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Laboratory Validation of Integrated Lighting Systems Retrofit Performance and Energy Savings

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Abstract: Light-emitting diodes (LED) fixtures and lamps have emerged as leading technologies for general illumination and are a well-established energy efficiency retrofit measure in commercial buildings (from around 2% of installed fixtures and lamps in 2013 to 28% by 2020). Retrofit approaches that integrate elements, such as networked controls, daylight dimming, and advanced shade technologies lag in comparison. Integrated retrofits have been shown to increase savings over single end-use retrofits, but are perceived as higher complexity and risk. More validation of integrated lighting system performance is needed. This study presents results from laboratory testing of three packages combining fixtures, networked controls, task tuning, and daylight dimming, advanced shades, and lighting layout changes. We characterize performance in perimeter open-office zones, finding energy savings from 20% for daylight dimming and automated shades (no LED retrofit) to over 70% for LED retrofits with advanced controls and shades or lighting layout changes. We present some implementation details, including lessons learned from installation and commissioning in the laboratory setting. We also discuss cost-benefit analysis approaches for the types of packages presented, including the need to quantify and incorporate energy and non-energy benefits for advanced shades packages, which enhance occupant comfort but add significant cost.

Keywords: integrated lighting retrofits; advanced lighting controls; daylighting; LEDs; commercial buildings; energy savings; automated shading systems

1. Introduction

The landscape for efficient lighting retrofits has changed significantly in recent years. Light-emitting diodes (LEDs) as a high-efficacy light source for general illumination have overtaken fluorescent lighting as the most energy-efficient technology. Linear LED fixtures (e.g., troffers and pendants) and lamps (linear or “tube-style” LEDs to replace fluorescent lamps) have made significant inroads in commercial buildings, increasing from only 1 to 2% of installed lighting in 2013 [1], to 12% penetration by 2017, and 28% by 2020 [2]. The Commercial Buildings Energy Consumption Survey (CBECS) trends in commercial lighting in 2017 underscored the impacts of new technologies and standards on building energy usage, noting the steep reduction in lighting’s share of commercial building energy usage from 38% in 2003 to 17% by 2012 [3]. In office environments, the move to more efficient fluorescent sources (T12 lamps to T8 lamps, electronic ballasts), followed by the adoption of LEDs, has resulted in continually declining lighting energy usage intensity, from 4.1 kWh/ft²/year (yr.) in 2010 [4] to 1.8 kWh/ft²/yr. by 2015 [5].

LEDs are now a well-established energy efficiency retrofit option. More recently, networked and cloud-connected lighting controls solutions have also proliferated in the market. These systems integrate well with solid-state, dimmable LED fixtures; so-called luminaire-level lighting controls with sensors on-board each fixture are offered by various vendors. Energy savings from the advanced

controls systems alone have been shown to be significant. A recent study of field data from over 100 installations found that networked lighting controls save an average of 47% energy, not including energy savings from switching to LED light source [6].

An option to integrate beyond lighting fixtures and controls is including façade-shading systems in a retrofit package, to further enable daylight availability while mitigating glare when necessary. Advanced shading systems can augment the daylight sensing and dimming that is a key feature of advanced controls systems.

Taken together, integrated lighting solutions including LED fixtures and advanced controls, with daylighting systems can be effective retrofit packages. Integrated building systems retrofits have been shown to increase savings over single end-use retrofits. One study found 30% whole building energy savings from component retrofits, but over 80% savings for integrated systems retrofits [7]. Research also indicates that energy efficiency programs could achieve larger energy savings by targeting integrated systems deployment at-scale [8]. However, integrated systems are more complex to implement and are inherently more customized than end-use retrofits alone, and are thus often perceived as higher-risk and more hassle.

Integrated systems have not yet reached widespread market adoption, lacking a track record of familiarity and proven successes among building owners and operators and project implementers. Even controls-based lighting retrofits have lagged significantly behind light source retrofits (LED change-outs). For example, as of 2019, daylighting control for electric lighting had only 2% penetration in existing buildings, with over 80% of commercial buildings employing no automated lighting controls beyond occupancy sensing [9]. Experience is still lagging among owners, operators, and implementers with respect to installing and operating advanced lighting controls systems in existing buildings [9]. Energy efficiency retrofit programs often rely instead on simple end-use retrofit models with deemed savings potential, and have been slower to move toward integrated system approaches.

Study Motivation

With a clear need for more substantiation of the value of integrated lighting system retrofits in order to scale adoption, this paper presents measured and validated performance from laboratory testing of three integrated lighting system retrofit packages. These tests helped address the perceived risk barriers associated with system retrofits by evaluating technologies through rigorous laboratory experiments.

The lab tests can help bound savings estimates and expectations in order to de-risk adoption of these packages and facilitate scaled deployment. System setup and operation experiences can also provide valuable insights into technology installation and commissioning issues that can help inform implementation (though experience at larger scale and in “real world” buildings cannot be replicated in the lab). The intention of the laboratory studies was to use validated results from the lab to develop standard performance and energy savings estimates. Utilities partnered in the research scopes, which included retrofit program and project guidance based on research findings.

Laboratory validation can be complementary to modeling and simulation as well as field site evaluations—both of which are useful, but have distinct limitations. Building energy simulations provide a flexible environment to evaluate systems’ energy performance, but a “performance gap” often exists between simulation predicted results and actual outcomes. The built environment’s many complex variables, from materials, occupancy and equipment schedules, plant operation, and climate conditions, often lead to uncertainties and serious discrepancies between model predictions and actual energy usage [10]. Field evaluations can provide “real world” results, but often do not involve the level of measurement and verification necessary to validate for other applications (it is difficult to sub-meter loads in existing buildings and to measure light levels and glare in occupied spaces). Field evaluations also rarely provide the side-by-side comparison of baseline and retrofit systems; if measurement and verification is done it is often before, and then after, changes are made, with uncertainties arising from variables that change over time (occupancy patterns, climate conditions, etc.). In contrast, in the

lab environment we are able to test baseline and retrofit systems in parallel, eliminating some of those uncertainties.

2. Integrated Lighting System Retrofit Packages

We tested three different integrated lighting system retrofits. The retrofit systems all involved daylighting strategies and were evaluated in perimeter daylit zones of commercial office environments. The packages were tested over several seasons in order to capture performance ranges under varying daylight and climate conditions. For energy savings analysis, each system was tested alongside representative baselines (detailed later in Section 4); either existing building conditions or minimally code-compliant conditions.

- Test System 1: wired networked zonal lighting controls, task tuning, daylight dimming, and automated solar tracking roller shades. This system package was developed with an electric utility considering a commercial incentive program for daylight dimming and automated roller shades in part to address barriers to integrated systems deployment (additional complexity and effort required for design and energy savings assessments) [11].
- Test System 2: wireless networked luminaire-level lighting controls and LED troffers, task tuning, daylight dimming, and self-powered mechanized roller shades and daylight-redirecting blinds. This evaluation was part of a larger research and field demonstration effort for a set of integrated commercial retrofit emerging technologies [12].
- Test System 3: wireless networked luminaire-level lighting controls and LED pendants, task tuning, daylight dimming, and workstation-specific lighting design. This system package was developed with a utility partner interested in the savings potential of the technologies in small and large commercial spaces, also attempting to address barriers to integrated system deployment through utility program channels [13].

