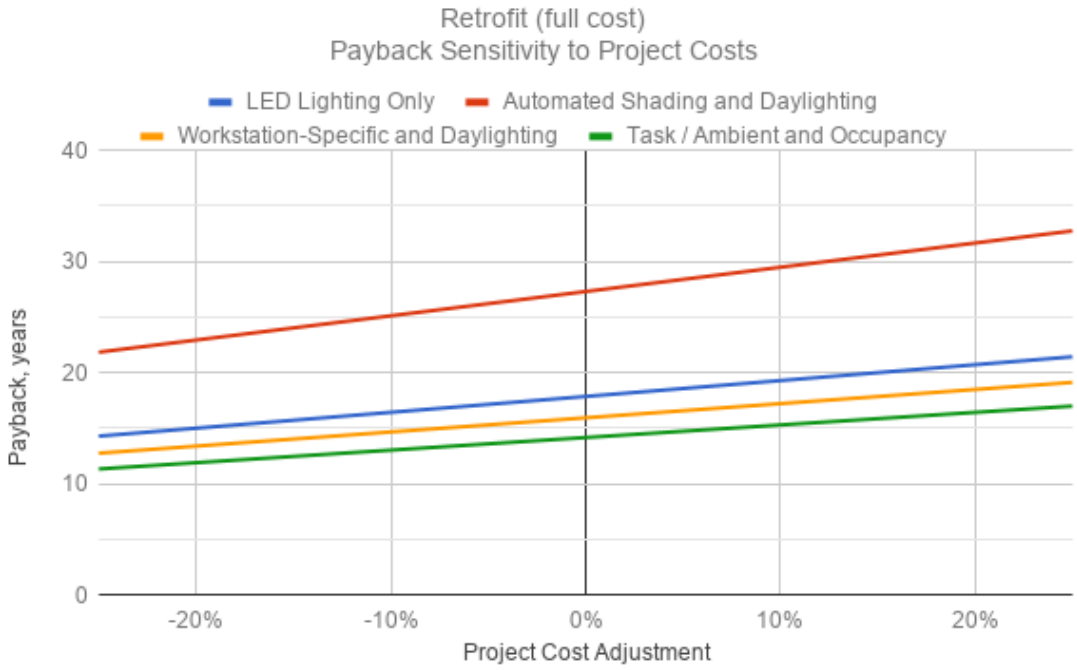


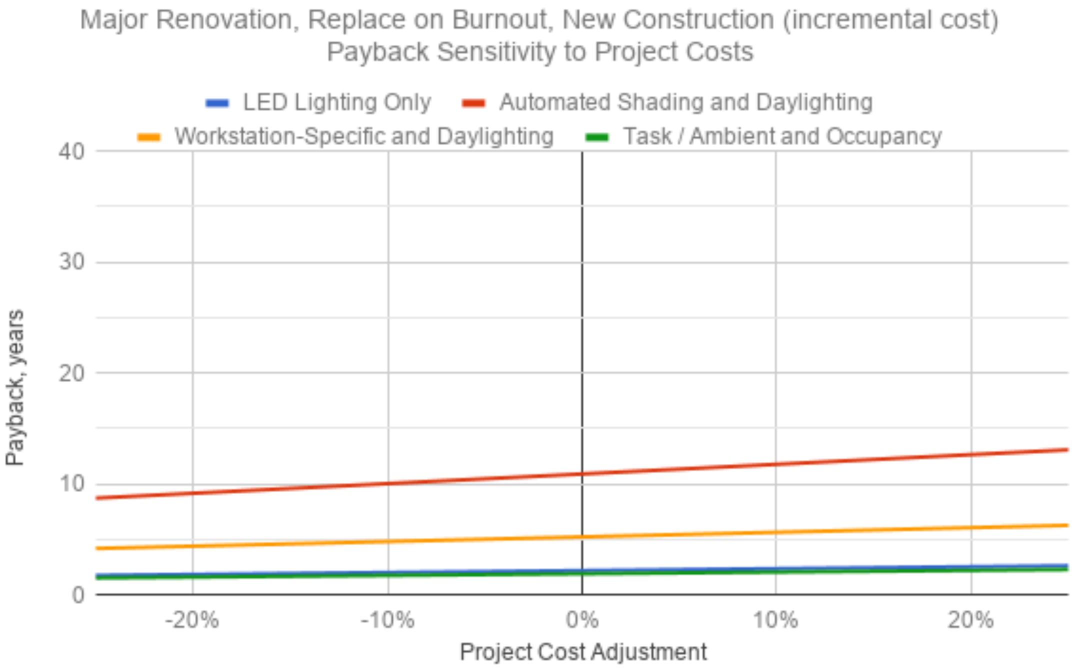


Figures 17 and 18. Simple payback sensitivity to electricity rate (retrofit and major renovation, ROB, new construction).

Similar to variability in utility rates, installation costs vary from location to location and project to project. Installation costs may also improve (decrease) in the future as markets mature, further economies of scale are achieved, and installers become more familiar with the technologies, though the expected rate of future cost decline was not investigated here. A sensitivity analysis was carried out scaling project costs above and below those estimated in this analysis, which are based on U.S. averages. Retrofit and major renovation, ROB, new construction payback results for each system are illustrated in Figures 19 and 20 below for a +/- 25% total installation cost range (at the U.S. average commercial electric rate of $0.11/kWh).

As expected, changes in installation cost assumptions have an impact on cost effectiveness. In this case, 25% increase or decrease in assumed project cost has around a 20% impact on years to payback, adding or subtracting 3 to 6 years to payback in the retrofit scenario, and half a year to 2 years in the major renovation scenario.





Figures 19 and 20. Simple payback sensitivity to project costs (retrofit and major renovation, ROB, new construction).

For the workstation-specific system, an additional sensitivity analysis was carried out for a less dense fixture spacing configuration. Instead of fixture density around 100 ft^2/fixture, a spacing of 130 ft^2/fixture was considered, reflective of a more open, spacious work plan design. At this lower occupant and fixture density, paybacks improve to 13.1 years (retrofit) and 2.5 years (major renovation), with total installation costs decreasing to \$5.43/ft^2 and 1.04/ft^2 respectively. The system lighting EUI improves to 0.21 kWh/ft^2/yr, which represents 95% savings relative to baseline lighting energy.

Conclusion and Outlook

