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Retrofit Demonstration of LED Fixtures with Integrated Sensors and Controls

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The Green Proving Ground program leverages GSA’s real estate portfolio to evaluate innovative sustainable building technologies and practices. Findings are used to support the development of GSA performance specifications and inform decision-making within GSA, other Federal agencies, and the real estate industry. The program aims to drive innovation in environmental performance in Federal buildings and help lead market transformation through deployment of new technologies.

DISCLAIMER

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Abbreviations

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ASHRAE 90.1-2010	ASHRAE–published Energy Standard for Buildings (except low-rise residential); the national standard for commercial building energy codes in the U.S.
CALiPER	Commercially Available LED Product Evaluation and Reporting (program of U.S. DOE)
CBP	Commercial Buildings Partnership (initiative of U.S. DOE)
CCT	Correlated Color Temperature
CEC	California Energy Commission
CRI	Color Rendering Index; a measure of the ability of a light source to reproduce colors accurately.
DOE	U.S. Department of Energy
EIA	Energy Information Administration
EUI	Energy use intensity. This is a metric for characterizing energy use defined as the amount of energy used in a space over a given time period divided by the area of the space and the time interval studied (kWh/ft^2/year).
FC	Foot-candle, a unit of illuminance (lumens/ft^2).
GHG	Greenhouse Gas
GPG	Green Proving Ground program of GSA
GSA	U.S. General Services Administration
GWE	Global warming effect. This is a metric for characterizing greenhouse gas emissions and is a product of GHG emissions and their specific time-dependent global warming potential (g $CO_{2,eq}$ /kWh electricity generated, kg $CO_{2,eq}$/ft^2/year).
HVAC	Heating, ventilation, and air conditioning systems
kWh	Kilowatt-hours; a unit of electric energy.
LBNL	Lawrence Berkeley National Laboratory
LCC	Life-cycle cost; cost-effectiveness metric that characterizes the costs over the lifetime of the tested technology and takes into account costs from the initial investment, energy savings, operation & management, and salvage. The costs are converted to present value (PV) and are recorded here in $/ft2 and $/fixture.
LEDs	Light-emitting diodes, also known as solid state lighting (SSL).
LPD	A metric for characterizing the lighting power in a given area, defined as lighting wattage divided by the corresponding floor area (watts per square foot).
LPW	Lumens per watt (lm/W); a unit of light source efficacy in converting electric energy to visible light.
MWh	Megawatt-hours; a unit of electric energy.

NPV	Net present value; the net present value is the sum of the present values of any present or future cash flows, both incoming and outgoing.
PBS	Public Buildings Service of GSA; the organization that has jurisdiction, custody, or control over more than 370 million square feet of building stock in over 9,000 Federal buildings.
PF	Power factor is defined as the ratio of the active power to the apparent power (the product of root mean square (rms) voltage and rms current) and is a unitless value ranging from -1 to 1. Power factor represents the amount of current and voltage that the customer uses as a fraction of what the utility supplies. In this study, we look at ballast power factor where high power factors (> 0.9) are preferred, as low power factors may result in unusable power capacity in the electrical distribution system.
R_9	The CRI related to strong red tones. R_9 is an important additional CRI to consider as strong reds are prevalent in skin tones and indicate whether the light source will be perceived as warm.
R_a	The general CRI, calculated as an average of the CRIs R1-R8, covering relatively low saturated colors evenly distributed over the complete range of hues.
RF	Radio frequency
RMS	Root mean square
SIR	Savings-to-investment ratio; the cost-effectiveness ratio of life-cycle savings from an energy improvement to the initial investment cost. If greater than one, the investment is cost-effective.
SPD	Spectral power distribution; the distribution of a light source's luminous flux per wavelength of visible light (380 to 760 nanometers).
SPP	Simple payback period; a cost-effectiveness metric that characterizes the length of time required to recover the cost of an investment, defined as the cost of project over the energy savings at the site per year.
THD	Total harmonic distortion characterizes the power quality of electric power systems and is a measure of the deviation from a sinusoidal waveform. Lower THD (<20%) means a decrease in peak currents, heating, emissions, and core loss in motors. A high THD may reduce power factor. THD is defined as the ratio of the sum of the powers of all harmonic components of a signal to the power of the fundamental frequency.
Tlm-hr	Teralumen-hour, a unit of lighting service defined as the product of a light level (lumen) and the annual hours of operation.
TWh	Terawatt-hours; a unit of electric energy.
WPE	Workplane efficacy.

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I. Executive Summary

A. BACKGROUND

The commercial sector in the United States uses more than a third of total end-use electricity, with interior lighting accounting for 26% of the electricity used in those buildings. Recessed linear fluorescent fixtures, also known as troffers, are the major lighting technology used to illuminate interior commercial spaces, accounting for more than 50% of the installed commercial fixture base.

Light-emitting diodes (LEDs) for use in general lighting applications, such as commercial interior lighting, are showing rapid and continuous advances, and LED fixtures to replace linear fluorescents are achieving efficacies (lumens/Watt) above those of modern fluorescent lighting systems. The rated lifetimes of LED fixtures are typically at least 50,000 hours, well above the expected life of fluorescent lamps; other advantages include higher controllability (*e.g.*, easier dimming and on/off cycling) and greater durability. Installations of indoor LED troffers are on the rise, growing by a factor of 11 in only two years, from 2010 to 2012, and the Department of Energy (DOE) is seeing LED fixture costs decrease, with the electricity and maintenance costs savings offsetting the extra costs of the LEDs in many applications.

A commercial lighting system also includes the controls that determine when and how fixtures operate. Lighting controls at the most basic level include only manually operated wall switches. Scheduled on/off operation based at the lighting relay panel level is common in commercial buildings. Additional control layers include institutional tuning (to reduce maximum fixture light output through dimming based on application), occupancy sensor-based light switching, and dimming based on daylight availability; these all are considered advanced lighting controls strategies for the purposes of this study. Most commercial buildings do not include advanced lighting controls systems due to high equipment costs and high labor costs related to controls wiring, commissioning requirements, system complexity, and laborer unfamiliarity. A previous GPG study underscored these issues, finding solid retrofit energy savings at seven demonstration locations (26-66%, averaging around 1.5 kWh/ft^2/year), but with high project costs resulting in most of the projects not being cost-effective.

A turnkey lighting system with efficient fixtures and integrated advanced controls capabilities that can be more easily installed and commissioned may lower the cost barrier and enable more widespread implementation. This GSA Green Proving Ground (GPG) program study seeks to demonstrate whether a market-available LED fixture system with integrated sensors and controls can significantly decrease energy consumption in existing commercial buildings while maintaining or improving lighting quality. With the controls and sensors integrated into the fixtures, the demonstration technology is meant to allow for implementation of advanced lighting controls at little to no additional labor costs, which has previously been a hurdle in advanced controls adoption. The integrated LED fixture and integrated controls system also allows for a simple path to building energy code compliance, with ASHRAE 90.1-2010 and other building codes including stringent lighting power density requirements and controls requirements, such as automatic shut-off, occupancy sensors in offices, and daylight dimming controls in certain situations.

This study examines results from two demonstration locations where the retrofit system was installed and evaluated. Both sites underwent a one-for-one replacement of existing 2’x 4’ fluorescent fixtures with the turnkey package of LED fixtures with integrated occupancy and daylight sensors and controls to turn the fixtures on and off, and dim and brighten them according to conditions in the office. This study evaluates the energy savings, photometric performance, occupant satisfaction, and cost-effectiveness associated with implementing LED fixtures with integrated controls compared to the existing lighting systems in the spaces. While this study's primary focus is an integrated LED lighting and lighting controls system, the energy savings that would be achieved from a simple fluorescent-to-LED fixture switch were also estimated and compared to the energy savings that were captured by the LED fixtures with integrated controls. Cost-benefit estimates for the two options are compared as well.

B. OVERVIEW OF THE TECHNOLOGY AND DEMONSTRATION LOCATIONS

The higher-efficacy LED light source evaluated here provides more lumens at a lower electric power demand compared to standard fluorescent systems. The integrated controls also allow for tuning of fixture groups to reduce fixture power from maximum output to medium or low levels, if those settings meet the lighting needs of the space. Occupancy sensors integrated on each fixture detect when the immediate surroundings are occupied and turn fixtures on to the tuned power setting in response. Fixture groups programmed during system commissioning respond to occupancy patterns such that all fixtures in the group turn on to a low background level if any fixture within the group senses occupancy. Fixtures relay occupancy readings to the group through wireless communication. Only fixtures that individually sense occupants in their immediate vicinity brighten to the full-tuned output setting. Finally, each fixture includes an integrated daylight sensor for daylight harvesting. Each fixture can lower its output and reduce electric lighting usage if sufficient daylight is present.

The LED fixtures with integrated sensors and controls were installed in two study areas, detailed below, with all fluorescent fixtures being replaced by LED fixtures. At both demonstration locations, the fixtures were commissioned to the medium institutional tuning setting to provide appropriate light levels while reducing fixture wattage and increasing energy savings.

CHICAGO METCALFE

The Ralph H. Metcalfe Federal Building is a 28-story building located in downtown Chicago, Illinois. The study area is the majority of the tenant office space on the 17th floor, excluding common areas such as the elevator lobby, mechanical rooms, and bathrooms. The study area consists primarily of a large open office area that extends along the north, west, and south perimeter of the building, with six private offices, six conference rooms, two break rooms, and two copy rooms. The study area covers approximately 19,750 ft^2. The existing lighting system was comprised of approximately 254 recessed 2'x 4' 3-lamp parabolic troffers and 5 recessed 2'x 2' parabolic troffers. The fixture density averaged about 76 ft^2 per fixture.

ATLANTA SUMMIT

The Peachtree Summit Federal Building is a 30-story building located in downtown Atlanta, Georgia. The study area is located on the south half of the 28th floor, excluding the non-tenant corridors and various interview rooms, a lobby/waiting area, and other non-office spaces. The demonstration area contains a large open office area that wraps around the perimeter of the space, two private offices, two conference rooms, and one break room. The study area covers approximately 12,900 ft^2. The existing lighting system included 131 recessed 2'x 4' 2-lamp troffers and 6, 2' X 2' 2-lamp fixtures. The fixture density averaged around 94 ft^2 per fixture for the study area.

C. STUDY DESIGN AND OBJECTIVES

This study characterizes the technical performance of the LED fixtures with integrated sensors and controls based on measurements and data collected at the demonstration locations. The focal points of the technical analysis are energy savings, photometric performance, occupant satisfaction, and cost-effectiveness. To carry out the analysis on energy usage, lighting circuit energy for the study areas was metered during pre-retrofit and post-retrofit stages. Energy delivered by the lighting branch circuits was measured at the lighting panels that power the fixtures in the study areas.

To determine whether the retrofit demonstrations supplied the necessary light levels and color characteristics for an office environment, illuminance (*i.e.*, "light levels," in foot-candles), color temperature (CCT) and color rendering (CRI) were measured pre- and post-retrofit. Desktop illuminance measurements were taken at the primary work location and mean, median, quartile, minimum, and maximum pre-retrofit and post-retrofit light levels were compared. Average light levels were reviewed against GSA's latest Facility Standard P-100, released in 2014 P-100, which establishes target light levels for offices, defined as greater than 30 fc (approximately 320 lux) based on Illuminating Engineering Society (IES) recommendations.

Measuring energy savings and photometric performance helps to quantify the technical and economic properties of the lighting system, but equally important is user satisfaction with the system. In order to measure occupant satisfaction, surveys with general questions about the lighting system were administered to the site tenants prior to and after the retrofits. Project contacts were informally interviewed on the ease of implementation of the retrofit system and whether it was operating to the satisfaction of the building staff.

Finally, a cost-effectiveness analysis was prepared to produce simple payback periods (SPP) for the implementation of the controls and fixture retrofits in retrofit scenarios, based on costs of installation and the annual energy savings from the system. New construction and major renovation cases were also considered, where only the incremental cost of the LED fixtures with integrated controls above standard fixture options was compared to annual savings. Finally, a Life-cycle cost model was prepared in order to calculate project internal rates of return (IRR), net present values (NPV), and savings-to-investment ratios (SIR) based on total avoided energy and maintenance costs over an assumed 15-year system life span.

Table 1 presents some of the most important quantitative and qualitative objectives of this study, and details what data and information were collected to compare the pre- and post-retrofit lighting systems at the study locations. The results column also indicates some of the outcomes from the measurements and analysis, which will be detailed later.

Table 1: Performance objectives for Chicago and Atlanta study sites

Quantitative Objectives	Metrics and Data Requirements	Success Criteria	Measurement & Verification Results
Reduce Energy Usage	Lighting Energy Usage Index (EUI), kWh/ft²/year, extrapolated from lighting circuit data monitoring.	Reduce kWh/ft²/year	Average lighting EUI savings of 69% relative to GSA average lighting EUI baseline, and 75% relative to national average lighting EUI baseline.
Reduce Costs	Annual lighting energy cost, $/ft²/year, based on lighting EUI results.	Reduce $/ft²/year	Average lighting energy cost savings of $0.229/ft²/year relative to GSA average lighting EUI baseline.
Meet Cost-Effectiveness Requirements	Simple payback, in years: Annual energy savings/project installation cost	Paybacks within GSA range for investment consideration	Two- to three-year payback in new construction scenarios, nine- to twelve-year payback in retrofit scenarios.
Reduce Greenhouse Gas (GHG) Emissions	kg $CO_{2\,equiv}$/ft²/year , based on lighting EUI results	Reduce kg $CO_{2\,equiv}$ / ft²/year	Average lighting EUI savings translate directly to GHG emission reductions: 69% relative to GSA average lighting GHG emissions, and 75% relative to national average lighting GHG emissions.
Maintain Satisfactory Light Levels	Average illuminance (foot-candles) at workplane	Average of at least 30 foot-candles, per P-100 Facility Standard	Both demonstration locations meet P-100 average illuminance requirement.
Qualitative Objectives	**Metrics and Data Requirements**	**Success Criteria**	**Measurement & Verification Results**
Easy Installation	Qualitative; questionnaire responses from building staff	Favorable responses regarding ease of installation	Mostly positive feedback from building staff regarding ease of installation and commissioning of system.
Reduce Maintenance	Estimated maintenance costs ft²/year, based on information from building staff	Reduced maintenance costs ft²/year due to long life of retrofit technology	Maintenance savings projected, but not verified at this time.
Increase Occupant Satisfaction	Occupant responses to Satisfaction Survey	At minimum, no decrease in satisfaction, and ideally, increased satisfaction regarding lighting and controls performance	Significant increases in satisfaction with lighting environment; equivalent to improved satisfaction with controls.