Baseline and retrofit system details are provided in Table 1. Note that each of the three tests was carried out independently, under unique schedules and test parameters as described later. The three evaluation methodologies were not designed to be equivalent or comparable per se. The intent of this study is to provide three examples of laboratory-validated performance of integrated lighting systems retrofits; results are not compared head-to-head.

2.1. Electric Lighting and Controls

All three retrofit packages included advanced networked lighting controls, defined by the non-profit energy efficiency organization the DesignLights Consortium as consisting of “an intelligent network of individually addressable luminaires and control devices, allowing for application of multiple control strategies, programmability, building- or enterprise-level control, zoning and rezoning using software, and measuring and monitoring.” [14]. Daylight dimming enabled by the controls was tested against baseline controls with no daylight dimming. (Systems were tested in daylit perimeter zones with minimal exterior obstructions outside of the test building, so daylight-related savings are greater than what would be experienced in spaces with sky obstructions from adjacent buildings or trees.) The advanced lighting controls also enabled task tuning to reduce lighting power (if necessary) to achieve target light levels at the desk; e.g., 300 lux or 500 lux setpoints. One of the integrated packages employed a zonal lighting controls solution with zonal daylight dimming. The other packages involved luminaire-level lighting controls with wireless network communication, and daylight sensors onboard each fixture. Two of the systems included retrofitting from fluorescent lighting fixtures common in existing office applications to dimmable LED fixtures for general illumination; either 2' × 4' troffers or 4' suspended direct-indirect fixtures. Finally, one package included modifying the fixture layout from a typical general lighting scheme with uniform grid spacing (e.g., 8' by 10' fixture spacing) to a workstation-specific configuration, locating one fixture over each workstation to target illumination to

where tasks are performed. The workstation-specific scheme allowed for lowering overall lighting power density while still meeting target illuminance levels.

2.2. Shading and Daylighting

Daylight dimming strategies for electric lighting are only possible in daylit zones of buildings (near windows or skylights for example). All three integrated system retrofits studied here include daylight responsiveness and were evaluated in a building perimeter zone with a window wall. Daylight dimming effectiveness is dependent upon daylight available in a space, so the methods by which windows are shaded to allow light in but manage glare and thermal comfort are important for daylight dimming.

Table 1. System descriptions and attributes.

System or Element	Baseline System	Test System 1	Test System 2	Test System 3
System Summary	General zonal lighting with scheduled on/off controls and no dimming	Advanced lighting controls (no source change) and automated roller shades	Light-emitting diodes (LEDs) with advanced controls and roller shades with daylight redirecting blinds	LEDs with advanced controls and workstation-specific lighting design
Fixture Type, Configuration	Various	2' × 4' LED troffer in general zonal lighting grid	2' × 4' LED troffer in general zonal lighting grid	4' suspended direct/indirect LED pendant with workstation-specific lighting design
Lighting Controls	Scheduled on/off only (typically 6AM to 8PM). No dimming.	Zonal networked lighting controls with wired digital communication, scheduled on/off, task tuning, daylight dimming	Luminaire-level sensors and networked wireless controls, scheduled on/off, task tuning, daylight dimming	Luminaire-level sensors, networked wireless controls, scheduled on/off, task tuning, daylight dimming
Window Shading System	Standard venetian blinds (louver tilt angle adjusted once per seasonal test to block direct sun)	Automated roller shade with solar tracking controls and local sensor inputs	Mechanized roller shades and daylight-redirecting blinds, controlled by remote or smartphone app-based schedules	Standard venetian blinds (louver tilt angle adjusted once per seasonal test to block direct sun)

Two of the integrated packages included roller shade retrofits, replacing standard venetian blinds. One system uses automated roller shades to control for visual comfort, with a solar tracking algorithm hosted in the controls server also connected to two local sensors, one rooftop irradiance sensor for real-time sky condition (e.g., cloudiness) and one window-based illuminance sensor as a proxy for glare. Based on solar position and sensor data, the system manages shade height to limit direct solar penetration depth and mitigate glare while allowing daylighting when possible. This method of control theoretically can provide more daylight availability than a manual shade scheme, since it has been found that most occupants in offices do not regularly adjust shade position, which is often set no more than monthly based on longer-term solar trends [15], potentially diminishing useful daylight day-to-day. The other test system with a roller shade element included mechanized roller shades and blinds with onboard batteries and photovoltaic chargers at the window, obviating the need for any hard wiring for power. This design employs roller shades for the bottom two thirds of the window and daylight redirecting blinds for the upper third of the window, with upwardly concave reflective louvers to reflect daylight onto the ceiling plane deeper into the room. The motorized shades and blinds are controlled by remote control or smartphone application, and at the time of the study did not offer automated control based on solar position or sensors.

3. Methods

In the FLEXLAB[®] test facility (Flexlab.lbl.gov), pictured in Figure 1, integrated building systems can be tested through varying weather, daylighting, occupancy, and load conditions. The facility enables evaluations of heating, ventilation, and air conditioning (HVAC), lighting, windows, building envelope, control systems, and plug loads, in any combination, with high-resolution measurements of relevant performance parameters (thermal loads, electric power, radiant flux, lighting and glare, interior, and exterior temperature, and more). To evaluate the performance and energy savings of the integrated lighting retrofit systems, three options were tested alongside specific baseline systems representing “standard” conditions (for example 3-lamp fluorescent troffers with scheduled on/off control and no daylight dimming). Equivalent interior thermal loads (occupant thermal generators and plug loads) and HVAC setpoints and operation were implemented in parallel, side-by-side baseline and retrofit cells.



Figure 1. FLEXLAB test facility; with the rotating testbed shown at center.

The FLEXLAB environment is heavily instrumented and calibrated to provide essential performance data, and can be custom configured to evaluate specific building and zone types (in this case, perimeter open-office). Measurement and verification was carried out at high spatial and temporal resolution (e.g., minute-by-minute lighting power per fixture, workplane illuminance, daylight glare probability). Data collected during the experiments was analyzed to estimate savings potential specifically for deployment in the type of space evaluated (i.e., perimeter open-office with windows and daylight; results do not apply to interior zones without daylighting).

Each test cell in FLEXLAB is 20' wide by 30' deep. In each experiment, an array of illuminance sensors was placed at desk surface level (2.5' above-floor). High dynamic range (HDR) digital imagery was used to evaluate glare conditions from the windows and electric lights in terms of daylight glare probability (DGP) [16]. Electric lighting load was measured and trended via current transformers and voltage probes on each lighting circuit (typically one fixture per circuit). Internal air temperature was measured at various locations as well as overall thermal load for each cell (via hydronic-side flow and temperature measurements). The measured performance parameters are presented in Table 2.

Table 2. Measured performance parameters.