We presented an analysis of three integrated lighting systems approaches to energy efficiency retrofits and compared them to component-based retrofits: automated shading with daylight dimming controls, workstation-specific lighting with daylight control, and task/ambient lighting with plug load occupancy controls. Specifically, our analysis sought to quantify the marginal energy savings of these systems relative to component-based approaches. The analysis was based on a combination of measured performance data from LBNL's FLEXLAB test facility and energy simulations. All three systems were compared to a simple fluorescent-to-LED retrofit, which represents the component-based approach. While the simple LED upgrade in and of itself provides significant lighting savings of 63%, the systems yielded savings of 81-93% lighting savings - which equates to *additional* savings of 49-82% over the simple LED upgrade. All systems tested provided satisfactory visual comfort as well, indicating good potential for market acceptance.

While the savings from systems are significant, cost effectiveness can vary considerably based on retrofit scenario, installation costs and utility prices. In general, they are only cost effective in the incremental cost analysis approach, for major renovations, ROB, and new construction, with simply payback ranging from 2 years for the task / ambient system to 11 years for the automated shading and daylighting system, assuming an average utility price of $0.11/kWh. This compares to the component-based LED fixture retrofit at a 2 year simple payback. These systems as evaluated were generally not cost effective for a pure retrofit scenario, with simple paybacks ranging from 14 years to 27 years at the same utility price. Notably, the component -based retrofit of an LED fixture replacement is also not cost effective with a simple payback of 18 years. All simple paybacks improve with higher utility prices that result in greater value from the energy savings. The workstation-specific lighting system and the task/ambient lighting system have better paybacks than the component-based approach in a retrofit scenario. The task /ambient system also achieves a better simple payback than the component based approach for major renovation, ROB, new construction projects. It should be noted that the potential value of any non-energy benefits from the integrated systems technologies evaluated here (e.g. occupant visual comfort improvements, glare control, access to views) was not quantified for this study and has not been factored into the cost effectiveness analysis.