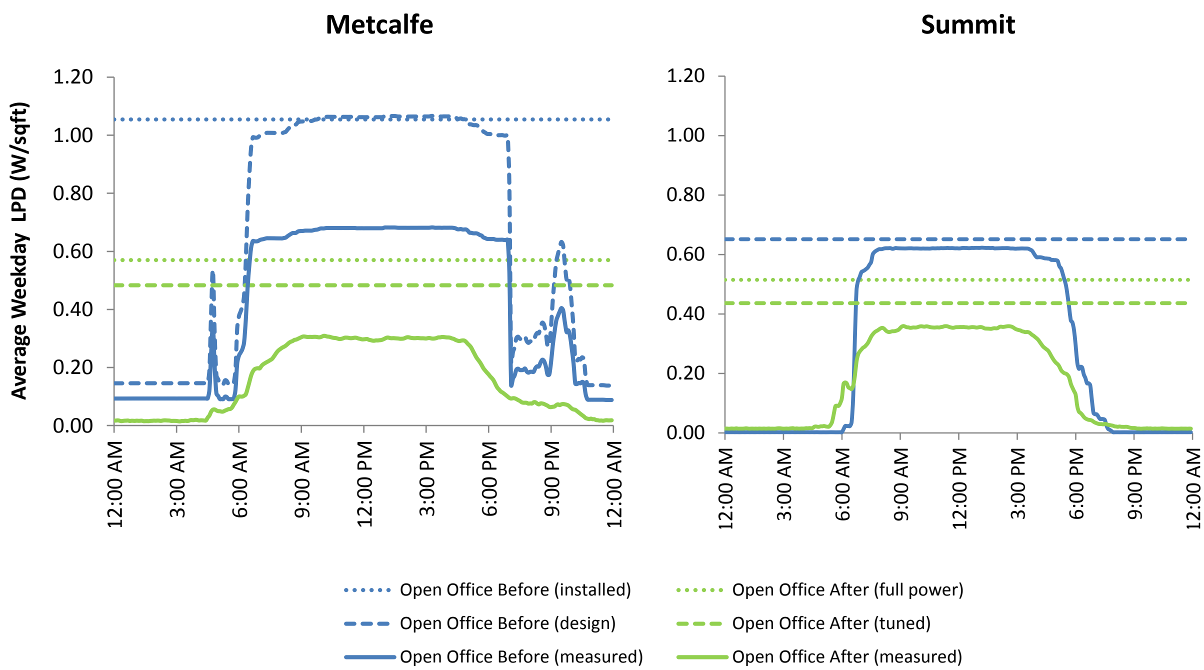
D. PROJECT RESULTS

ENERGY SAVINGS

The pre-retrofit installed lighting power density (LPD, W/ft^2) at each study site was calculated from the pre-retrofit number of fixtures and ballasts in the study space, the square footage of the space, and the fixture input power, which was measured at Lawrence Berkeley National Laboratory (LBNL). The pre-retrofit design LPD of the lighting system at Metcalfe was 1.09 W/ft^2. However, many of the three-lamp fixtures in the study space had only one or two lamps operating, and in some fixtures all three lamps were out. The actual lighting power density in the space was found to be 0.69 W/ft^2. With the retrofit LED fixture wattage commissioned to the medium power setting (39W), the post-retrofit LPD was 0.50 W/ft^2. At the Summit demonstration location, the pre-retrofit installed LPD in the study space was 0.66 W/ft^2. Unlike the study space at Metcalfe, the lighting system in the Summit study space was operating per design, with all lamps in the two-lamp fixtures operational. Post-retrofit LPD with the LED fixtures commissioned to the medium power setting was 0.44 W/ft^2.

Figure 1 below shows average daily LPD for the open office portions of the two study spaces during normal workdays. The daily average lighting power curves show the normal operating cycles of the lighting system; noticeably, the overall amplitude of the lighting power curve for the open office spaces is much lower after the retrofit.

Figure 1: Average pre and post retrofit open office workday lighting power density



Based on measured lighting energy usage over time at the study locations, annual energy savings were calculated for the retrofit of the LED fixtures with integrated sensors and controls in comparison to the baseline fluorescent lighting systems. Pre- and post-retrofit lighting energy usage on workdays, weekends, and holidays was averaged and multiplied by the annual total days of each type, assuming 251 weekdays, 104 weekend days, and 10 holidays. Results are tabulated in Table 2, below.

At the Metcalfe study location, lighting energy savings of almost 62% were found compared to the measured baseline, and over 75% relative to the design baseline. At Summit, the lighting energy dropped 40% from pre- to post-retrofit. To apply study results to typical buildings in the GSA portfolio, average post-retrofit lighting energy usage at the demonstration locations (weighted according to floor area) was compared to GSA typical pre-retrofit (baseline) lighting energy usage intensity (EUI, kWh/ft^2/year), calculated from average lighting EUI data for a sample of seven GSA buildings located in California, Nevada, Illinois, Indiana, and Missouri. The GSA baseline lighting EUI of 3.25 kWh/ft^2/year is substantially higher than the baseline energy usage of the Summit or Metcalfe demonstration locations. Energy savings were calculated relative to a national average baseline commercial lighting EUI of 4.1 kWh/ft^2/year.

Table 2: Pre- and post-retrofit annual lighting energy usage and savings

	Metcalfe	*Metcalfe Design*	Summit	GSA Average Lighting Baseline	National Average Lighting Baseline
Pre-retrofit Annual EUI (kWh/ft^2/year)	2.56	*3.96*	1.78	3.25	4.1
Post-retrofit *Annual EUI (kWh/ft^2/year)*	0.98	*0.98*	1.06	1.02 (weighted avg. of demo sites)	1.02 (weighted avg. of demo sites)
% Savings	**62%**	***75%***	**40%**	**69%**	**75%**

It is important to differentiate between the energy savings due to changing the light source from fluorescent to LED and the savings due to the advanced controls features of the retrofit lighting system. The LED fixtures are a higher-efficacy, lower-wattage light source, and the retrofit system can be tuned to a lower maximum output, depending on the needs of the space. Integrated sensors allow each fixture to dim if the group of fixtures to which it is assigned is triggered on but no occupants are present directly under the fixture, and all fixtures also dim individually based on daylight availability.

At Metcalfe, energy savings of 16% were achieved by switching from fluorescents to the LED fixtures at full power. With the LED fixture output tuned to medium, and the sensors and controls effecting dynamic dimming throughout the day, 46% additional energy savings were achieved, for a total of 62% savings for the entire system. At Summit, the lighting operation in the demonstration space was already highly efficient, even before the lighting retrofit (the baseline lighting EUI was very low). The LED lighting system with integrated sensors and controls saved the most energy simply by the change to LED fixtures, at 21% energy savings. The benefits of the institutional tuning, occupancy sensor dimming and shut-off, and daylight dimming contributed around 19% energy savings, for a total of 40% savings for the system.

PHOTOMETRIC PERFORMANCE

Based on photometric measurements at the study locations, average illuminance at the work plane was found to be within the P-100 guidance under both the baseline fluorescent and the retrofit LED systems. For Metcalfe, the LED system tuned to the medium output setting provided significantly higher average illuminance than the baseline system (+26%). For the Summit study location, average light levels were considerably higher than the required minimum under both the pre- and post-retrofit conditions. Based on the lighting power densities and average workplane illuminance results, the average workplane efficacy (WPE) at each location was calculated. This metric quantifies the lighting available at the work surface per unit of electric power drawn by the system. Workplane efficacy results for both the Metcalfe and Summit study locations were very favorable for the new LED fixtures, with 79% and 63% improvements, respectively, over the baseline systems. The color rendering values and color temperature remained similar at both locations before and after the LED retrofit.

Table 3: Average study location light levels pre- and post-retrofit

	Metcalfe		Summit	
	Pre-retrofit	Post-retrofit	Pre-retrofit	Post-retrofit
Mean Illuminance (fc)	31.7	39.9	40.1	43.7
Workplane Efficacy (lm/W)	44.6	79.8	60.8	99.3

OCCUPANT SATISFACTION

Occupant satisfaction surveys were circulated before and after the lighting retrofits at both sites. For Metcalfe and Summit, the response rates for both the pre- and post-retrofit surveys exceeded the study target response rate of 30%. At Metcalfe, the total number of respondents for both surveys was above the desired total of at least 30, indicating good statistical confidence that the results are accurate and representative of the occupant population in the study space. At Summit, there were fewer than 30 respondents, so results do not provide high statistical confidence, but they still deliver valuable feedback to consider along with the other study outcomes.

For both locations, occupants' responses expressed similar- to improved-comfort levels under the retrofitted LED lighting system, compared to the pre-retrofit fluorescent lighting system. More respondents found the LED lighting system to provide pleasant brightness and well-lit room surfaces. It is clear from the survey results that occupants were as satisfied or more satisfied with the LED lighting compared to the baseline fluorescent systems. Comments provided in the free response boxes were positive overall, although several respondents indicated a desire that individual fixtures be controllable and dimmable by individual occupants.

COST-EFFECTIVENESS

The cost-effectiveness analysis examines whether the value of the future energy savings from the installation of the LED fixtures with integrated sensors and controls justifies the expense of the investment. For retrofit analysis, estimated project costs include the full cost of all materials (*i.e.*, fixtures and any other equipment installed) and the labor cost associated with installation and commissioning of the system. Importantly, the turn-key aspect of the integrated sensors and controls system enabled an advanced controls system to be rolled out at almost no additional labor costs beyond those of simply replacing one fixture for another (save the commissioning of fixture groups, which was only a few hours of labor per site). An analysis is also included for new construction situations or major renovations where an existing lighting system has reached the end of its useful life and needs to be replaced. In these cases, the cost of the project is simply the difference in cost between the LED fixtures with integrated sensors and controls and the cost of the lighting and controls system that would be installed otherwise, such as typically-specified code compliant systems. This cost difference is commonly called the project incremental cost.

Lighting energy savings are valued according to a national average electricity rate of $0.10/kWh. For results that are more informative to GSA investment choices regarding lighting and lighting controls the energy savings and project costs were normalized from the demonstration-specific results to figures applicable to standard GSA buildings and project scales and processes. The lighting performance of the retrofit technology was compared to the typical GSA baseline lighting operation (3.25 kWh/ft^2/year). Results were also calculated based on energy and cost savings from the national average baseline commercial lighting EUI of 4.1 kWh/ft^2/year. Labor costs for the demonstration projects were determined by communication with GSA and the technology vendor provided a GSA - bulk purchase price estimate for the LED fixtures with integrated controls.

Simple payback is calculated by dividing the cost of an energy savings investment by the annual avoided energy costs resulting from implementation of the technology. The result of the calculation is the number of years it would take for the avoided energy costs to pay for the initial investment.[1] Paybacks for the retrofit cases were around 10 to 14 years. In the case of new construction and major renovation projects, paybacks were as low as three to four years. A lower-cost LED fixture option from the same equipment vendor will be available in the coming year with the same integrated controls technology, at around a 20% cost reduction. Simple payback was calculated for the projected lower-cost option but with the same energy savings. Retrofit paybacks were around 9 to 12 years and new construction and major renovation paybacks were one to two years.[2]

Simple payback results were also calculated for hypothetical LED fixture projects without the integrated sensors and controls. Estimated energy savings were lower (totaling around 41%), but the estimated material costs would be lower as well, estimated at $0.47 less per square foot. For retrofit cases, the loss of

[1] As the term simple payback connotes, it is a relatively simple approach to cost-effectiveness analysis. It does not consider the service life of the technology, nor does it account for time value of future avoided costs. It typically also does not include avoided maintenance costs that would accrue over the lifetime of the equipment.

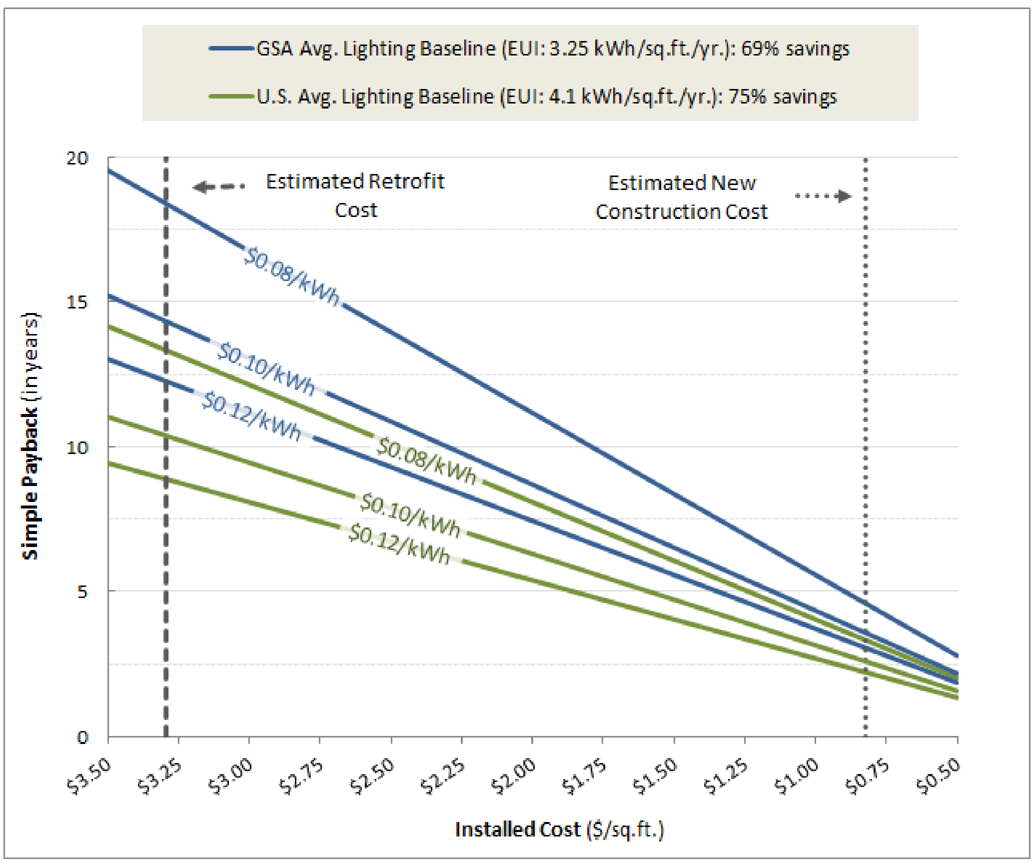
[2] Photometric performance, energy usage, and occupant satisfaction criteria were not evaluated for any alternate LED fixture models during this study. As such it is not possible to guarantee that performance of or satisfaction with any alternative, such as the proposed lower – cost model, would be equivalent to that of the evaluated fixtures.

future energy savings from forgoing integrated controls was not worth the upfront material cost savings; the payback range increased to 16 to over 20 years. In the case of new construction however, where installation labor is not included in the analysis, the material cost savings from the LED fixtures without controls made a bigger difference and paybacks actually improved by about one year, to the two- to three-year range.