Monitored Parameter	Measurement System	Unit
Light level	Illuminance sensors and amplifiers	Illuminance (lux)
Glare	High dynamic range (HDR) cameras located at occupant eye height and facing occupant field of view, central processing units (CPUs) for processing data.	Daylight glare probability (DGP)
Lighting energy	1-min. average current, voltage, power per circuit	Power (watts), energy (kWh), normalized by area: W/ft ² , kWh/ft ²
Heating, ventilation, and air conditioning (HVAC) load	Instantaneous HVAC load and cumulative daily HVAC energy	Instantaneous thermal power (W) and thermal energy over time (kWh) and to maintain setpoints.

The testbeds in which the systems were evaluated had ceiling tiles with visible light reflectance of 0.88 and wall paint reflectance of 0.65, with measured ground reflectance outside of the test cells’ windows of around 0.20. The testbeds were operated over consecutive days on a normal workday schedule and each experiment involved several weeks of testing over multiple seasons (e.g., summer, fall, winter), to capture performance variation over a range of solar positions and climate conditions. Some experimental designs included reconfiguring building characteristics (window-to-wall ratio, dimming zone depth, and building orientation) so that findings could be applied to a broader set of buildings. We commissioned the integrated retrofit systems to operate according to experimental design parameters (i.e., scheduled on/off operation, daylight dimming, automated shade deployment), and verified proper operation through daily checks of trended data. At test conclusion, we aggregated, processed, and analyzed collected data. From the datasets, we computed hourly, daily, and seasonal averages for light levels, lighting energy usage, HVAC thermal load, and glare. In some cases, we then developed regression models to predict annualized performance, such as lighting energy savings as a function of sun position (maximum daily solar angle) and sky condition (average daily horizontal irradiance). Table 3 details the ranges of dates for the lab test of each system.

Table 3. Test period dates.

Season	Test System 1	Test System 2	Test System 3
Summer (highest sun angles, mostly clear sky)	9 May–10 August 2016	18 July–13 August 2018	n/a (test period used for different technology)
Fall (lower sun angles, mostly clear sky)	3 October 2016–4 January 2017 (continuous testing through seasons)	17 September–8 October 2018	29 September–10 October 2016
Winter (lower sun angles, often cloudy)		5 January–30 January 2019	6 December 2016–24 January 2017

For lighting energy, we calculated savings as the average daily difference between the baseline and retrofit lighting energy as measured in FLEXLAB over each test period, and typically normalized energy by area (kWh/ft²). To characterize light levels, we calculated average illuminance at the workplane during occupied hours. Lighting design criteria often prescribe minimum illuminance levels at the workplane, such as the Illuminating Engineering Society (IES) recommended practice of around 300 lux for common office work [17]. Glare was measured for typical seated occupant fields of view, including “worst-case” locations such as that of the occupant seated closest to the window. We compared baseline and retrofit cells’ daily fraction of time in each class of glare using the DGP scale [18]. (Imperceptible (<0.35; glare not noticed), perceptible (0.35–0.39, minor glare that does not impact ability to work),

disturbing (0.40–0.45, would prefer to lower shade or move, productivity is reduced), and intolerable (>0.45, glare bad enough to preclude working) [18].)

4. Results

4.1. Test System 1

Energy savings results for Test System 1 are summarized in Table 4.

Table 4. Test System 1 characteristics and energy savings.

Baseline System	Retrofit System	Lighting Energy Savings
LED lighting with no daylight dimming, manually operated venetian blinds. (existing building condition)	LED lighting with digital networked controls and zonal daylight dimming, automated roller shades.	South orientation: 19% West orientation: 24%

4.1.1. Configuration

The cell configuration for this evaluation was an open office layout with no cubicle partitions in the daylit perimeter zone of a commercial building. This test was carried out in the rotating FLEXLAB test cells, which allowed us to evaluate performance for south-facing and west-facing window configurations. We also tested performance for larger and smaller window-to-wall ratios. The baseline and retrofit lighting fixtures were pendant-mounted LED fixtures in three 12' rows running parallel to the window wall, with 8' spacing between rows. The dimmable LED fixtures were controlled by networked digital lighting controls with low voltage control wiring from a web-connected controls cabinet to the banks of lights and zone daylight sensor. The fixtures were tuned to provide 500 lux at the workplane and were scheduled on from 7AM to 7PM daily. For the retrofit package, zonal daylight dimming controls were set to standard (out of box) operation. The zonal configuration involves dimming multiple fixtures based on a single photosensor. In this case, each of three rows of fixtures was a unique dimming group, responding to one photosensor for the whole zone, with different responsiveness set for each group based on proximity to window wall (first row was the most responsive, and last row was the least responsive). Various attributes of the test system are shown in Figure 2 below.

An automated roller shade system was also implemented for this package. The roller shade fabric was a dark grey material with an openness factor of 3%. The system uses a solar position algorithm and radiation model and local radiometer and illuminance sensor inputs to determine shade position, blocking direct solar penetration deeper than 36" into the space at floor level (based on the building geometry, orientation, and latitude). The system relies on the ASHRAE clear-sky model to predict hourly solar radiation (direct normal irradiance and diffuse irradiance) for the building's latitude, every hour of the year [19], and sets roller shade position accordingly. The system compares the predicted clear-sky value to its radiometer reading; if the reading is below 65% of clear-sky (the default threshold in the system), the sky condition is considered cloudy and the shade position is moved up to allow more light in.

The baseline was an existing building condition with a lighting system of the same configuration and fixture type as in the retrofit case but with no daylight dimming. The baseline shade condition was venetian blinds with louvers set to horizontal (0°) position for all tests. Importantly, this test evaluated only the savings from daylight dimming and automated shading; the lighting systems were the same in both cells, so there were no source change energy savings (e.g., fluorescent to LED).

The window glazing for this test (baseline and retrofit) consisted of double-pane insulated glass units. Visible light transmittance was 64% with solar heat gain coefficient of 0.27. Two window-to-wall ratios were evaluated for this system; a standard of 0.4 and a smaller ratio of 0.3, accomplished by adding custom cut foam blocking to portions of the window.



Figure 2. Photograph of Test System 1 setup in the lab, with automated roller shades along the window wall, and daylight-responsive suspended LED fixtures overhead. Thermal loads are emulated with the mannequin and the vertical cylinders shown. Illuminance sensors are shown on the desk surfaces and the digital cameras capturing HDR imagery are visible near the window wall.

4.1.2. Lighting Energy Performance

Lighting energy savings varied widely through the seasons based on changing solar angles and automated shade deployment. For the south-facing configuration, higher savings were achieved in the summer test season (high sun angles meant roller shades were normally up) and lower savings in the winter season (lower sun angles resulted in shades often being rolled down to cover windows). (Note that managing glare for occupant visual comfort was prioritized over energy savings, including any strategy to increase solar heat gains during the heating season (e.g., winter) by keeping roller shades up to allow more sunlight in. Moreover, unless the shade material has a highly reflective outward-facing surface (not the case for this system), interior roller shades have minimal impact on overall thermal load in the space. Incident shortwave solar radiation that is transmitted through the window heats the conditioned space regardless of shade position via absorption by shade material or other mass in the room and reemission at longer wavelength.)The system was evaluated in a daylight perimeter zone, so energy savings results are relevant only for that space type and are not applicable to interior zones without daylight availability.