This cost effectiveness analysis result perhaps underscores the need for and the value of utility incentive programs targeting these integrated packages, to help buy down the project costs. A key challenge is also to reduce the transaction costs of designing, specifying, installing and operating integrated systems. They are inherently more complex, likely to involve more stakeholders, and thereby require more skill and effort. Furthermore, there are real and perceived risks with ensuring savings persistence. One way to de-risk and reduce transaction costs is to develop quasi-standardized validated systems 'packages', consisting of technology specifications, validated savings data, design and implementation guidance, operation procedures, and standardized M&V protocols. This is especially applicable for utility incentive programs.

There are several technical strategies that may be further explored to help improve the cost of these three lighting systems as well. This includes advancements in approaches to retrofit lighting controls in existing fixtures, possibly through lamp replacements or retrofit kit installations with onboard sensors and controls, potentially resulting in cost reductions that could apply to several systems.

Further research is also needed to properly assess and quantify transaction costs, and to develop methods and tools to reduce them. Additionally, work is needed to quantify and monetize the non-energy benefits attributable to systems, especially pertaining to improved indoor environmental quality. Finally, it should be reiterated that this study was limited to three systems, focused on lighting controls. There are many other opportunities for systems integration, particularly around HVAC and building envelope that are ripe for further exploration and analysis.

References

ASE. 2016. Greater than the Sum of its Parts: The Case for a Systems Approach to Energy Efficiency. Alliance to Save Energy, Systems Efficiency Initiative Year 1 Report. May 2016.

ASE. 2017. Going Beyond Zero: A Systems Efficiency Blueprint for Building Energy Optimization and Resilience. Alliance to Save Energy, Systems Efficiency Initiative Year 2 report. May 2017.

Chan, Y., and Tzempelikos, T. 2013. Impact of Shading Control and Thermostat Set Point Control in Perimeter Zones with Thermal Mass. Proceedings of Conference of International Building Performance Simulation Association.

Deru, M., Field, K., Studer, D., Benne, K., Griffith, B., Torcellini, P., Liu, B., Halverson, M., Winiarski, D., Rosenberg, M., Yazdanian, M., Huang, J., Crawley, D. 2011. U.S. Department of Energy Commercial Reference Building Models of the National Building Stock . Technical Report NREL/TP-5500-46861 February 2011 https://www.nrel.gov/docs/fy11osti/46861.pdf

Dikel, E., Newsham, G., Xue, H., and Valdés, J. 2018. Potential energy savings from high-resolution sensor controls for LED lighting. National Research Council Canada. Energy and Buildings 158: 43-53.

DNV GL (KEMA, Inc.) 2015. “Beyond Widgets” Systems Energy Efficiency – Market Segmentation Potential for Adoption of System-Based Utility Energy Efficiency Programs. Prepared for Lawrence Berkeley National Laboratory.

Elliot, N., Molina, M., and Trombley, D. 2012. A Defining Framework for Intelligent Efficiency. American Council for an Energy-Efficient Economy. ACEEE #E125.

Galasiu, A., Newsham, G., Suvagau, C., Sander, D. 2007. Energy Saving Lighting Control Systems for Open-Plan Offices: A Field Study, LEUKOS, 4:1, 7-29.

Harrington, E., and Carmichael, C. 2009. Project Case Study: Empire State Building. Retrofit - An RMI Initiative. Rocky Mountain Institute.

Inoue, T., Kawase, T., Ibamoto, T., Takakusa, S., and Matsuo, Y. 1988. The development of an optimal control system for window shading devices based on investigations in office buildings. ASHRAE Transactions 104 1034–1049.