Figure 2, below, illustrates the sensitivity of the simple payback results to several variables, such as project costs, electric utility rates, and lighting energy baselines. The annual energy savings are held constant at the level predicted by study results relative to both the GSA average baseline and the national average baseline. Project costs vary on the X axis, and payback is shown to decrease steadily at lower project costs. The dotted lines bound the estimated cost for retrofit projects (around $3.29/ft²) and new construction projects (around $.82/ft²), clearly showing the shorter payback times for new construction projects. The costs per square foot of the integrated controls portion of the technology studied here, at $0.47/ft², compare favorably with recent GPG research finding around $1/ft² incremental cost for advanced lighting controls that were not integrated into fixtures [1]. This is consistent with the design intent that integrated controls reduce the cost of advanced controls implementation.

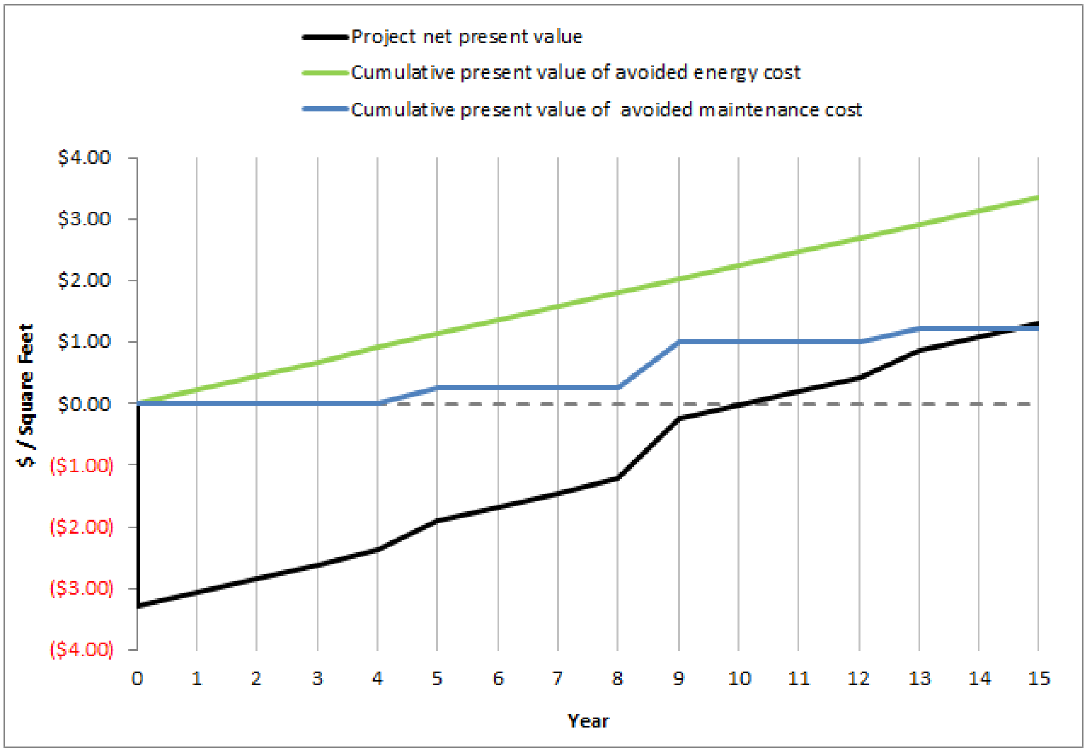
Isopleths for a higher electric utility rate ($0.12/kWh), an average utility rate ($0.10/kWh), and a lower rate ($0.08/kWh) are plotted to illustrate payback ranges for the different lighting energy baselines. Essentially, the analysis shows that higher project installation costs result in longer project paybacks, and at higher electric rates and higher baseline lighting energy usages, paybacks are more favorable.

Figure 2: Sensitivity of simple payback to installed cost, EUI, and utility rate



A discounted life-cycle cost analysis provides a more comprehensive method of accounting for the cost savings resulting from an energy efficiency investment. While the simple payback methodology divided project cost by estimated annual energy savings, the life-cycle approach sums the future avoided costs that will accrue from the technology over the estimated lifetime of that technology, compared to the system that would be operating in the space otherwise. Because the LED fixtures are a longer-lifetime, lower-maintenance option than standard fluorescent systems, maintenance savings that occur periodically during the system life-cycle can also be included in the life-cycle analysis. The costs of replacing fluorescent lamps and ballasts every few years are avoided if the LED option is installed, as illustrated in Figure 3, below.

Figure 3: Present value of avoided costs for retrofit deployments in GSA buildings



For typical GSA buildings, the retrofit SIR was found to be around 1.4, indicating good future savings from the project relative to the initial investment. The NPV of the discounted future savings (minus the initial project cost) is positive as well, and the IRR for the project was found to be around 6.9% (well above the assumed nominal discount rate of 2.5% used here), which indicates a cost-effective investment. For normalized costs and savings in new construction, major renovation, and replacement at end of useful life cases, the SIR is even higher, at 4.37, and the project IRR is around 31%. Maintenance savings were quite compelling in this analysis; responsible for around one quarter of the system savings over the 15-year lifetime. It is safe to say that under the assumed project costs and savings for this scenario, this investment option is a “slam dunk.”

E. CONCLUSIONS

GSA has jurisdiction, custody or control over an inventory of more than 9,000 federally owned and leased buildings that use nearly 2.6 million MWh of electricity usage annually. If LED fixtures with integrated controls can reduce lighting energy usage in commercial buildings and can be installed in a cost-effective manner, there may be considerable potential for deep energy savings through the deployment of these technologies within GSA buildings.

LED fixtures with integrated controls saved significant lighting energy in the evaluated demonstrations, but LED fixtures are often more costly than fluorescent alternatives. There is an incremental material cost associated with implementing the integrated controls compared to a standard static LED fixture option, though the demonstrated product enables the roll out of an advanced lighting controls system along with the fixtures with little incremental labor cost. The estimated incremental cost per square foot for the advanced controls component for the integrated solution studied here comes in at around half of the $1/ft^2 estimated in previous GPG advanced lighting controls research where the system was not entirely integrated into the fixture [1].

For a building to move forward with an LED fixtures and integrated controls project, the incremental costs of the fixture and controls may need to be recovered by the energy and maintenance savings from the higher-efficacy, longer-lasting LED light source and the energy savings from the advanced controls features. Other factors, such as lighting appearance and aesthetics, also will influence what fixture is specified for retrofit and new construction projects. The turnkey, ease-of-implementation emphasis of the technology design is meant to reduce the costs and complexities that have hindered advanced lighting and controls system uptake in the past. Informal interviews with project contacts indicated that overall installation went smoothly at both demonstration locations. Both sites' project contacts indicated that the systems are operating as expected and that the buildings are satisfied with the results of the retrofit installations.

Based on the results of this study, it is clear that LED fixtures with integrated controls can reduce lighting energy usage in GSA's commercial buildings. There may be considerable potential for deep energy savings through the retrofit deployment of these technologies within GSA buildings where project cost-effectiveness is likely. This would include buildings with average or high baseline lighting energy usage and electric utility rates at or above the national average of $0.10/kWh. For new construction or major renovation cases where the project cost is only the incremental cost of the LED fixtures with integrated controls relative to standard fluorescent fixtures and simple controls, it appears that cost-effectiveness is likely for these systems so they should be strongly considered in any such project.

II. Introduction

A. PROBLEM STATEMENT

The commercial building sector in the United States uses more than a third of total end-use electricity [2], with interior lighting accounting for 26% of the electricity used in those buildings [3, Table 3.1.4]. Linear fluorescent fixtures are the predominant lighting technology used to illuminate the interior of these spaces. Over the past several decades, fluorescent technology has improved, with the transition from T12 to more efficient T8 and T5 fluorescent lamps, and more efficient electronic ballasts overtaking the market. Improved fluorescent fixture designs continue to appear, but it is not apparent that further major advances in essential fluorescent light source technology are forthcoming.

Light-emitting diode (LED) technology, on the other hand, is showing rapid and continuous advances and is increasingly being used in general lighting applications. LEDs are semiconductors that produce light through the physical phenomenon known as electroluminescence. First used for purposes such as indicator lamps and backlighting, innovations in design have allowed LEDs to cover a wider set of lighting needs, including replacing linear fluorescent fixtures for general office lighting. These new LED fixtures achieve efficacies (visible light output per unit of power input, lumens/Watt) above those of modern fluorescent lighting systems, and LED efficacy is expected to continue to rise over the next few years. Rated lifetimes of LED fixtures are typically at least 50,000 hours, roughly twice the lifetime ratings of standard fluorescent lamps, which are around 25,000 hours. Other advantages include higher controllability (*e.g.*, easier dimming and on/off cycling) and greater durability. LEDs are solid-state electronics and, as such, are robust by nature with no filaments, cathodes, or gases to worry about. Despite all of these advantages, LEDs still have only a small share of the general illumination indoor fixture market, estimated at less than 1% [4] largely related to the relative "newness" of the technology compared to incumbent technologies.

A lighting system is more than just the fixtures installed in a space; it also includes the controls that determine when and how the fixtures operate. The most basic lighting controls in commercial buildings are manual switches, which occupants choose to turn on or off to activate the fixtures. A more automated controls strategy, where scheduled on/off operation is based at the lighting relay panel level, is common in commercial buildings. More advanced lighting controls options are available to turn fixtures on and off based on automated occupancy detection, to set fixture power at a lower-than-maximum level if a space requires less illuminance (known as institutional tuning), and to dim fixtures dynamically through the day based on available daylighting. For this report, we define advanced lighting controls systems as ones that include wall switches, institutional tuning, occupancy sensor-based light switching, and daylighting. Most commercial buildings do not include advanced lighting controls systems, and previous work by GSA [1, 5] indicates that installing new controllable lighting systems in existing buildings is costly due to the extensive labor required and the complexity of most design, installation, and commissioning processes.

This GSA Green Proving Ground (GPG) program study seeks to demonstrate that LED fixtures with integrated sensors and controls can significantly decrease energy consumption in existing commercial buildings while maintaining or improving lighting quality. This GPG study examines results from two locations. Both sites underwent a one-for-one replacement of existing 2'x 2' and 2'x 4' fluorescent fixtures with a turnkey package of LED fixtures with integrated occupancy and daylight sensors and controls to turn the fixtures on and off or dim and brighten them according to conditions in the office. The LED fixtures, once grouped and commissioned, are designed to auto-calibrate and dim according to available daylight to provide appropriate light levels. With the controls and sensors integrated into the fixtures, the technology essentially allows for an advanced lighting controls system to be implemented along with the new fixtures at no, or very little, additional labor cost. The integrated lighting and controls system also allows for a simple path to building energy code compliance, with ASHRAE 90.1-2010 and other building codes, such as California's title 24 including lighting power density requirements that lower-wattage LED fixtures should meet, as well as controls requirements, such as automatic shut-off, occupancy sensors in offices, and daylight dimming controls in certain situations.

The goal of the retrofits is to reduce overall lighting energy use and electricity demand and to minimize the installation costs and complexities associated with advanced lighting systems. This study evaluates the energy savings, photometric performance, occupant satisfaction, and cost-effectiveness associated with implementing LED fixtures with integrated controls compared to the existing lighting systems in the spaces.

B. OPPORTUNITY

The U.S. General Services Administration (GSA) Public Buildings Service (PBS) has jurisdiction, custody or control over more than 9,000 federally owned and leased assets and is responsible for managing an inventory of diverse buildings, totaling more than 377 million square feet of building stock [6]. In FY 2013, GSA procured and generated nearly 2.6 million MWh of electricity and was responsible for emissions of around one million metric tons of carbon dioxide equivalent ($CO_{2,eq}$).[3] Assuming that the proportion of lighting energy usage in GSA buildings relative to total energy is the same as the national average (26%), lighting equates to around 676,000 MWh annually for GSA. Since the large majority of GSA's buildings are office buildings and GSA is mandated to meet ambitious energy reduction targets by 2015 and greenhouse gas reductions by 2020, GSA's Green Proving Ground (GPG) program has selected cost-effective, energy-efficient commercial office lighting solutions as a priority focus area. LED fixtures and advanced lighting controls have not yet been widely deployed nationally. If LED fixtures and advanced controls can greatly reduce lighting energy usage in commercial buildings, there may be considerable potential for deep energy savings through the deployment of these technologies within GSA buildings.

This study focuses on the energy savings, photometric performance, occupant satisfaction, and cost-effectiveness of the LED fixtures with integrated sensors and controls. The hypothesis of the study is that significant lighting energy savings can be achieved through the reduction in lighting power demand due to the LED fixtures and increased operational efficiency due to the sensors and controls. The turnkey aspect of the fixture and controls package, as well as the simplicity of the commissioning process, should reduce installation cost and implementation complexity, ultimately improving cost-effectiveness. The longer lifetime of the LED fixtures should further reduce operation and maintenance costs relative to the existing fluorescent fixtures. Finally, due to the high-quality LED light source and photometric performance and the lighting system dynamic switching and dimming, including maintained background levels of lighting

[3] Includes Scope One and Two emissions, encompassing electricity generated on-site and procured, as well as GSA fleet vehicles emissions; FY 2014 Strategic Sustainability Performance Plan (p. 31) includes around 300,000 gallons of fuel and around 2,600 tons of $CO_{2,eq}$ (at 8.8 kg CO_2/gallon)

throughout occupancy zones, it is hypothesized that greater occupant satisfaction with the lighting system will result.