Lighting energy savings were actually higher on average for the west-facing configuration, and were highest for the winter period, as roller shades were mostly up (until later afternoon) due to there being no direct sunlight on the west façade for significant periods of each day. An example of lighting energy savings for the south-facing configuration for different test seasons is plotted below in Figure 3. Average energy savings for each hour are represented by the blue dashes, and for each day by the green dashes. The red lines represent average savings over the test period.

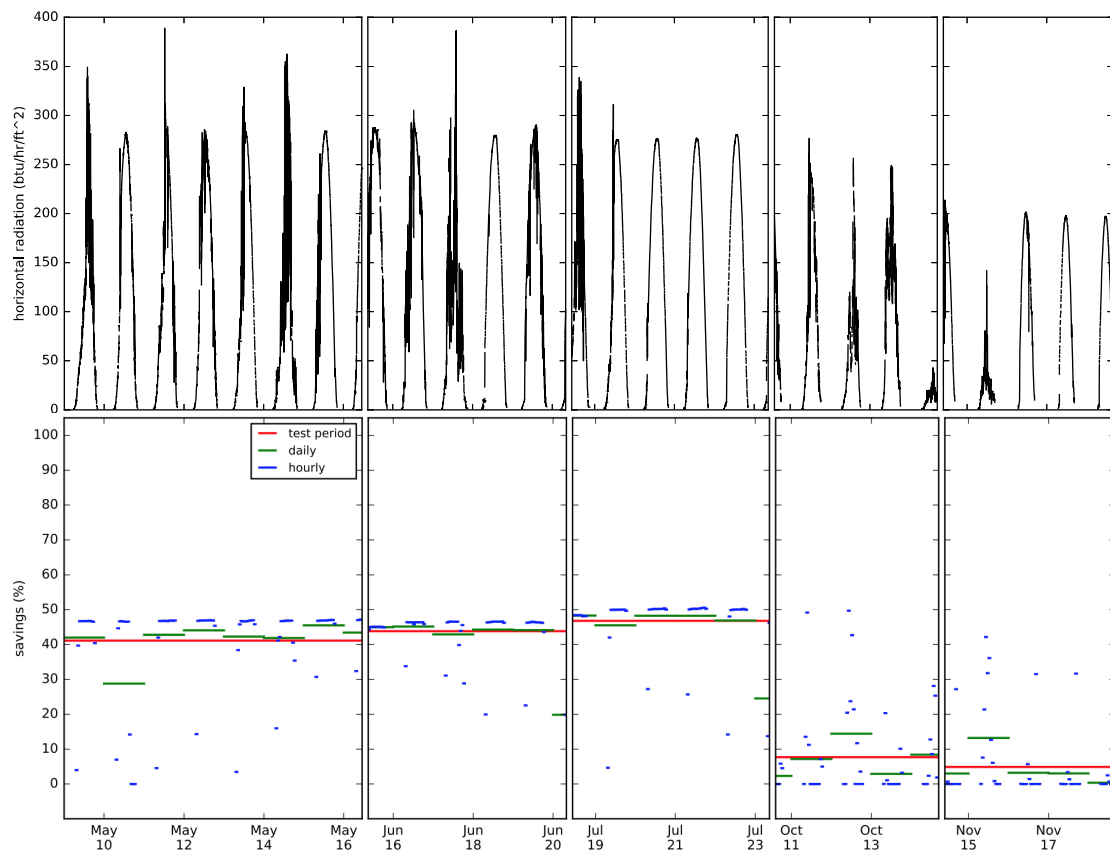


Figure 3. Exterior horizontal radiation measured at the test facility is plotted along with hourly, daily, and test period lighting energy savings for each seasonal test. This test configuration includes a south-facing window wall, for which low sun angles in the fall and winter correspond to the automated shades closing, reducing available daylight for dimming. Note that the cloudier days in October and November with the least horizontal radiation correspond to roller shade retraction allowing diffuse light in and actually increasing electric light dimming.

Based on experimental data, we developed a best fit regression model that predicted lighting energy savings as a function of maximum solar altitude per day and average daily horizontal radiation, as daylight dimming behavior depends on solar angle, atmospheric conditions (e.g., cloudy versus sunny), and how the shades are deployed. For the south orientation, we found an average annual lighting energy savings of 19%, with a range of 12–26% at 95% confidence. For the west orientation, savings were 24% on average with a range of 19–30% at 95% confidence.

4.1.3. Light Levels and Visual Comfort

Illuminance data showed that the integrated lighting retrofit system maintained illuminance at or above the 500 lux target through the test period. The system also maintained acceptable DGP levels, while for the baseline case (venetian blinds with horizontal louvers), there were significant periods of DGP values in the disturbing or intolerable range (direct sunlight entered field of view at lower sun angles), as illustrated in Figure 4.

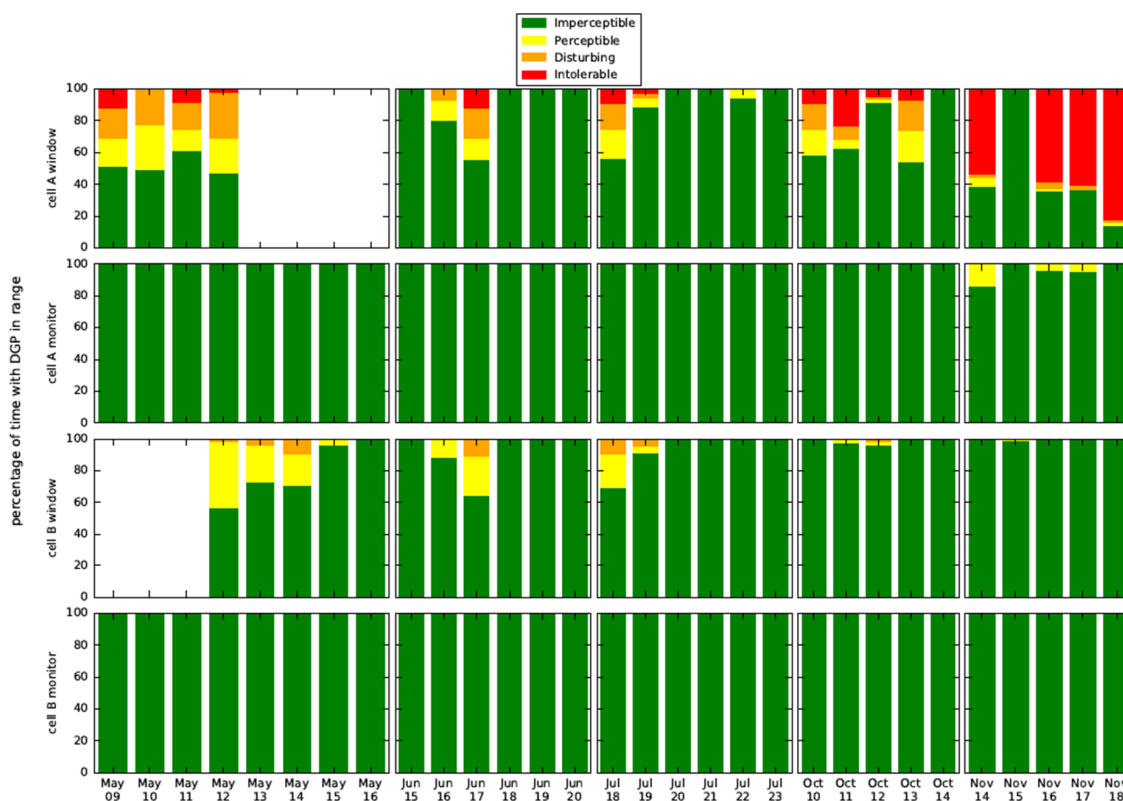


Figure 4. The daily fraction of time spent in each daylight glare probability (DGP) class (imperceptible (<0.35), perceptible (0.35–0.39), disturbing (0.40–0.45), and intolerable (>0.45)) is illustrated, with days lacking data shown in white. Day-to-day comparisons of the baseline cell (A) and retrofit cell (B), particularly for the view location facing the window, show improved glare performance for the retrofit cell. DGP classes are further described in Footnote 2.