Kisch, T., Wade, J., Nahabani, S. 2017. Memorandum for the Northwest Energy Efficiency Alliance (C. Wolgamott): Incremental Cost of Luminaire Level Lighting Controls (LLLC). Prepared by Energy Solutions, Oakland, CA.

Lee, E.S., Fernandes, L., Coffey, B., McNeil, A., Clear, R., Webster, T., Bauman, F., Dickerhoff, D., Heinzerling, D., and Hoyt, T. 2013. A Post-Occupancy Monitored Evaluation of the Dimmable Lighting, Automated Shading, and Underfloor Air Distribution System in The New York Times Building. Lawrence Berkeley National Laboratory. LBNL - 6023-E.

Mathew, P., Regnier, C., Walter, T., and Shackelford, J. 2017 ComEd – LBNL 'Beyond Widgets' Project Automated Shading Integrated with Lighting and HVAC Controls System Program Manual. Lawrence Berkeley National Laboratory. LBNL-2001132

Metzger, I., D. Cutler, and M. Sheppy, 2012. Plug Load Control and Behavioral Change Research in GSA Office Buildings, General Services Administration.

Newsham, G. 1994. Manual Control of Window Blinds and Electric Lighting: Implications for Comfort and Energy Consumption. Indoor Environment 3:135-144.

Olgyay, V., and Seruto, C. 2010. Whole-Building Retrofits: A Gateway to Climate Stabilization. ASHRAE Transactions, vol 116, part 2.

Regnier, C., Sun, K., Hong, T., and Piette, M. 2017. Quantifying the benefits of a building retrofit using an integrated system approach: A case study. Energy and Buildings, 2017.

Regnier, C., Mathew, P., Robinson, A., Schwartz, P., Walter, T. 2016. Beyond Widgets – Systems Incentive Programs for Utilities. ACEEE Summer Study in Buildings. American Council for an Energy Efficient Economy. August 2016

Robinson, A., C. Regnier. 2015. Zone Level Occupant-Responsive Building Energy Systems at the GSA. LBNL-182574

Rubin, A., Collins, B., Tibbott, R. 1978. Window blinds as a potential energy saver – a case study. NBS Building Science Series 112. National Bureau of Standards, Washington, DC. 1978

Shackelford, J. A. Robinson, and F. Rubinstein, 2015. Retrofit Demonstration of LED Fixtures with Integrated Sensors and Controls, General Services Administration.

Shen, E., Hong, T. 2009. Simulation-based assessment of the energy savings benefits of integrated control in office buildings. Building Simulation Vol. 2, No. 4: 239 - 251.

U.S. Department of Energy. 2017. Adoption of Light-Emitting Diodes in Common Lighting Applications Prepared for: Solid-State Lighting Program. Building Technologies Office. U.S. Department of Energy Prepared by: Navigant Consulting. July 2017. https://www.energy.gov/sites/prod/files/2017/08/f35/led-adoption-jul2017_0.pdf

U.S. Department of Energy. 2016. Energy Savings Forecast of Solid-State Lighting in General Illumination Building Technologies Office, U.S. Department of Energy. Prepared by: Navigant Consulting. September 2016. https://www.energy.gov/sites/prod/files/2016/09/f33/energysavingsforecast16_2.pdf

Van Den Wymelenberg, Kevin. 2012. Patterns of occupant interaction with window blinds: A literature review. Energy and Buildings 2012 51:165–176.

Wei, J., Enscoe, A., and Rubinstein, F. 2012. Responsive Lighting Solutions. GSA Proving Ground.

Wei, J., F. Rubinstein, J. Shackelford, and A. Robinson, 2015. Wireless Advanced Lighting Controls Retrofit Demonstration, LBNL-183791.

Wen, Y., and Agogino, A. 2011. Control of wireless-networked lighting in open-plan offices. Lighting Research and Technology 2011; 43: 235–248.

Xu, L., Pan, Y., Yao, Y., Cai, D., Huang, Z., Norber. 2017. LinderLighting energy efficiency in offices under different control strategies. Energy and Buildings 138 127–139.