III. Project and Technology Overview

A. TECHNOLOGY DESCRIPTION

This GPG program study evaluates the technical performance, energy savings potential, user acceptance, and cost-effectiveness of commercial office general illumination LED fixtures with integrated sensors and controls. The higher efficacy LED light source should provide more lumens at a lower electric power demand. The fixtures and controls also allow for tuning of fixture groups to reduce maximum fixture power to medium or low power levels if the light output at full power is more than necessary for a given space. The fixtures' embedded occupancy sensors detect when the immediate surroundings are occupied and turn fixtures on in response. The fixtures are organized in large zones that operate in concert through on-board wireless communication, such that all fixtures in a group turn on to a very low background level if any area(s) within the zone are occupied, while only the fixture(s) that individually sense occupancy brighten to the full output. Finally, each fixture also includes an integrated daylight sensor for daylight harvesting. Each fixture can independently lower its output and reduce electric lighting usage if sufficient daylight is present (daylight dimming is not a group function but is determined at each fixture based on its own sensor). Because the sensors and controls are integrated into the LED fixtures and no other devices are required for the system to operate, advanced controls strategies are enabled simply by the installation of the fixtures, with a small amount of fixture group programming also required during set-up.

COMMERCIAL LIGHTING

Of the estimated total U.S. site electricity consumption of 3,500 TWh in 2010, the Energy Information Administration (EIA) estimated that lighting technologies use around 700 TWh, and that around half of that energy was used in the commercial building sector, across approximately 81.2 billion square feet of floor space. For context, one TWh is equivalent to the average annual energy usage of more than 92,000 U.S. households.[4] Recessed linear fluorescent fixtures, commonly called troffers, are the most prevalent light source in U.S. commercial buildings, with 1'× 4', 2'× 2', and 2'× 4' dimensioned troffers accounting for over 50% of the installed commercial light fixture base [7]. In the United States, lighting accounts for 26% of the electricity used in commercial buildings [3]. It is estimated that linear fluorescent fixtures in commercial buildings are responsible for more than 87 TWh of electricity use annually [7]. PBS's Federally owned and leased building assets use almost 2.6 million MWh of electricity per year, with lighting equating to around 676,000 MWh annually, as discussed in the Introduction of this report.

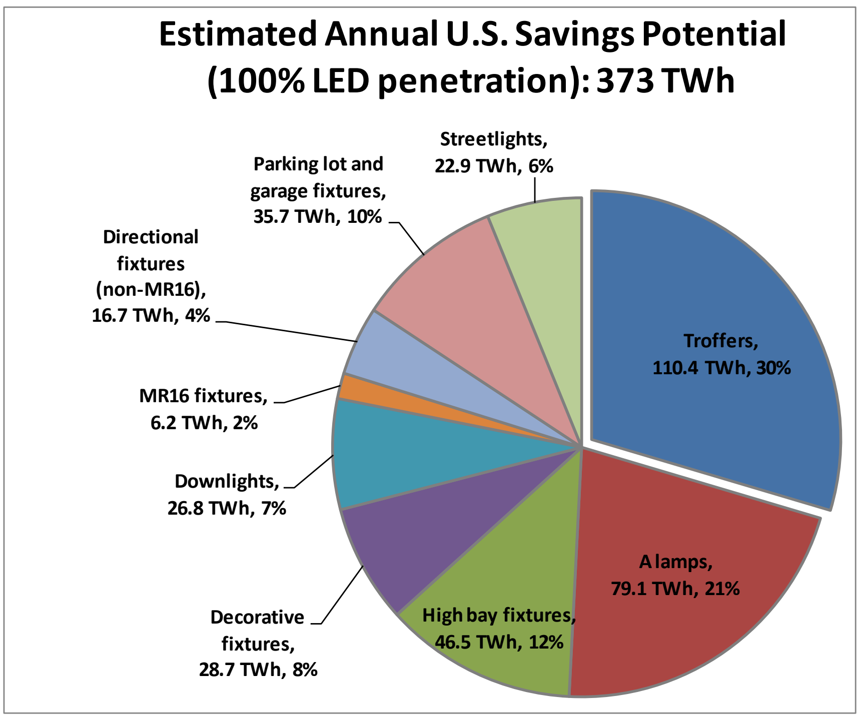
A 2013 Navigant Consulting, Inc. study expanded the analysis of lighting energy savings potential to include all site lighting installations, not just lighting in commercial buildings. The study estimated a stock of 964 million indoor fluorescent fixtures that use more than 228 TWh annually, which equates to the annual energy usage of more than 21 million U.S. homes. The report found that "over the past decade, LEDs have emerged as a competitive lighting technology, capturing market share in several general illumination applications from traditional light sources [4]." DOE sees LED fixture costs continuing to decrease, with the electricity savings and maintenance costs savings offsetting the extra costs of the LEDs in many applications

[4] Based on the average U.S. household usage of 10,837 kWh annually, per http://www.eia.gov/tools/faqs/faq.cfm?id=97&t=3

[4]. Installations of indoor LED troffers specifically are on the rise, growing by a factor of 11 in only two years, from 2010 to 2012, from an estimated 40,000 to almost 700,000 units during that time [4]. Despite the rapid growth in installations, LED troffer usage still equates to market penetration of less than 1% [4] so there is plenty of room for growth.

The Navigant study estimates current annual electricity savings for the installed base of LED troffers at only 0.1 TWh, but extrapolating to 100% LED penetration in all troffer applications results in an impressive 110 TWh in savings, which is equivalent to the electric energy usage of 10 million U.S. homes. DOE analyzed nine major lighting applications where LEDs are increasingly competitive with incumbent lighting technologies, and found that LED troffers are becoming particularly competitive with fluorescent baseline in terms of light output and distribution, color rendering, and fixture efficacies. Figure 4 illustrates the findings of the report (adapted from Figure 5.2 of [4]) and shows LED savings in the U.S. troffer market as the most promising of all the major lighting categories.

Figure 4: LED energy savings potential by lighting application (adapted from Navigant, 2013)



THE STATE OF THE LED TROFFER MARKET

LED technology options to take the place of linear fluorescent fixtures come in several form factors and design approaches. There are three widely available LED-based product types for fluorescent troffer replacements [7]:

- LED T8 lamps ("replacement lamps" or "tubes"), which may include an integral driver or may require swapping the existing fluorescent ballast for LED drivers;
- Dedicated LED fixtures with integral drivers; and

- LED retrofit kits, where, in most cases, a fluorescent troffer's housing is retained and the ballast is replaced with a driver that powers linear boards of LEDs. The kit either uses the fixture's existing optical system (*e.g.*, lens, and louver), or replaces it with a diffusing acrylic panel for a refreshed look.

The DOE CALiPER study characterized several baseline fluorescent fixtures and 21 LED models in the three categories described above. DOE found that the dedicated LED troffers performed the best on average and were ready to compete with fluorescent troffer efficacy and match or improve upon glare performance, light distribution, visual appearance, and color quality. On average, LED tube lamp retrofits showed similar efficacy to the fluorescent benchmarks, so energy savings were not guaranteed, especially compared to high-efficiency fluorescent lamp replacement options (25W or 28W) with electronic dimming ballasts. As for the LED retrofit kits, various challenges were found, including color discrepancies, unappealing brightness patterns (and sometimes overall unappealing appearance), and glare issues. Consistent concerns were raised by electricians during inspection of the modified fluorescent fixtures regarding safety of LED lamps and retrofit kits in existing fixtures.

LED Lighting Facts is a program of DOE that showcases LED products for general illumination from manufacturers who commit to testing products and reporting performance results according to industry standards. The Lighting Facts program includes a massive database of listed LED fixtures that have gone through rigorous product testing. As the database has grown, DOE has periodically prepared analyses on the listed products to evaluate performance metrics over time and compare performance trends with incumbent, non-LED lighting technologies, as well.

In a Lighting Facts Product Snapshot from 2011, LED troffers were only 2% of the 1,991 LED fixtures listed in the database [8]. The average efficacy of the listed fixtures at that time, 67 LPW, was already better than the fluorescent benchmark of 55 LPW. However, the study found high variability in product performance, although overall efficacy was increasing faster for the troffer category than for other indoor LED lighting products. The moving average efficacy trend for higher performing fixtures (the eightieth percentile and up), was under 60 LPW in the first half of 2010, but over 75 LPW by the third quarter of 2011.

Another Lighting Facts Product Snapshot on LED troffers was prepared in April 2014 [9]. By this time, more than 1,500 LED troffers were listed, representing over 10% of the more than 10,000 LED fixtures listed in all categories. The average efficacy of LED troffers by April 2014 was over 90 LPW. In terms of light output, more than half of the listed LED troffers provided output between 2,000 and 4,000 lumens, similar to the output range for various two-lamp fluorescent troffers.

With growth in the LED lamp and fixture marketplace, various regional and national organizations have developed standards and methods to promote quality LED products with proven performance and help ensure that adoption of LED options in the general lighting market is as smooth as possible. The Energy Star program of the U.S. Environmental Protection Agency (EPA), a voluntary program to list and label various consumer products with proven superior energy efficiency, certifies various lighting technologies for residential and commercial applications, including LED options. However, several product categories for commercial fixtures with quality LED options are not covered by the Energy Star program. In part to cover various lighting categories not addressed by Energy Star, the DesignLights Consortium (the DLC) launched a Qualified Products List of commercial grade LED fixtures in 2010.

The DLC's stated goal is to "promote quality, performance and energy efficient commercial sector lighting solutions through collaboration among federal, regional, state, utility, and energy efficiency program members."[5] LED troffers are covered by the DLC Qualified Products List, with requirements for LED fixtures, whether integrated fixtures or retrofit kits designed to replace the fluorescent components in existing fixtures, detailed in Table 4, below.

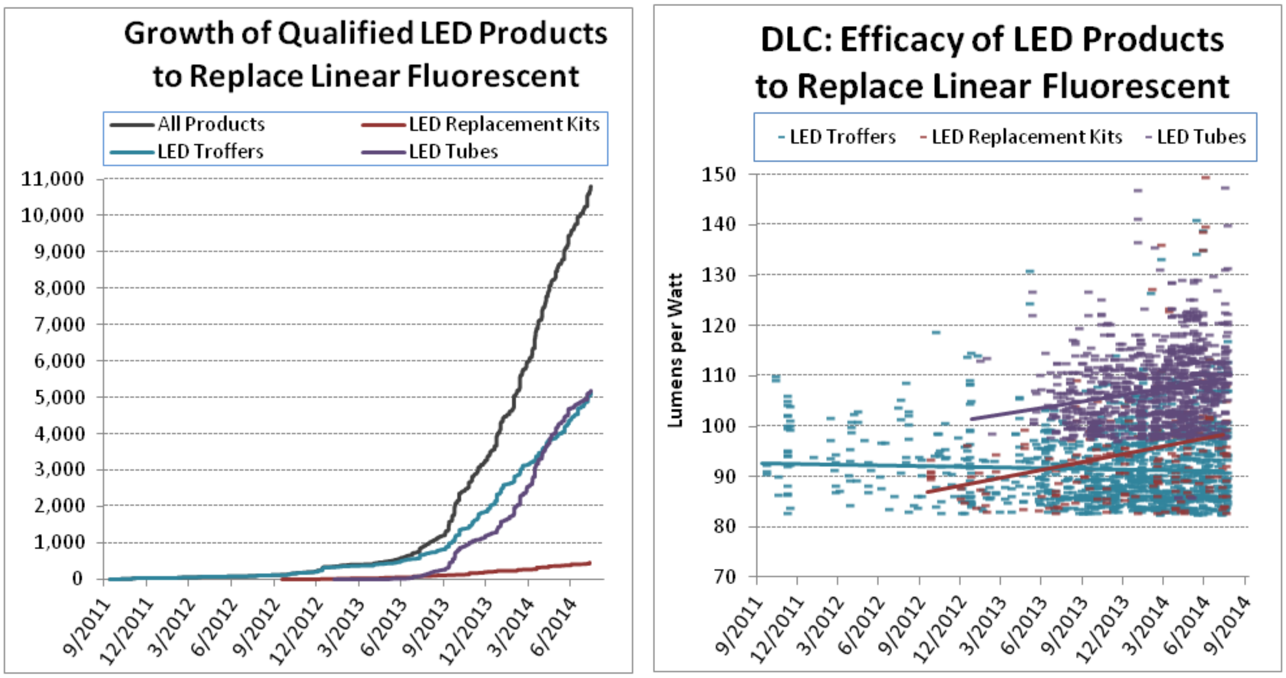
Table 4: DesignLights Consortium performance requirements for LED troffers

Minimum Output	Minimum Fixture Efficacy	Maximum CCT	Minimum CRI	Lumen Maintenance	Minimum Warranty
1,500 (1X4s) 2,000 (2X2s) 3,000 (2X4s)	85 lm/W	≤5000K	80	50,000 hours or more	5 years or more

The DLC list currently includes more than 5,000 LED linear replacement lamp options, over 5,000 1'X 4', 2'X 2', and 2'X 4' LED troffers, and several hundred retrofit kit options. The DLC database listings for LED troffers were analyzed for this study to characterize the evolution of LED troffer products and performance developments over time. Product listings were first sorted by date and type to evaluate growth in the marketplace. Figure 5 illustrates the results with a scatter-plot of the measured efficacy values for each product type by listing date, showing efficacy trends over time.