4.1.4. Whole Building Energy

Whole building energy savings depend on how much of the building is impacted by the integrated lighting system retrofit. We estimated the impacted floor areas for medium and large office buildings using United States Department of Energy (DOE) reference buildings [20] and ran EnergyPlus simulations with reference HVAC system types to determine whole building energy impacts. The lighting energy savings as measured and then annualized per regression model were applied to the building model to calculate whole building savings. From our modeling, we estimated 2.6–3.5% savings for large and medium office buildings respectively.

4.2. Test System 2

Energy savings results for Test System 2 are summarized in Table 5.

Table 5. Test System 2 characteristics and energy savings.

Baseline System	Retrofit System	Lighting Energy Savings
Existing building baseline: 3-lamp T8 (90 W), no daylight dimming. California Title 24 (2016) code-compliant baseline: 2-lamp T5 (62 W), with zonal daylight dimming.	Dimmable LED fixtures with wireless networked luminaire-level sensors and daylight dimming. Motorized, self-powered shades and daylight-redirecting blinds.	62% to 76% (existing building baseline) 49% to 62% (code-compliant building baseline)

4.2.1. Configuration

This integrated lighting retrofit system was tested in a south-facing daylit perimeter zone. The window type for this test was single pane clear glass with 89% visible transmittance and solar heat gain of 0.97, with aluminum frames. The office layout for this test consisted of one row of three desks (from south window wall to back wall) with 5' cubicle partitions separating each, shown in Figure 5 below. The lighting layout was 2' × 4' recessed troffers at spacing of 8' × 10' on-center. Two baseline lighting conditions were defined; one being an existing building standard with basic scheduled on/off control of 3-lamp T8 fluorescent lights (around 90 W each), with no daylight dimming, and the other being a code-compliant baseline condition (California Title 24, 2016) consisting of lower-wattage, dimmable 2-lamp T5 fluorescent fixtures (62 W at full power), scheduled on/off, and with zonal daylight dimming. Two window-to-wall ratios (0.40 and 0.50) were also tested to compare performance and energy savings with different glazing areas.

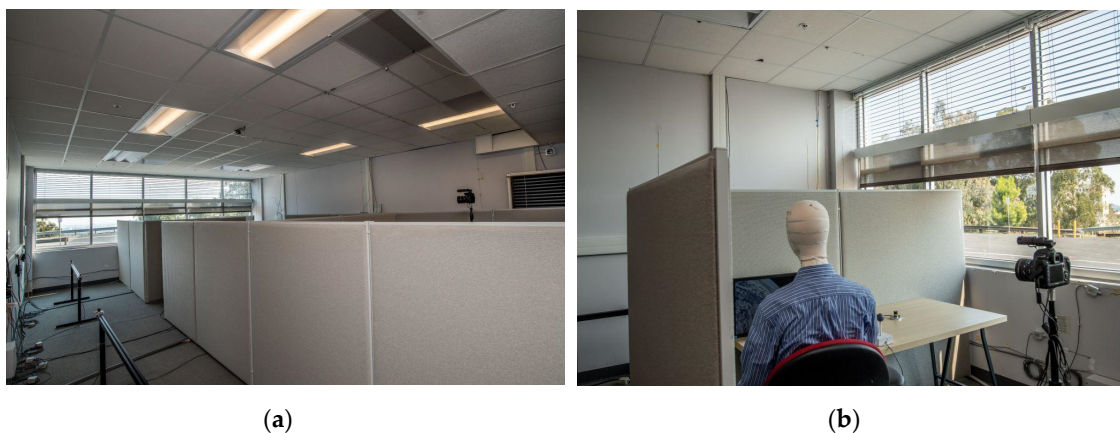


Figure 5. Photographs of Test System 2 setup in the lab: (a) view from back of test cell showing daylight dimming LED lighting system and three office cubicles; (b) view of cubicle near windows, with HDR camera for glare evaluation at occupant seated position. The mechanized roller shades and daylight redirecting blinds are shown along the window wall.

The baseline shading system was simply standard venetian blinds, lowered across the windows, with louver tilt angle adjusted seasonally to block direct light on the desks nearest the windows. The premise of this adjustment schedule conforms to research indicating that manual shade devices in offices are commonly adjusted with low frequency (perhaps only monthly) to control for longer-term solar conditions rather than daily sun movement [15].

The retrofit fixtures were 35 W dimmable LED retrofit kits with wirelessly networked luminaire-level sensors and controls. From nameplate wattage alone, the lower-wattage LED fixture retrofit represents 61% energy savings from the existing building baseline, and 44% energy savings from the code-compliant baseline. For daylighting, each fixture was equipped with luminaire-level controls and dimmed based on its own photosensor. Fixtures closer to the window dimmed the most when daylight levels were high, while fixtures in the rear of the room dimmed very little.

The retrofit shading system consisted of a mechanized roller shades and blinds package that is self-powered via onboard lithium ion rechargeable batteries and photovoltaic charging modules at the window. The bottom two thirds of the window area are covered by white/bronze roller shade material with a 3% openness factor fabric and the white side facing the window for higher reflectivity. Aluminum blinds with a reflective upper surface for daylight redirection into the space cover the top third of the window area. The shading system was controlled by smartphone-based application or remote control and was seasonally adjusted to reduce glare based on seasonal sun angles. The shade and blind positions were dictated by seasonal sun angles and the building geometry; in the summer, the roller shade portion was rolled all the way up and the blinds were tilted to -37° to redirect sun

deeper into the space. In the fall, the shade was rolled mostly down (9" of window exposed) and the blinds were tilted to +10° for some redirection of sunlight while avoiding direct glare, and in the winter the shade was all the way down with blinds at +45° [12]. Control events could be scheduled in the smartphone application, but at the time of the test, automated control based on sun position and local sensors was not an available feature.

4.2.2. Lighting Energy Performance

From test data we calculated lighting energy for the existing building baseline and the retrofit condition and found energy savings of around 62% for the winter season (less daylight dimming) to 76% for the summer season (more daylight dimming). Relative to the Title 24 baseline, lighting energy savings ranged from 49% in winter to 62% in summer. Importantly, the system was evaluated in a daylit perimeter zone, so energy savings results are relevant only for that space type and would be different for an interior location without daylight availability.