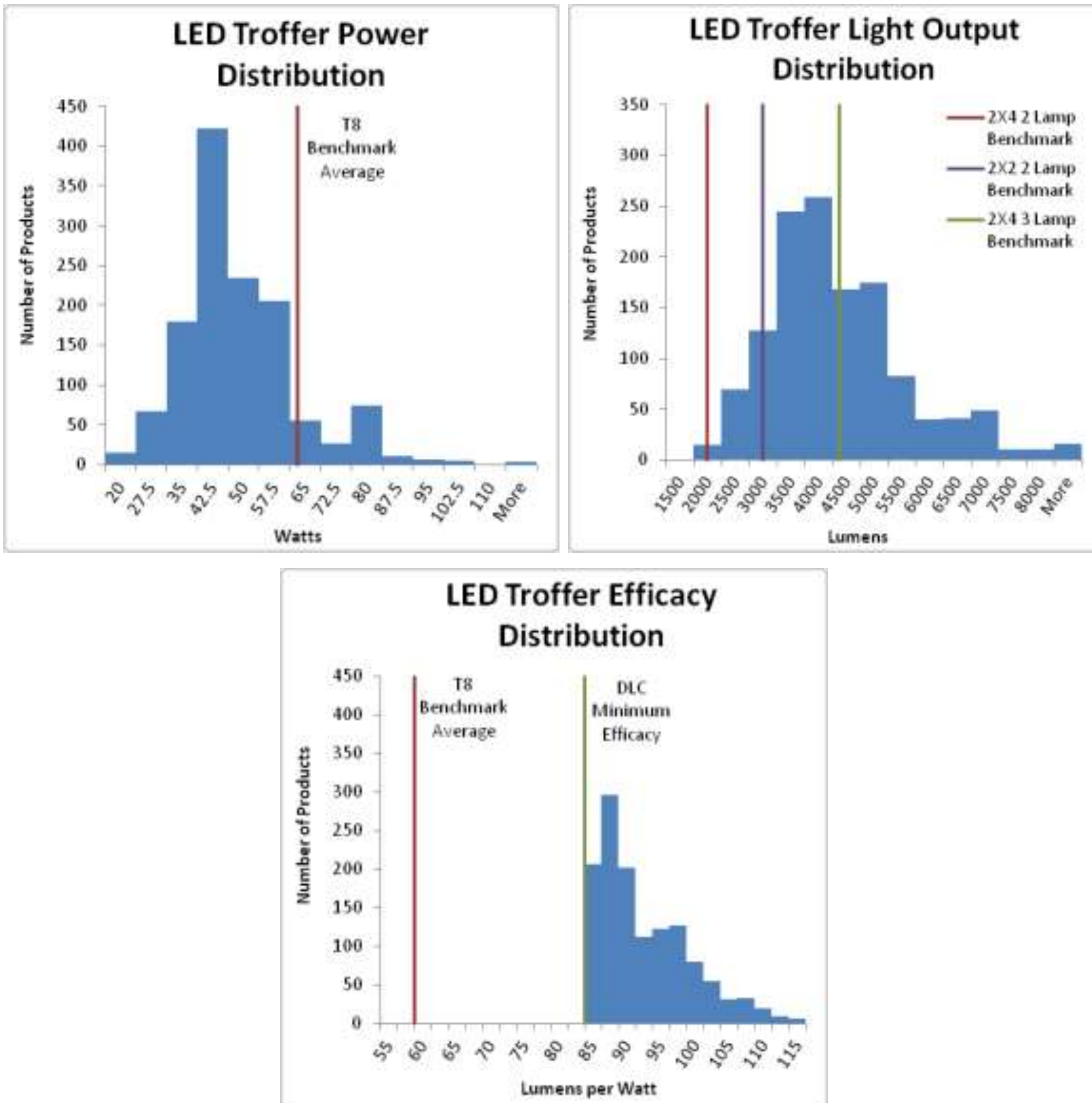
[5] *About the DLC webpage:* https://www.designlights.org/content/about

Figure 5: Market growth and efficacy trends for qualified LED products to replace linear fluorescents



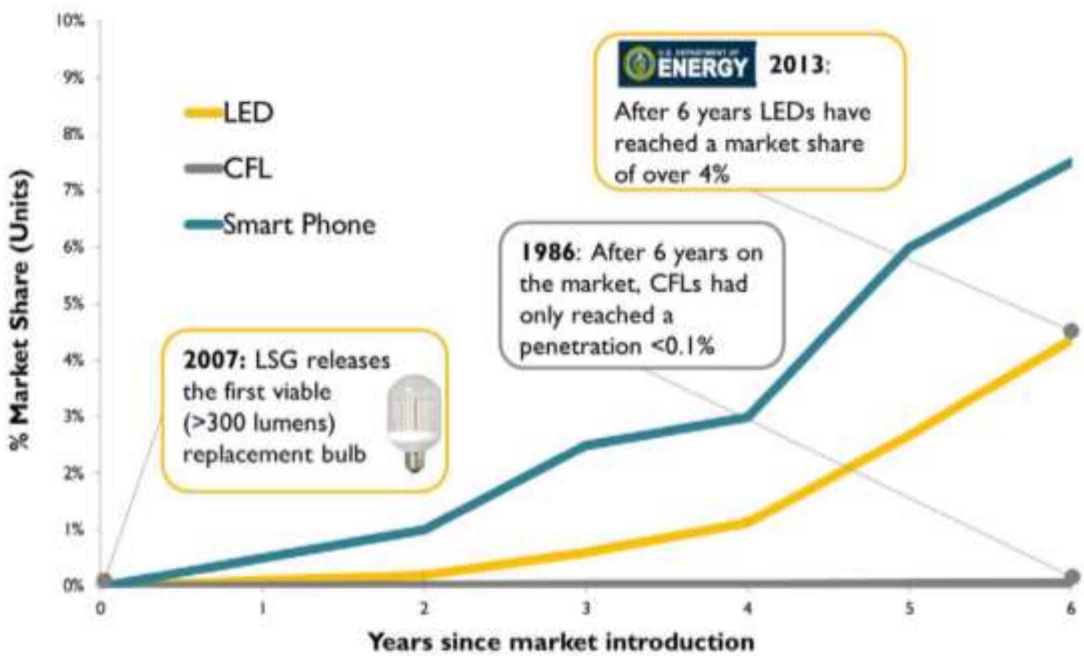
Binned distributions of various performance metrics were prepared to evaluate the range and frequency of LED troffer performance variables, with comparisons to T8 benchmarks. The T8 benchmark values are taken from the DOE CALiPER exploratory study on recessed troffer lighting from 2013 [7]. It is clear from this analysis that the high-quality LED products listed by DLC are highly competitive with fluorescent benchmarks, with lower fixture power, equivalent or higher light output, and better fixture efficacy being commonplace.

Figure 6: Distribution of performance attributes for LED troffers compared to fluorescent benchmarks



LED products are capable of very high efficacy, color quality, power quality, dimming performance, and longevity, but product performance depends on design, application, operations and maintenance profiles, and other constraints. Efforts by DOE and other major stakeholders at providing a smoother "on ramp" for LED technology in general lighting than was experienced in the market during compact fluorescent adoption appear to be paying off. These efforts, including performance standards, development of testing protocols, consumer education programs, and continued research and development, coupled with some of the inherent advantages of the technology itself, have helped result in a much smoother transition to LEDs. Market adoption of LEDs has actually been more similar to consumer electronics such as smart phones, which is not surprising since some of the technology manufacturing and production is similar (*e.g.*, diodes printed on silicon substrates). This point is illustrated in the following graphic from the January 2014 DOE report *Solid-State Lighting: Early Lessons Learned on the Way to Market*, prepared by Pacific Northwest National Laboratory (PNNL) [10].

Figure 7: Comparison of market growth for CFLs, LEDs, and smart phones (PNNL, Jan. 2014)



ADVANCED LIGHTING CONTROLS

Basic lighting systems in commercial buildings typically include manual wall switches to control individual office fixtures and larger zones of fixtures in open plan areas. Very often, some form of automated lighting schedule is included in the controls scheme to turn lights off after hours, based on occupancy schedules set on timers that control circuits, zones, or entire floors. These can be either manual on and automatic off, requiring occupants to turn lights on upon entering a space so that lights are not turned on automatically when the operating schedule begins even if occupants have not yet arrived, or automatic on and off. Normally, either option can be overridden by wall or zone switches or relays if after-hours occupancy is necessary. Emergency lights that stay on 24 hours a day to illuminate ingress and egress zones are common in these floor spaces, as well, and normally operate on separate, dedicated circuits not subject to the automated schedules.

Occupancy sensors that automatically turn lights off after a space is vacated are less common than simple manual switches and automated schedules, but are implemented in many commercial office buildings. These are most common in individual private offices, where typical operation is manual on, automatic off, giving occupants the option of using or not using their overhead lights. Occupancy sensors are less commonly deployed in open office areas; when they are, it is typically in an automatic on and off configuration. Occupancy sensors in open offices are very rarely installed at the density of one per individual workstation or fixture. Instead, zones of fixtures covering multiple work stations are typically configured to be controlled by a single sensor.

Compared to manual controls and automated schedules typical in offices, advanced lighting control systems can better match lighting system operation to the needs of the occupants, providing light when needed and at illumination levels more appropriate to the conditions of the space, and saving energy by not operating lights when they are not needed or at a higher power and light output level than necessary. These systems can do so at a higher spatial and temporal resolution than basic lighting controls and can give users greater control over workplace light levels. The most complex advanced systems even provide a central control platform, such as a PC- or web-based interface, to manage and monitor the lighting system, set-points, and schedules.

The following lighting controls strategies are considered advanced controls strategies for the purpose of this study; all are features of the retrofit LED fixtures and controls system evaluated:

- **Institutional tuning:** Allows building managers or tenants with a dimmable lighting system to decrease light levels and lighting energy consumption by programming default power levels for fixture zones or individual fixtures at a lower level than maximum power and light output to reflect actual building lighting needs and policies regarding light levels provided.

- **Occupancy sensing:** Reduces lighting energy consumption and unnecessary lighting system operation by lowering light levels or turning lights off in offices and zones when occupants leave an area. Electrical demand can be reduced by taking advantage of variable occupancy patterns within individual zones throughout an office or building.

- **Daylight harvesting:** Allows lighting systems to reduce lighting energy by taking advantage of the available natural light, typically along the perimeter of a building floor, close enough to windows for daylight to penetrate. Photosensors detect the level of illumination in the area and adjust the electric light output level to achieve a target lighting level.

Various studies have addressed the energy savings potential of advanced lighting controls systems, looking at the implementation of different advanced controls strategies in various commercial spaces and, in many cases, measuring energy savings of specific controls options (*e.g.*, occupancy sensors compared to manual control) and combinations of options (*e.g.*, occupancy sensors and daylight sensors).

To aggregate the experiences and results from the many lighting controls studies available in the published literature, a meta-analysis of lighting controls energy savings in commercial buildings was carried out in 2011 [11]. The study evaluated the energy saving effects of occupancy sensing, daylight sensing, personal tuning, and institutional tuning. For studies in which actual energy usage was monitored over time, energy savings averaged 24% for occupancy sensors, 28% for daylighting controls, 31% for personal dimming control, 36% for institutional tuning, and 38% when more than one of these strategies were combined.

A more recent Pacific Gas and Electric (PG&E) Emerging Technology study in a GSA building in San Francisco in 2012 found energy savings of 21% when fluorescent troffers were replaced with LED fixtures, and an additional savings of 41% when advanced lighting controls were added, including task tuning to 80% power, occupancy sensors, daylight sensors, and individual dimmers [12]. A recent GPG program study in GSA buildings evaluated advanced wireless lighting controls retrofit on existing fluorescent fixtures in one location and advanced controls with LED fixtures in another. The study found significant energy savings resulting from the LED fixtures, the advanced controls, and the combination of both [1]. Advanced controls alone saved around 32% energy compared to a baseline of basic lighting schedules, wall switches, and some private office occupancy sensors. The LED fixtures saved an additional 30%. Controls savings were not uniform across the offices in each study location, however; those that already had occupancy sensors in the base case saw little energy savings, while other spaces saw larger savings, up to nearly 50%. Also, depending on where and how the controls were installed, occupant satisfaction varied, with some concerns over implementation at one location leading to slightly negative occupant feedback on some of the controls functions. The findings underscore how important good design and commissioning of controls schemes and zones is and some of the challenges of implementing complex controls systems in the real world.

Despite the availability of advanced lighting controls, only 2% of commercial buildings in the U.S. employ photosensors for daylighting control and only 1% utilize installed energy management and lighting control systems [11]. Advanced lighting controls uptake in the commercial market has been hindered by high installation costs, which can include high equipment costs as well as high labor costs, due to factors such as extensive controls wiring, system complexity, laborer unfamiliarity, and commissioning requirements. Previous GPG program studies underscored these issues while investigating advanced lighting controls retrofits at various office buildings in California and Nevada. While retrofits have achieved solid energy savings (26-66%, averaging around 46%), high project costs have resulted in most of the projects not being cost-effective (defined as a savings-to-investment ratio greater than one) [13]. As another case in point, the payback analysis for the previously mentioned PG&E LED fixtures and advanced controls project found that energy savings would only recover the cost of the retrofit after 50 years or more, presenting a major challenge to market adoption.

A DOE study from 2014 on early lessons learned during LED entry into the general lighting market includes a detailed finding on the interplay between LEDs and lighting controls [10]. The report finds that “greater interoperability of lighting control components and more sensible specifications of control systems are required to maximize energy savings delivered by LEDs.” The study points out that the inherent controllability of LEDs opens up opportunities for unprecedented energy savings, but quality design suited for the application is critical for the technologies to succeed and be more widely adopted. Well-designed controls systems may still fall short of owner or user expectations if implemented incorrectly, and the willingness of building tenants and managers to engage with sophisticated controls systems and strategies varies widely. The study concludes that the continued improvement in lighting controls design and implementation will help the LED lighting and controls market deliver solutions that save energy and satisfy users.

B. TECHNICAL OBJECTIVES

This study aims to characterize technical performance of the retrofit systems with real data and measurements. The focal points of the technical analysis are energy savings, photometric performance, occupant satisfaction, and cost-effectiveness. Descriptions of the analysis methodology and metrics used to characterize each focal area are described in the following sections.

ENERGY SAVINGS

To carry out the analysis on energy usage and savings from LED fixtures with integrated sensors and controls, lighting circuit energy for the study areas was metered during pre-retrofit and post-retrofit stages. Energy savings results are presented in the form of Energy Use Intensities (EUI) normalized by project square footage to compare results across studies (Table 5). Greenhouse gas (GHG) emissions savings also were assessed by calculating the reduction in global warming effect (GWE) due to energy savings at each site, which provides insight into the environmental benefits of implementing efficient lighting controls and fixtures. To assess power quality impacts from the replacement of fluorescent fixtures with LED fixtures and integrated controls, power factor (PF) and total harmonic distortion (THD) were measured on a test bench at LBNL and compared to GSA's Facility Standard P-100 guidelines for power quality of light fixtures (PF greater than or equal to 0.90 and THD of less than or equal to 20%.)

Table 5: Energy savings analysis metrics

Metric	Definition
Lighting Power Density (LPD)	A metric for characterizing the lighting power in a given area, defined as lighting wattage divided by the corresponding floor area (watts per square foot, W/ft^2).
Energy Use Intensity (EUI)	A metric for characterizing energy use, defined as the amount of energy used in a space over a given time period divided by the area of the space and the time interval studied. In lighting, EUI is usually calculated in watt-hours per square foot per day ($W/ft^2/day$) or kilowatt-hours per square foot per year ($kWh/ft^2/year$).
Global Warming Effect (GWE)	A metric for characterizing greenhouse gas emissions by summing the product of instantaneous greenhouse gas emissions and their specific time-dependent global warming potential. In this study, GWE was calculated for each utility provider (g $CO_{2,eq}$ /kWh electricity generated) and also normalized by floor area and calculated based off of annual energy savings (kg $CO_{2,eq}/ft^2/year$).

PHOTOMETRIC PERFORMANCE

To determine whether the retrofit demonstrations supplied the necessary light levels and color characteristics for an office lighting environment, illuminance, spectral distributions, color temperature, and color rendering from the pre- and post-retrofit systems were measured (Table 6). GSA's latest Facility Standard P-100, newly released in 2014, establishes target light levels for Federal offices and refers to the Illuminating Engineering Society (IES) Handbook for all light level requirements.[6] Appropriate light levels are defined as greater than 30 foot-candles (fc), or approximately 300 lux, which is the IES recommended light level for the type of office environments studied here. In determining whether the lighting color quality was acceptable, GSA considers a Color Rendering Index (CRI) above 80 to be appropriate.

[6] The *Facilities Standards for the Public Buildings Service* (P-100) establishes design standards and criteria for new buildings, major and minor alterations, and work in historic structures for the Public Buildings Service of the U.S. General Services Administration. This document contains policy and technical criteria to be used in the programming, design, and documentation of GSA buildings.
http://www.gsa.gov/portal/mediaId/187607/fileName/P100_Version_2014.action

Table 6: Photometric performance metrics

Metric	Definition
Illuminance	The density of luminous flux incident on a surface. In less technical terms, a measure of the amount of incoming light reaching a surface. Recorded here using the unit fc (foot-candle).
Color Rendering Index (CRI)	Quantitative measure of the ability of a light source to reproduce colors accurately. Useful in comparing the quality of light emitted by fluorescent lamps and LEDs. This measure has no units. The reference source is defined as having a CRI of 100. There are 14 pigment color samples that color tests measure, the first eight are pastels (R_1-R_8), the next four consist of saturated solids (R_9 - R_{12}), and the last two represent earth tones (R_{13} and R_{14}). CRI is calculated as an average of the renderings of R_1 - R_8, which covers relatively low saturated colors evenly distributed over the complete range of hues.
Spectral Power Distribution (SPD)	The distribution of a light source's luminous flux per wavelength of visible light. Provides information about the visual profile of the color characteristics of a light source. These curves are created by determining the radiant power a fixture produces per unit wavelength as a function of wavelength over the visible region (380 to 760 nm).
Workplane Efficacy (WPE)	A metric for quantifying the lumens available at the surface where visual tasks are performed per unit of power required. This metric helps describe the energy efficiency of a fixture and allows for relevant comparison between fixtures with different light outputs. In this study, the workplane is taken to be the desk surface. WPE is usually calculated in lumens per watt (LPW).

OCCUPANT SATISFACTION

Measuring energy savings and photometric qualities helps to quantify the technical and economic properties of lighting system performance, but an equally important factor is users' satisfaction with the technology. To measure occupant satisfaction, surveys with general questions about the lighting system were administered to the site tenants prior to and after the retrofits. Survey responses have an inherent degree of variation so achieving statistical confidence from the study population responses was a challenge. As much as possible, the same population was surveyed for the pre- and post-retrofit periods, and a response rate of 30% or more was targeted. Anonymity of responses was enforced and free response boxes were provided in order to encourage a more complete understanding of successes and challenges the occupants experienced with the lighting systems.

PROJECT IMPLEMENTER SATISFACTION INTERVIEW

To better understand ease of implementation for the systems and how well the LED fixtures and integrated controls delivered on the promise of simple turnkey installation, brief e-mail interview questions were forwarded to the local GSA building staff responsible for managing the retrofit installations and familiar with the implementation of the systems. The e-mail included questions about the process of programming/commissioning the zones of fixtures to respond to occupants, staff training regarding operation of the lighting system, whether the system operated as expected, whether any occupant complaints or feedback have been received, and whether enough information was provided by the vendor to maintain, commission, and re-commission the system.

COST-EFFECTIVENESS

The cost-effectiveness analysis provides simple payback periods (SPP), savings to investment ratios (SIRs), project net present values (NPV), and internal rates of return (IRR) for the implementation of the controls and fixture retrofits (Table 7). Costs are normalized by both floor area and the number of fixtures retrofitted in order to compare results across studies.

Table 7: Cost-effectiveness analysis metrics

Metric	Definition
Simple Payback Period (SPP)	Characterizes the length of time required to recover the cost of an investment, and defined as the cost of project over the energy cost savings at the site per year.
Savings to Investment Ratio (SIR)	The ratio of discounted life-cycle savings from an energy improvement, including projected operations and maintenance savings over time, to the initial investment cost. If SIR is greater than 1, the investment is cost-effective over the investment's lifetime. This metric has no units.
Net Present Value (NPV)	The sum of the original project cost and the discounted present values of future cash flows (or avoided costs) resulting from an investment.
Internal Rate of Return (IRR)	The discount rate at which the net present value of an investment's discounted future cash flows would equal zero; essentially the interest rate earned by the capital invested in the project.

C. DEMONSTRATION PROJECT LOCATIONS

CHICAGO METCALFE

The Ralph H. Metcalfe Federal Building (Metcalfe) is a 28-story building located in downtown Chicago, Illinois. The Metcalfe building is a steel-framed building constructed in 1991 in the Mies van der Rohe international style aesthetic to match the adjacent Federal Center buildings. The building has a rectangular footprint approximately 27,000 ft^2, with the long axis oriented north-south. The study area is the majority of the tenant-occupied space on the 17th floor, which excludes the common spaces of the elevator lobby, mechanical rooms, and bathrooms located on the east side of the floor. Occupants in the study space perform primarily paperwork and desk/computer work. Based on GSA e-mails, most of the occupants are present between the hours of 8 AM and 5:30 PM, and building operating hours are Monday through Friday, from 7:15 AM to 5:15 PM.

Figure 8: Photo of the exterior of the Metcalfe Federal Building[7]

The study area consists primarily of a large open office area that extends along the north, west, and south perimeter, as well as seven private offices, two conference rooms and four breakout rooms. The open office area has a dense distribution of cubicles. Three of the six private offices are located in the interior of the floor; the other three are located along the north wall. Windows are approximately 4' wide by 6' tall, and sets of two windows are spaced approximately every 10', which provides substantial potential for daylight harvesting. During the technical kick-off meeting on June 20, 2013, most of the blinds were observed to be open. The study area covers approximately 19,750 ft^2.

[7] Photo Credit: http://www.gsa.gov/portal/content/101887

Figure 9: Metcalfe study location floor areas

The existing lighting system in the Metcalfe study space was comprised of approximately 254 recessed 2'x 4' parabolic troffers typically spaced 8'x 10' on center, and five recessed 2'x 2' parabolic troffers located in the back corridors. The 2'x 4' fixtures were designed for three F32T8 lamps, and louvers divide the fixture into 18 cells. The fixture density averaged about 76 ft^2 per fixture. Automated timers were scheduled to switch all lights off at 7 PM, which occupants were able to override for two-hour segments using switches located near the three major entrances to the tenant space. Manual switches with built-in occupancy sensors were located in three enclosed conference rooms, two private offices, two break rooms, and two copy rooms, although some were broken or disabled. Other private offices and conference rooms had dimmers or toggle switches for recessed can lights that were out of scope for this study and were not retrofitted.

ATLANTA SUMMIT

The Peachtree Summit Federal Building (Summit) is a 30-story building located in downtown Atlanta, Georgia. The Summit building was completed in 1976 and is a glass and concrete office building with a triangular footprint. The building's triangular footprint is approximately 31,000 ft^2, with the hypotenuse oriented in the true north-south axis. The study area is located on the south half of the 28th floor, excluding the non-tenant corridors, various interview rooms, a lobby/waiting area, and other non-office spaces. Occupants perform primarily paperwork and desk/computer work.

Figure 10: Photo of the exterior of the Summit Federal Building[8]

The demonstration area located in the Summit building contains a large open office area that wraps around the perimeter of the space, two private offices, two conference rooms, one break room, and miscellaneous areas, including a reception area and file storage rooms. The open office area has a dense distribution of cubicles. Windows are located continuously along all walls in the study area and are approximately 4.5' wide and extend the whole height of the floor, providing a large opportunity for daylight harvesting. During the technical kick off meeting on June 20, 2013, most of the blinds were observed to be open and pulled to half height. The study area covers approximately 12,900 ft^2.

[8] Photo Credit: http://www.atlantaarchitecture.info/Building/1499/Peachtree-Summit-One.php

Figure 11: Summit study location floor areas

The existing lighting system in the study space on Summit's 28th floor included 131 recessed 2'x 4' 2-lamp troffers and six 2'X 2' 2-lamp fixtures. The 2'x4' fixtures were designed for two F32T8 lamps with reflectors that curve around each lamp and louvers that divide the fixture into six cells. The 2'X 2' fixtures were also 2-lamp T8 fixtures. The fixture density averaged out to around 94 ft^2 per fixture for the study area. Manual switches for offices, training rooms, and zones of open office fixtures were located throughout the study area.

D. TECHNOLOGY DEPLOYMENT

The LED fixtures with integrated sensors and controls were installed in the study areas of the Metcalfe and Summit buildings, with all 2'x 2' and 2'x 4' fluorescent fixtures being replaced by LED fixtures of matching dimensions. The LED lighting system installed for the study is essentially a turnkey package. Each fixture has integrated daylight and occupancy sensors that inform its operation; controls logic is stored and processed onboard the fixture, and each fixture also has a wireless radio device that allows it to communicate its operating state with other fixtures in the space. Once installed, the system is commissioned with an infrared remote; each fixture is assigned to a group based on the layout of the space, with large swaths of adjacent fixtures organized into groups that operate in concert. During commissioning, each group of fixtures is set to a high, medium, or low maximum light level based on the illuminance needs of the space. This is referred to here as institutional tuning. At both demonstration locations, the fixtures were commissioned to the medium setting to provide appropriate light levels while reducing fixture wattage and increasing energy savings.

All fixtures in a given group turn on to a low background level (approximately 13W, or 33% of the 39W full power value at the medium setting) when any single fixture in the group senses the presence of an occupant and relays that information wirelessly to the rest of the fixtures in its group. The fixtures in the group that are directly above occupants detect this with the integrated sensors and brighten to the highest level commissioned during institutional tuning. Those fixtures in the group that do not sense occupancy will remain at the background level. This creates a uniform lighting environment and appearance for occupants in the space, who observe that all fixtures in the group appear on, even if only the fixtures nearest to them are actually on at full brightness.

Finally, the LED fixtures are programmed to dim gradually in response to daylight availability as detected by each fixture's onboard sensor. The fixtures also auto-calibrate daylight harvesting set-points daily to adapt to changes in space usage. For example, furniture layout changes and other changes in a space alter surface reflectances and the amount of light detected by each fixture.

Table 8: LED fixture nameplate performance

Description	Color Temperature	CRI	Rated Efficacy	Setting	Input Power	Lumen Output
2'x 4' LED with integrated sensors and controls	4000 Kelvin	80	94 lm/W	High	46W	4300 lm
				Medium	39W	3800 lm
				Low	35W	3300 lm

Design guidance from the lighting system vendor indicates that fixture grouping in open office layouts should be commissioned such that large numbers of adjacent fixtures in the open plan are grouped together, with around 40 to 50 fixtures per group being the goal. This is meant to ensure that occupants within each group experience a uniform lighting environment during the workday. If groups of fixtures are too small, the lighting environment might appear more patchwork, with groups where no occupants are present remaining completely off but being visible to occupants in adjacent groups that are on. On the other hand, smaller groups mean that when occupancy rates are low, more fixtures remain completely off, saving more energy. Naturally, the system design and implementation must balance lighting appearance and aesthetics with energy efficiency goals. The following figures show the fixture grouping schema implemented in the two study spaces. Note that each private office or conference room is essentially programmed as its own group, since the fixtures in enclosed spaces should only turn on if occupants are present in those spaces.

Figure 12: Metcalfe LED fixture control groups programmed during system commissioning

Figure 13: Summit LED fixture control groups programmed during system commissioning

IV. Measurement and Verification Summary

During the pre- and post-retrofit study periods, site characterization visits, energy monitoring activities, photometric characterizations, and occupant satisfaction surveys were conducted at each site to analyze the effectiveness of the installed technology. Measurement of the baseline lighting ballast power draw was carried out at a test-bench at LBNL.

A. PROJECT SCHEDULES

Metering equipment to characterize pre- and post-retrofit lighting energy usage was installed at both locations in late October 2013, with monitoring of pre-retrofit conditions beginning November 1, 2013. At Metcalfe, installation of the LED fixtures with integrated sensors and controls began December 13, 2013, and the new lighting system was fully commissioned operational by December 23, 2013. The retrofit system was installed at the Summit building the weekend of December 14, 2013. As discussed later, some system implementation and commissioning issues had to be addressed in December 2013 and January 2014; the system was fully operational by January 23, 2014.