4.2.3. Light Levels and Visual Comfort

For work plane illuminance, the design target was at least 500 lux during occupied periods. We computed the distribution of light levels during occupied hours (median, 1st and 3rd quartile, and 5th and 95th percentile) for each desk, as shown in the Figure 6 plots for summer and winter data. We primarily compared results for the desk in the center cubicle (desk 2), which due to its location in the center of the test cell was more completely surrounded by the electric lighting system (fixtures over desk and on either side) and therefore the best representation of the electric lighting system performance. The front and rear cubicles were close to walls and received less illumination from the fixtures. Experimental data showed illuminance in the retrofit cell to be slightly below the design target of 500 lux on average (essentially under-specified LED fixture power), so illuminance and lighting power data were post-processed to raise light levels to the design target before comparing with the baseline cell and calculating energy savings.

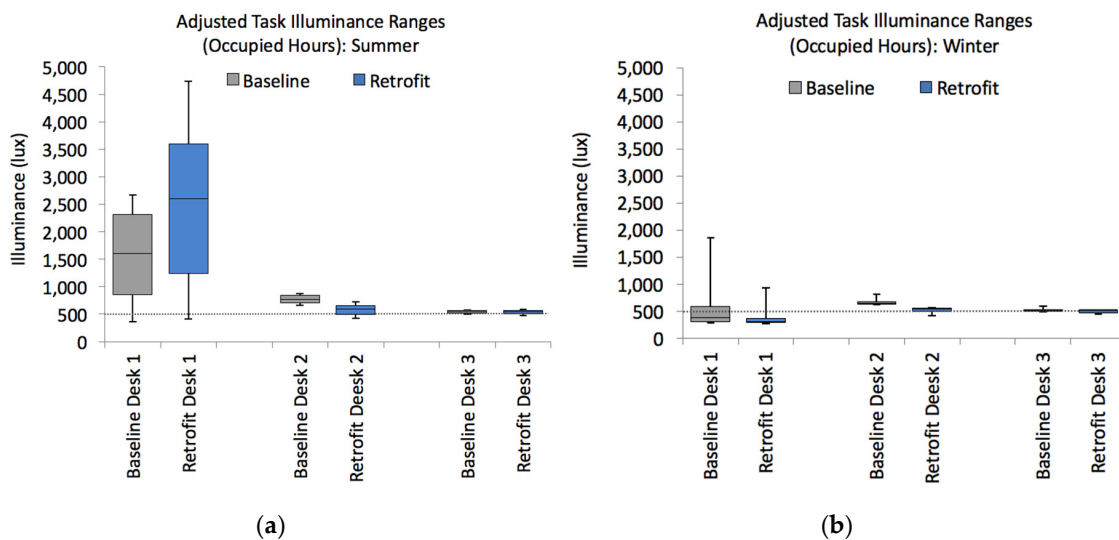


Figure 6. Box and whisker plots of baseline and retrofit horizontal illuminance data distributions on the three desks in the test space, for the full window height, existing building baseline (FWEB) test configuration: (a) summer test period; (b) winter test period. The plots illustrate 5th and 95th percentile values at the whiskers, and first and third quartile values at the box boundaries, and median values at the box inner line. The data were adjusted via post-processing as described in text above to achieve design target for Desk 2, the desk in the center cubicle.

Glare was well controlled in the baseline and the retrofit cells by the respective shading strategies. Very little time was logged in glare ranges other than imperceptible. As an example of how glare data is captured in the test cells, Figure 7 shows false color luminance mapping captured by the HDR cameras at the occupant field of view in the front cubicle for one time-stamp (noon) of one test day (27 September 2018), with points of highest luminance labeled.

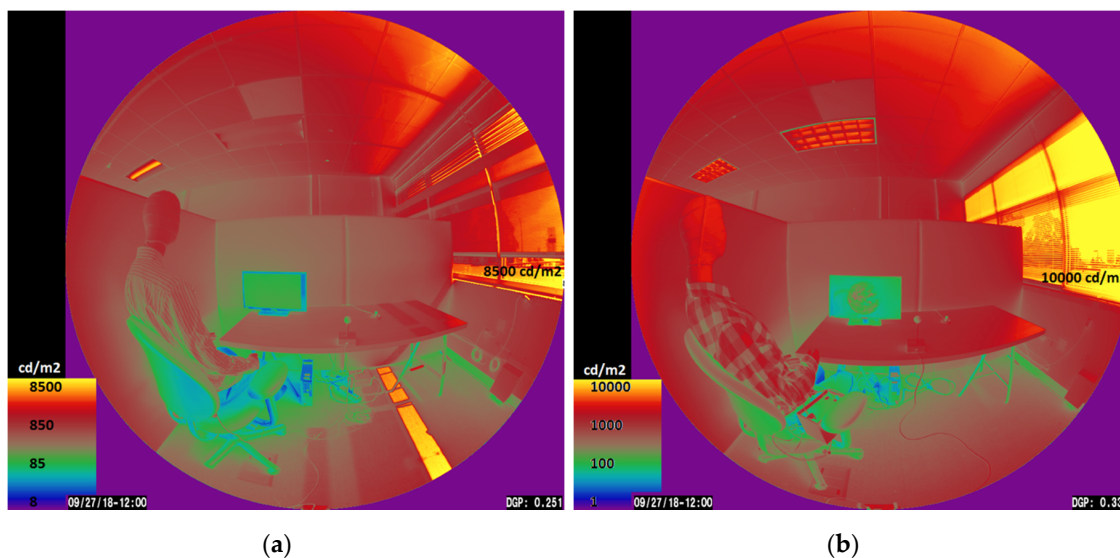


Figure 7. False color images from the HDR cameras and processors show luminance distributions in the space and calculated DGP, for: (a) the retrofit test cell, and (b) the baseline test cell.

4.2.4. HVAC Energy

The lower-wattage lighting system leads to lower internal heat gains in the perimeter zone and changes in the facade may impact heat gains from the windows as well, given the roller shade fabric’s white reflective surface. The integrated lighting system retrofit generally resulted in daily cooling load savings ranging from 28% to 43% relative to the existing building baseline condition (higher wattage fluorescent fixtures, venetian blinds), and some heating load penalty, from −17% to −53%.

4.3. Test System 3

Energy savings results for Test System 3 are summarized in Table 6.

Table 6. Test System 3 characteristics and energy savings.

Baseline System	Retrofit System	Lighting Energy Savings
General lighting plan grid of 3-lamp T8 fluorescent fixtures, no daylight dimming (existing building baseline condition).	Workstations-specific LED fixtures, wireless networked luminaire-level sensors and controls, tuning, daylight dimming.	72%

4.3.1. Configuration

The office layout for this test system was a low-partition shared work environment with a work surface divided into six workstations as pictured in Figure 8. The window glazing was single-pane clear glass representative of the existing building vintage designated for the baseline. Visible light transmittance was 89% with solar heat gain coefficient of 0.84. The window-to-wall ratio for the south-facing wall was 0.48. The window shading condition included manual venetian blinds in the baseline and retrofit case, with blind louvre angle seasonally adjusted to block direct sun. Like the Test

System 2 baseline, the premise of this adjustment schedule is research findings regarding frequency of adjustment of manual shades by typical office occupants [15].