Figure 14: Metcalfe project schedule

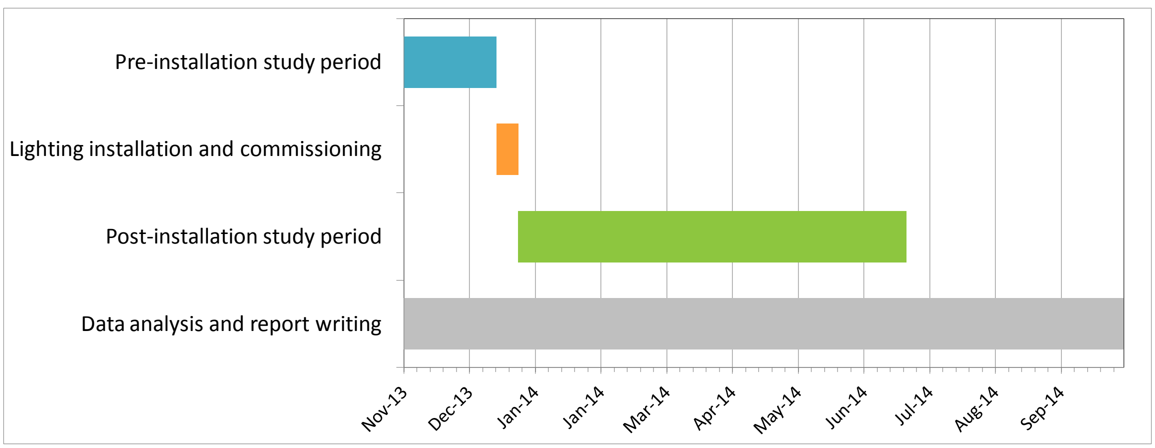
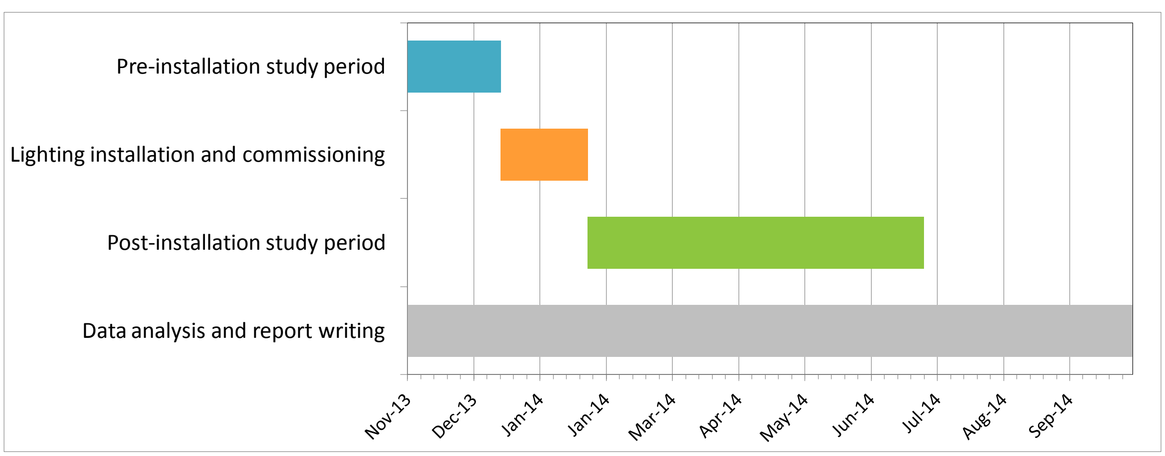


Figure 15: Summit project schedule



B. SITE CHARACTERIZATION

During the site visits, lighting levels and color characteristics were measured at desks throughout the spaces and site characteristics were documented, including overhead lighting layout, number of workstations, location of workstations, and general office layout. Cubicle partition heights and workspace dimensions were recorded, and task lighting, occupant schedules, and work styles were noted to the extent possible. Changes between pre- and post-retrofit site layout and occupancy conditions were also documented. Photographs were taken throughout the spaces during these visits to document office and workstation layout, window locations and blinds usage, lighting system equipment (*e.g.*, ballasts, lamp type, and fixture model information), and controls details (*e.g.*, switch location, zone controls, relay panels and circuit panels).

Chicago Metcalfe:

LBNL conducted a pre-retrofit site visit at Metcalfe on October 29, 2013, to characterize the operation of the baseline lighting system. A post-retrofit visit was conducted March 25, 2013, to characterize the new system. During the characterization visits, it was found that the 17th floor study location at Metcalfe included seven enclosed private offices and around 120 workstations in the open office plan. During the pre- and post-retrofit visits, around 80% of the desks appeared to be regularly occupied. Sixteen lighting circuits were found to power the roughly 190 overhead lighting fixtures in the open office spaces (excluding emergency fixtures on separate circuits), and four circuits were found to power around 40 fixtures in the closed office areas and reception (excluding emergency fixtures on separate circuits). These circuits were monitored for lighting energy usage data.

Atlanta Summit:

The pre-retrofit site visit at Summit was carried out on October 30, 2013. A post-retrofit visit was conducted March 24, 2013. The 28th floor study location at Summit included two enclosed private offices and around 36 workstations in the open office plan. During the pre- and post-retrofit visits, around 75% of the desks appeared to be regularly occupied. It was found that 3 lighting circuits served roughly 80 overhead lighting fixtures in the open office spaces, and 2 lighting circuits served around 40 fixtures in the 2 private offices and reception, mailroom, hallway, and training room (considered closed office areas for the purposes of this study). These circuits were monitored for lighting energy usage data. Emergency fixtures in the spaces that used separate circuits were not monitored, and a small number of recessed can fixtures powered by the same circuits as the study fixtures, but not a part of the project, were excluded from the study analysis.

C. ENERGY SAVINGS

To assess the lighting system energy usage at each site, lighting energy was measured by energy data acquisition systems during pre- and post-retrofit periods. The lighting branch circuits powering the overhead fixtures in the study areas at Metcalfe and Summit were identified through as-built circuit diagrams and confirmed by circuit tracing on-site to identify accurately which circuits served each fixture. Lighting energy was measured on each circuit at the lighting panels. This study used energy meters that measured true RMS voltage, amps, and power, and recorded kWh usage at five minute intervals.

Current transformers were installed on each circuit at the lighting panel level and were wired to data loggers. LBNL oversaw an electrician for installation of the data acquisition systems. The data loggers connected wirelessly to a remote server where measurement data could be accessed by LBNL.

Pre- and post-retrofit metering periods varied in length due to retrofit schedules and site access timing. Post-retrofit metering was conducted to capture as much of a half-year, solstice-to-solstice period, as possible to capture seasonal daylight trends, since this affects daylight harvesting strategies. Days that were deemed atypical were excluded from the analysis. These included days when daylight savings time began or ended, days with incomplete or unusual power metering data (such as during power outages), and days when site work interfered with typical operation.

Metered circuit power data was converted into lighting power density (LPD) in terms of watts per square foot based on the floor area under each lighting circuit. Daily energy use intensities (EUI) were then calculated in watt-hours per square foot per day. Days were separated into workdays, weekends, and holidays, and average LPDs and EUIs were calculated for each type of day. Finally, annual EUIs (in kilowatt-hours per square foot per year) were calculated for each site based on an assumed typical distribution of 251 workdays, 104 weekend days, and 10 holidays per year. Calculated pre-retrofit and post-retrofit annual EUIs were then compared to determine energy savings at each site.

Chicago Metcalfe:

The pre-retrofit period for analysis began November 1, 2013, and ran until installation of the LED fixtures, starting December 13, 2013. The new system was fully operational and commissioned by December 23, 2013, when the post-retrofit period of analysis began. The data collection period ended on June 21, 2014.

The pre-retrofit lighting system at Metcalfe consisted of around 250 3-lamp T8 fluorescent fixtures (excluding emergency fixtures), a large number of which were de-lamped fixtures (*i.e.*, one or two lamps in a fixture not operating). In the open office spaces, the overhead fixtures averaged around 1.64 operating lamps, while in the closed office spaces overhead fixtures averaged around 1.83 operating lamps. Contacts at the study location indicated that many tenants felt the space was overlit when all lamps were operating, so the de-lamping observed at the site was determined to be intentional for the purpose of lowering the lighting provided by the system. An adjustment factor was used to scale the measured lighting energy during the pre-retrofit period to the lighting energy that would have been used if all lamps had been operational per system design. Post-retrofit energy savings were then determined in relation to the measured baseline and the baseline adjusted to design condition.

Table 9: Metcalfe lighting energy metering periods

Phase	Start Date	End Date	Weekdays	Weekend days	Holidays	Total Days
Pre-retrofit	11/01/2013	12/13/2013	29	12	2	43
Post-retrofit	12/23/2013	06/21/2014	122	51	5	178

* During the pre-retrofit period, there was a data acquisition outage on two circuits from November 4-8, 2013; that data window for the two circuits is excluded from analysis. Post-retrofit, there was a 22-day data acquisition outage from March 31-April 21, 2014, for many of the open office lighting circuits. The date of the post-retrofit characterization visit (March 25, 2014) is excluded from the study period.

Atlanta Summit:

The pre-retrofit period for analysis at Summit began November 1, 2013, and ended December 13, 2013. The post-retrofit lighting controls system was installed the weekend of December 14, 2013, and post-installation data collection began Monday, December 16, 2013.

The pre-retrofit lighting system at Summit consisted of around 140 2-lamp T8 fluorescent fixtures, with both lamps operational in all overhead fixtures. As such, there was no need for any adjustment factor to scale measured lighting energy to a design level because the system was already operating per design intent. However, a few of the lighting circuits providing power to the overhead fluorescent troffers also powered recessed can fixtures that were not part of the project scope. For these spaces, pre- and post-retrofit lighting energy data was filtered to remove days with significant load from the recessed cans.

During installation of the retrofit system, all light switches in the space were initially removed, in the open offices as well as in closed spaces such as private offices and training rooms. While removing zone controls and wall switches for the open offices was in line with the project intent, wall switches in enclosed spaces should have remained in place so that tenants in these spaces had the choice of using or not using overhead lighting. Without switches to control overhead lights in enclosed spaces, tenants used the handheld commissioning remote to turn individual fixtures on and off, inadvertently erasing commissioning settings for the fixtures in the offices as well as for larger groups of LED fixtures in the space. This resulted in large swaths of overhead fixtures remaining on at a dimmed level overnight. The wall switches had to be reinstalled to address this issue. A representative from the lighting system vendor then revisited the site in January 2014 to re-commission the LED fixture groups. All issues were resolved and the system was operating as intended by January 23, 2014, when the post-retrofit period of analysis for the affected circuits began.

Table 10: Summit lighting energy metering periods

Phase	Start Date	End Date	Weekdays	Weekend days	Holidays	Total Days
Pre-retrofit	11/01/2013	12/12/2013	28	12	2	42
Post-retrofit	12/16/2013	06/21/2014	123	53	6	182

* Pre-retrofit, data acquisition for one circuit did not come online until November 18, 2013. Over this data collection period, 10 days of data for one circuit with recessed can lights were excluded due to the can lights being on, which skewed measurements. Post-retrofit, 10 days during which the overnight load was measured were excluded from the dataset for one of the circuits. There were two extreme weather events in Atlanta in the winter of 2014; the offices at Summit were closed January 29-30, 2014, and February 11-13, 2014. These dates were excluded. Data for the date of the post-retrofit site visit on March 24, 2014, also was excluded.

To assess power quality impacts from the replacement of fluorescent fixtures with LED fixtures and integrated controls, input wattage, PF, and THD were measured on a test bench at LBNL for the pre-retrofit ballasts at Metcalfe and Summit and for the post-retrofit LED fixtures. The LED fixture power quality values were measured at various power level settings, from full power to medium and lower power levels, using the infrared commission remote supplied by the fixture vendor for controls commissioning. GSA's P-100 guidelines for power quality of light fixtures are PF greater than or equal to 0.90 and THD of less than or equal to 20%.

D. PHOTOMETRIC CHARACTERIZATION

Photometric measurements were taken in each study location's workspaces during the characterization visits to evaluate electric light levels (illuminance measurements), spectral power distributions, CRI, and CCT. Desktop illuminance measurements were taken at the primary work location, assumed to be the front edge of the main desk's center section. Objects directly obstructing the overhead lights were removed temporarily while the measurements were taken, but otherwise desktop objects and clutter were not modified. Any task lights were turned off during measurements so that measurements reflected lighting service from only the overhead lighting system. Mean, median, quartile, minimum, and maximum pre-retrofit and post-retrofit light levels were calculated from all measurements and compared.

E. OCCUPANT SATISFACTION SURVEY AND PROJECT IMPLEMENTER INTERVIEW

Surveys were administered online and occupant responses were recorded anonymously. The survey contained 17 multiple choice questions and 3 free-response boxes (where respondents could type in their own comments) that addressed satisfaction with lighting levels, lighting control, and lighting quality. Occupants were asked to respond to qualitative questions about their workspace and overall office light conditions. Reminder emails were sent out during the survey period to encourage occupants to take the survey. Post-retrofit occupant satisfaction surveys were distributed two to three months after the installation to allow tenants to acclimate to the new lighting system. Survey responses were compiled and comparisons between pre-retrofit and post-retrofit responses were made.

In addition, brief e-mail interview questions were forwarded to the local GSA building staff responsible for managing the retrofit installations to better understand the ease of implementation for the systems and how well the LED fixtures and integrated controls delivered on the promise of simple turnkey installation. Questions were posed regarding the process of programming/commissioning the zones of fixtures to respond to occupants, staff training regarding operation of the lighting system, whether the system operated as expected, whether any occupant complaints or feedback had been received, and whether enough information was provided by the vendor to maintain, commission, and re-commission the system.

V. Results

A. ENERGY SAVINGS

CHICAGO METCALFE

The pre-retrofit installed LPD was calculated from the pre-retrofit number of fixtures and ballasts in the study space, the square footage of the space (excluding areas served by 24/7 emergency fixtures), and the input power of the ballasts, which was measured on a test bench at LBNL. The pre-retrofit design LPD of the lighting system was 1.09 W/ft^2 if all three lamps per fixture were operating. This is well within the range of typical LPD for office lighting systems. However, it was found in the Metcalfe study space that, in many of the fixtures, only one or two lamps were operating and, in some fixtures, all lamps were out. The actual lighting power density of the space had decreased, based on the widespread lamp outages, to only 0.69 W/ft^2, lower than average office LPD. Recall also that the fixture spacing on average for this study space is 76 ft^2 per fixture.

Based on the LED fixture wattage, commissioned to the medium power setting (39W), post-retrofit LPD was determined to be 0.50 W/ft^2 with all fixtures on (excluding any occupancy- or daylight-based dimming). The installed LPD in the study area decreased by 54% relative to the design condition due to the switch from fluorescents to LED fixtures at the medium power setting, but only by 27% relative to the LPD found at the site due to all the lamp outages. If the LED fixtures were commissioned to operate at the full power setting (46W), the new LPD would have been around 0.59 W/ft^2, so institutional tuning of the LED fixtures during commissioning lowered the post-retrofit power by around 15%.