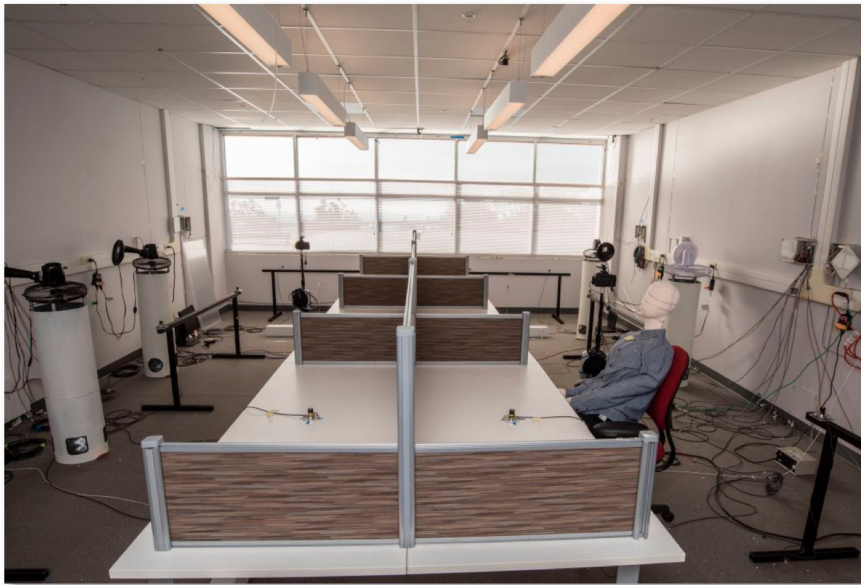


Figure 8. Photograph of Test System 3 setup in the lab. The workstation-specific lighting design is visible, with daylight responsive LED pendants located over each workstation.

The general lighting plan for the basecase included $8' \times 8'$ spacing for six fixtures, in a typical ceiling grid. The baseline was existing building conditions, and baseline fixtures were non-dimmable $2' \times 4'$ 3-lamp T8 fluorescent troffers, around 90 W each, controlled by schedule to turn on during occupied hours. For the integrated lighting system retrofit, a workstation-specific lighting design with one fixture over each workstation was implemented to deliver light to the workplane in a more targeted fashion. The dimmable 4' LED direct/indirect pendants were around 56 W at full output, representing 38% energy savings from the baseline fixtures. The LED fixtures included luminaire-level controls, task tuning, and daylight dimming. Similar to Test System 2, each fixture dimmed based on its own photosensor, with fixtures closer to the window dimming the most when daylight levels were high, and fixtures in the rear of the room dimming very little. Multiple configurations were tested including different tuned light levels at the occupant's workstation (300 and 500 lux setpoint). The system was also controlled by automated schedule to turn on only during occupied hours.

4.3.2. Lighting Energy Performance

The LED fixtures with dimming controls installed in the workstation-specific lighting design saved significant energy compared to the fluorescent fixtures in the zonal configuration. Savings depended on daylight availability, with highest savings in the summer periods. The system was evaluated in a daylit perimeter zone, so energy savings results are relevant only for that space type and would be different for an interior location without daylight availability. We found up to 91% lighting energy savings in the daylit zone during daylit hours, and 72% annual lighting energy savings overall. Similar to Test System 2, we developed a regression model to predict lighting energy savings as a function of horizontal global radiation, with measured and model-predicted results shown in Figure 9 below.

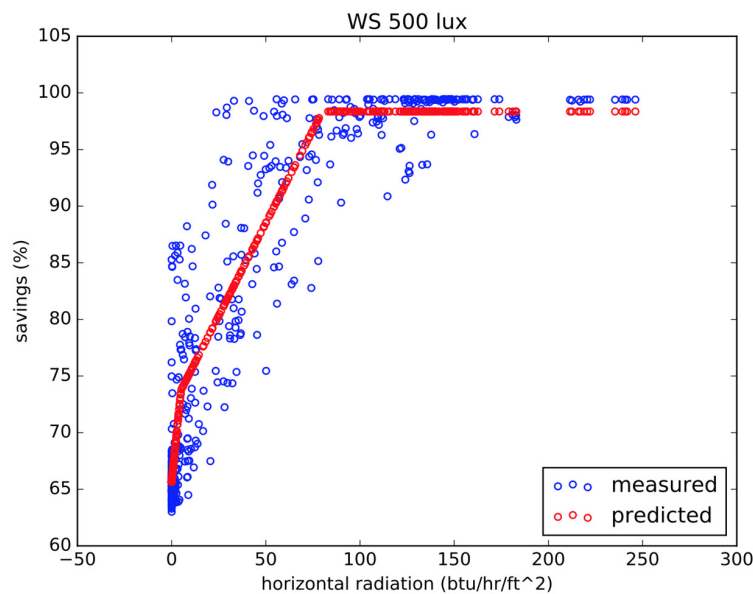


Figure 9. Plot of energy savings test data for the 500 lux setpoint test configuration (WS 500 lux) as a function of measured external horizontal radiation (blue), and predicted savings (red) from our piecewise regression model.

4.3.3. Light Levels and Visual Comfort

For all test conditions, workplane illuminance levels met or exceeded the minimum design criteria. Generally, we found higher light levels closer to the window. There was no appreciable difference in DGP measured between the basecase and test system conditions. In both cases we found that glare near the window was sometimes an issue during periods of high illuminance and low sun angles. Solutions would include manual blinds operation to close louvers at those times, or an automated system to control glare.

4.3.4. HVAC Energy

Using the annual lighting energy savings validated through FLEXLAB testing, an equivalent whole building energy savings was determined from EnergyPlus simulation of DOE reference models [20]. The annualized lighting energy savings were applied to the south facing perimeter zones in each floor of the reference model building, along with all southeast and southwest corners. Based on building energy simulations we calculated whole building energy savings of 5% to 11% for large and medium commercial offices respectively.

5. Discussion

5.1. Proven Energy Savings

Results from laboratory testing of the three retrofit systems were positive in terms of quantified energy savings and lighting performance (all systems were evaluated in south-facing perimeter office zones). Savings varied based on the zone configuration and elements of the integrated packages, with systems that included a retrofit from fluorescent to LED along with daylight dimming controls offering more benefit than controls alone. Additional features such as layout changes (e.g., from general lighting to workstation-specific lighting) provided higher energy savings. Mechanized and automated shading components also provided better glare control from the window façade. Savings ranged from around 20% for the system with daylight dimming and automated shading controls, but no source change savings (fluorescent to LED), to over 70% savings for retrofit packages that included source change to LEDs with advanced controls and either shading system changes (venetian blinds

to mechanical roller shades with daylight redirecting blinds) or lighting layout improvements (workstation-specific lighting design).

5.2. Integrated System Elements

Integrated systems are more complex to implement than the simple LED fixture change-outs and are less commonly included in commercial retrofit projects. Energy efficiency retrofits and retrofit programs could however achieve larger energy savings by promoting integrated systems that are shown to save more energy and potentially improve lighting system performance, including daylighting elements. Continued research to further validate benefits of integrated lighting system retrofits is still needed in order to support scaled adoption.

There is an important distinction between what might be called passive interaction versus active interaction between disparate building systems. In the case of daylighting, the systems we studied integrated electric lighting and advanced controls elements and in two cases window shade elements into individual packages. The interaction between shading systems and lighting controls however, was essentially passive; the shade's effect on admitted daylight results in light level changes detected by the lighting controls, which respond accordingly. There is no digital data exchange between the two systems however. On the HVAC side, we have another passive interaction, in that lighting power in the space affects HVAC cooling and heating requirements, again, without any data exchange between systems. We were able to quantify some of the HVAC energy impacts from implementing the lighting retrofit packages, typically cooling savings due to lower internal loads, but there was no active interaction or communication.

However, there is an emerging opportunity for deeper integration of lighting and controls packages with other building systems, including HVAC. For example, it is possible with market-available technologies to exchange sensor data from the lighting system to the HVAC system in order to implement occupancy-based setpoint adjustments and ventilation strategies for example. This may represent a step-change in energy savings potential from these advanced lighting controls systems and even more efficient integrated retrofit packages. The systems studied here did not include active HVAC integration, but current and upcoming research is exploring lighting packages with this additional level of integration.

5.3. Evaluating Daylighting Performance

The laboratory evaluations of the three test systems were primarily focused on overall energy performance along with maintenance of acceptable glare and illuminance conditions in the space. The data analysis was less focused on specific daylighting performance, such as disaggregating measured light into electric and daylight components and assessing daylight availability, autonomy, saturation, etc. For a more in-depth treatment of the daylighting performance of the lighting and shading packages, it would be possible to process the project data for more daylight-specific metrics, such as Daylight Autonomy and Continuous Daylight Autonomy [21], and Useful Daylight Illuminance [22], though this was outside of the scope of this study.

5.4. Implementation Experience

Success of integrating lighting retrofit packages will not just hinge on energy and lighting performance. Implementation considerations are also key, including the ease, or difficulty, of installation and integration with existing building infrastructure, commissioning and programming, and operation and maintenance over time. From the implementation experience in FLEXLAB, we found that the LED retrofit step is relatively straightforward (simply swapping fluorescent fixtures with LED fixtures), and that the controls systems with wireless networking and sensors integrated into fixtures were the easiest to set up. Wired digital controls (Test System 1) required more on-site labor, for example to run low voltage wire pairs from controls cabinet to fixtures, and a field technician for more complex commissioning. For the façade integration, we found that automated operation of roller shades, such as

demonstrated in Test System 1, was the most effective and reliable shading strategy. Mechanized systems that require ongoing user inputs and interventions, such as the periodic adjustments via remote control or smartphone app for shade control in Test System 2, were more tedious (the manufacturer of that system is currently developing automated shade control features). Overall, however, implementation experience at the experimental level may not be scalable, so high priority should be placed on collecting actionable information on implementation experience during field evaluations of integrated lighting system retrofits. Well-documented lessons from installation, commissioning, and initial operation will be critical. As the base of knowledge and experience around integrated lighting system retrofits grows, the barriers of unfamiliarity that might lead to reluctance on the part of project implementers and installation contractors should be lowered.

5.5. Cost Effectiveness

Cost effectiveness will also play a significant role in adoption of integrated lighting retrofit packages. LED cost competitiveness has improved dramatically in the last decade, but integrating sensors and controls adds costs, from \$53 to \$136 per fixture according to a 2018 study [23], depending on the type and complexity of the system. These costs need to be justified by the added benefits. For Test Systems 2 and 3, the retrofits from fluorescent fixtures to LEDs provided energy savings from 38% to 61% before including energy savings due to controls performance. The incremental energy savings from the advanced controls (task tuning and daylight dimming for example) may or may not pay for the extra costs of the controls, depending on the quantity of those savings and electricity costs. In some cases, the motivation to install the integrated package will come down to more than energy savings benefits alone, especially for costly façade retrofits, such as automated shading systems. So-called non-energy benefits, such as comfort, satisfaction, productivity, and even aesthetics, could prove more valuable than the energy savings. Quantifying these benefits is inherently more difficult, but for something like a façade retrofit, where incremental savings due to daylight dimming will likely not justify the extra costs, accounting for these benefits will be crucial.

A recent study on cost-effectiveness of simple LED retrofits and several integrated lighting system retrofits, including two of the Test Systems discussed here, found that for retrofit calculations that include full project cost (the alternative being no action, or theoretically zero cost), integrated lighting systems simple paybacks (project cost / annual cost savings) ranged from 14 to 27 years [24]. Such long paybacks do not meet many decision-makers' thresholds to invest. Cost-effectiveness improved for renovation, replace on burnout, and new construction scenarios that consider only the project's incremental cost over a "standard specification" option (what would be installed otherwise), with simple payback ranging from 2 to 5 years for lighting and controls packages, and almost 11 years for a package that includes automated roller shade technology. The study underscored the ongoing need at current market costs for utility incentives targeting integrated lighting packages to promote adoption, and identified reduction of transaction costs through standardized guidance as key to streamlining implementation.

6. Conclusions

LED fixture technology for general lighting applications is a mature retrofit solution for commercial buildings, but with installed penetration at 28% in 2020, there is still significant opportunity for energy savings from fixture retrofits alone. Networked lighting controls technologies, including luminaire-level sensing and control, pair well with dimmable LED fixtures and offer additional functionality and savings. With most existing buildings still using lighting controls, such as simple on/off switching and scheduling controls, or occupancy sensing at the most, there is clearly much room for growth in implementation of advanced lighting controls. Integrating controls upgrades with lighting retrofits is therefore a logical pairing; indeed, modern building energy codes in most locations will require some level of controls upgrade during major retrofit, to include for example photocontrol for daylight zones. Finally, facade-shading systems that optimize daylight availability while controlling for glare

represent another opportunity to integrate project impacts across technologies and systems to improve daylighting, dimming potential, and energy savings.

We studied three unique integrated system packages. Each was effective in delivering expected functionality (high levels of sensing, control, and automation for electric lighting performance), providing the required lighting service, and saving lighting energy. It is important to emphasize that we found a wide range of energy savings for the different packages, from 20% to over 70%, depending on baseline conditions (what systems are already installed in a building and how much energy they use) and retrofit technologies implemented (fixture retrofits, advanced controls, façade systems, lighting design changes).

Results from these lab tests help validate and bound energy savings assumptions for the system packages studied, and can help to promote larger-scale adoption in the retrofit marketplace, including through utility efficiency program support, where validated energy savings are key. The impetus for these laboratory studies was to establish performance ranges and results that can be used to develop standardized savings estimates and program or project guidance useful to stakeholders, such as utilities and building owners/operators.

Along with these findings and further lab validation in the future, more field experience, and shared learnings on implementation will be crucial for scaled adoption. Similarly, for better evaluating integrated systems packages, cost effectiveness targets and expectations need be developed holistically, based on lab-validated and field-verified avoided costs due to energy savings and quantified non-energy benefits, where possible. Finally, new opportunities to integrate across building systems, including active sharing of lighting controls data with HVAC systems for energy efficiency strategies, such as demand-controlled ventilation, represent a next frontier for integrated system retrofit packages.

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