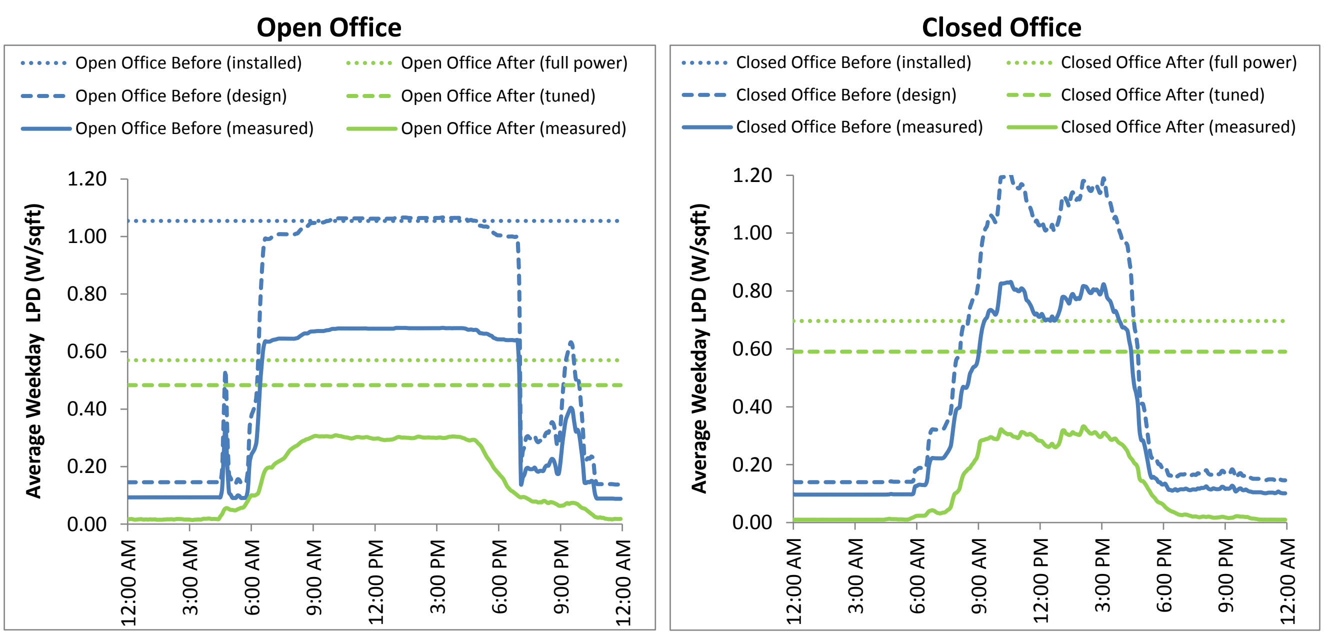
Table 11: Metcalfe installed lighting power

Study Period	Net Floor Area (ft^2) Emergency fixture space subtracted	Installed power (W)	Installed LPD, W/ft^2	Decrease, relative to measured baseline	Decrease, relative to design baseline
Pre-retrofit, design	17,623	19,188	1.09	- 60.0%	—
Pre-retrofit, actual		12,465	0.71	—	35.2%
Post-retrofit, full power		10,396	0.59	16.3%	45.8%
Post-retrofit, tuned		8,814	0.50	29.1%	54.1%

Figure 16 shows average daily LPD calculated from the study period data during normal workdays for the open office areas and the enclosed office spaces, including private offices, conference room, and copy rooms. From the calculated daily averages, some of the normal operating cycles of the lighting system are clear. During the baseline period, the open office area lighting schedules and occupancy patterns had lights turning on around 6:45 AM daily, with a small amount of lights on as early as 6:00 AM, and most lights were turning off around 7:15 PM. Private offices and other enclosed spaces tended to turn on between 8:00 and 9:00 AM and were mostly off by 4:30 to 5:00 PM, with some dip in lighting usage around the lunch hour. Importantly, most of the enclosed spaces already had occupancy sensors in them to control the lights. In the open offices, there also was clearly some regular activity outside of working hours, likely custodial and security details, occurring around 4:30 AM and 9:30 PM. Also, enough fixtures were apparently operating continuously to result in around 0.1W/ft^2 lighting load, on average, around the clock in the open and enclosed office spaces. This was true of weekends and holidays (not shown in Figure 16).

After the retrofit of the LED fixtures with integrated controls, the most obvious change in average daily lighting power was a large reduction in the amplitude of the LPD curve, with average measured power over 50% lower. Also, with the new lighting system, sensors turn lights on gradually based upon actual occupancy in the space, rather than all at once as with the previous automated schedules. The open office lighting load now slowly ramps up from 6:00 to 9:00 AM and down from 4:30 to 7:15 PM. This reflects the various schedules of the different occupants that use the work spaces and shows how occupancy controls can tailor lighting operation more efficiently than automated schedules. The occupancy controls also appear to have addressed the issue of lighting load staying on overnight; the after-hours LPD is now close to zero, as it should be when no occupants are present. For the enclosed office spaces, because there were already occupancy sensors to control the lights, the operating schedules pre- and post-retrofit look largely the same, even though the total lighting power is much lower and the after-hours lighting power has been reduced to near zero.

Figure 16: Metcalfe average workday lighting power density



*The pre-retrofit metering period included 29 weekdays, 12 weekend days, and 2 holidays. The post-retrofit metering period included 122 weekdays, 51 weekend days, and 5 holidays. Pre- and post-retrofit annual EUIs were calculated assuming 251 weekdays, 104 weekend days, and 10 holidays.

Based on measured lighting energy usage over time at the study location, annual energy savings were calculated for the retrofit of the fluorescent lighting system to the LED fixtures with integrated sensors and controls. Pre- and post-retrofit lighting energy usage over workdays, weekends, and holidays was averaged and multiplied by the annual total days of each type. For this study location, it was found that the baseline lighting energy usage intensity (EUI) was 2.56 kWh/ft^2/year, less than the average for GSA office buildings (discussed in the Cost-effectiveness section below). It is estimated that if there were not widespread lamp outages and the fixtures were operating with all lamps functional, the baseline lighting EUI would have been 3.96 kWh/ft^2/year, actually quite close to the national average lighting energy for offices (also discussed below). The post-retrofit lighting EUI was found to be 0.98 kWh/ft^2/year, saving almost 62% lighting energy over the measured baseline and more than 75% relative to the estimated design baseline with all lamps functioning.

Table 12: Metcalfe lighting energy usage intensities

	Weekday EUI (Wh/ft^2/day)	Weekend EUI (Wh/ft^2/day)	Holiday EUI (Wh/ft^2/day)	Annual EUI (kWh/ft^2/year)
Pre-retrofit, measured	9.80	0.92	0.33	2.56
Pre-retrofit, design	*15.21*	*1.35*	*0.44*	*3.96*
Post-retrofit	3.71	0.40	0.31	0.98
% Savings, measured	62.1%	56.4%	4.8%	61.9%
% Savings, relative to design	*75.6%*	*70.3%*	*29.1%*	*75.4%*

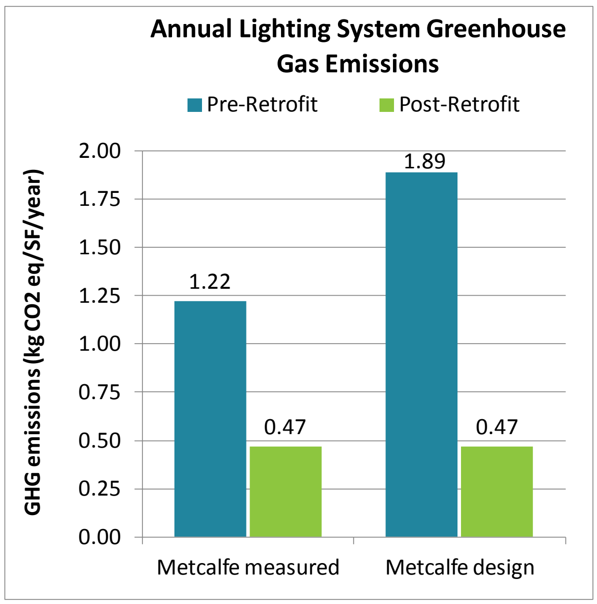
It is useful to differentiate the energy savings from the various features of the retrofit lighting system, from the lower wattage of the LED light source to the energy saving behaviors of the sensors and controls. To start with, the LED fixtures are a higher-efficacy, lower-wattage light source, even if sensors and controls are not included in the system. The LED fixtures are dimmable and can be tuned to the lower maximum output settings described in the technology deployment section, depending on the needs and priorities of a given space. Finally, the integrated sensors allow individual fixtures to dim to a low background level if the group of fixtures to which they are assigned is triggered to the on state but no occupants are present directly under the fixture. All fixtures can dim if enough daylight is present to reduce the need for electric light.

As Table 11 shows above, the power density of the installed lighting system was actually only reduced around 16% by switching to the LED fixtures at full power. The LED fixtures were then commissioned to operate at the medium institutional tuning level, reducing lighting power another 13%, resulting in total LPD savings of around 29%. The other sensor and controls features are responsible for operational changes and dynamic dimming throughout the day that result in 33% additional savings, totaling 62% savings for the entire system, as shown in Table 12. Of those 62% energy savings, around 46% come from controls features.

A GREENHOUSE GAS EMISSIONS

Greenhouse gas emissions from the energy usage of the lighting system were calculated based on the estimated annual energy consumption under pre- and post-retrofit conditions. With energy savings from the LED fixtures and integrated controls at 61.9%, a reduction in lighting energy greenhouse gas emissions of approximately 0.75 kg CO_2/ft^2/year was calculated. This rate is based on Illinois' electricity generation fuel mix and emissions rate of 476.7 g CO_2 eq/kWh. The emissions reduction relative to the design condition at Metcalfe would be 75.4%, or approximately 1.42 kg CO_2/ft^2/year.

Figure 17: Metcalfe lighting energy greenhouse gas emissions



ATLANTA SUMMIT

Input power for the pre-retrofit ballasts and lamps at Summit was measured on a test bench at LBNL. Based on ballast power, the number of fixtures and ballasts in the study space (excluding areas served by 24/7 emergency fixtures) and the square footage of the space, the pre-retrofit installed LPD was found to be 0.66 W/ft^2 when two lamps per fixture were powered. Unlike the study space at Metcalfe, the lighting system in the Summit study space was operating per design (all lamps were operational). Even with all lamps operating, based on the fixture spacing and the fact that the fixtures in the space are all two-lamp fixtures, the baseline LPD found at this location was quite low compared to 1W/ft^2 typical for office environments. Compared to the Metcalfe demonstration area, not only is the fixture wattage lower but the fixtures are also placed less densely, at around 94 ft^2 per fixture.

With the LED fixtures commissioned to the medium power setting, post-retrofit LPD with all fixtures on is 0.44 W/ft^2. The installed LPD in the study area decreased by 33% due to the switch from fluorescents to LED fixtures. If the LED fixtures had not been institutionally tuned from the maximum power setting, the post-retrofit LPD would be 21% lower than the baseline, so institutional tuning saved around 12% additional lighting power.

Table 13: Summit installed lighting power

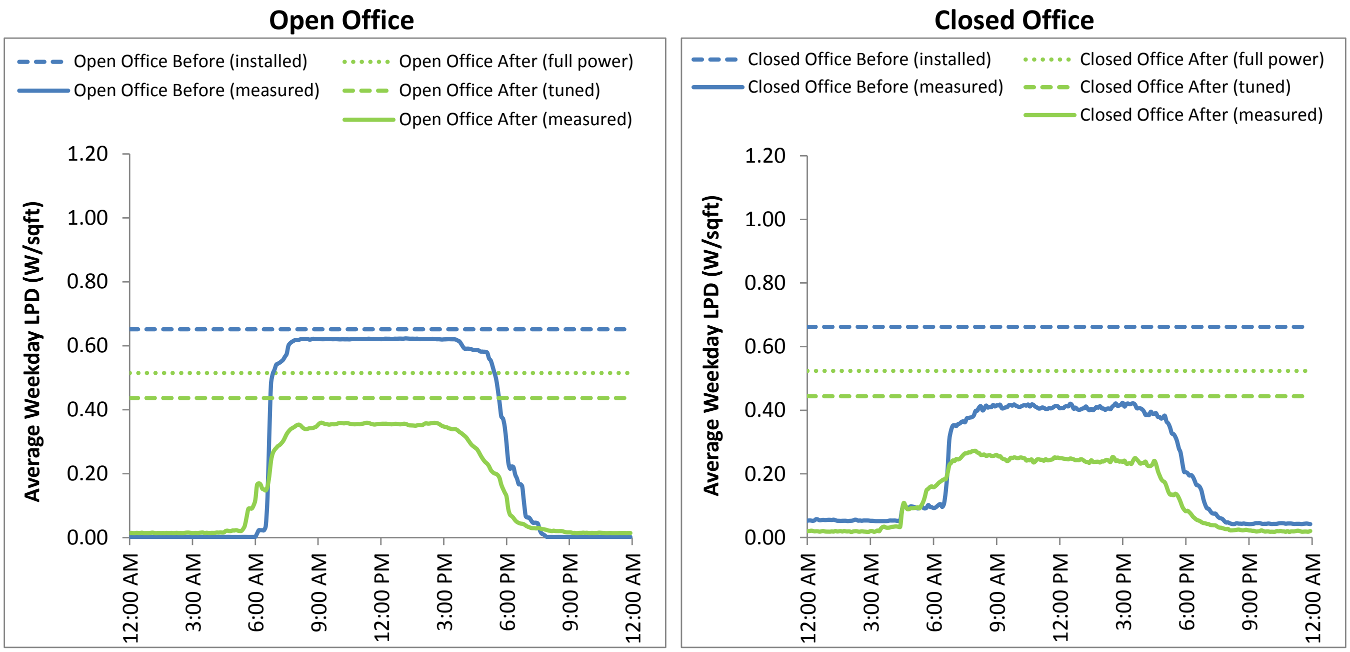
Study Period	Net Floor Area (ft^2) Emergency fixture space subtracted	Installed power (W)	Installed LPD, W/ft^2	Decrease, relative to measured baseline
Pre-retrofit	11,194	7,332	0.66	—
Post-retrofit, full power		5,796	0.52	21.0%
Post-retrofit, tuned		4,914	0.44	33.0%

Figure 18, below, shows average daily LPD in the Summit study space during normal workdays for the open office areas and the enclosed office spaces, including private offices, conference room, and copy rooms. Similar to the Metcalfe case, the daily average lighting power curves show the normal operating cycles of the lighting system. For the open office areas, during the baseline period the lights were turned on by automated schedules and occupancy patterns at 6:45 AM and lighting usage tapered off between 5:30 and 7:15 PM. This would indicate that occupants were diligent about turning off the fixtures in their vacated zones when leaving in the evening, rather than simply letting the automated schedules shut off the open office lighting off later. There were zone-level wall switch plates in the open office area that allowed this type of zone switching to occur.

Noticeably, the overall amplitude of the lighting power curve for the open office spaces is much lower after the retrofit: about 42% lower than the pre-retrofit case. In the post-retrofit case, the open office lighting power during the work day ramps up from up from 6:00 to 7:30 AM and tapers off from 4:00 to 6:15 PM. While the fixtures are powering down slightly sooner at the end of the work day, they are turning on earlier, indicating that the occupancy sensors are picking up activity early in the morning, and turning some of the LED fixtures on, even before occupants or automated schedules turned the fluorescent fixtures on previously. Evidently some users of this space arrive to the office quite early, causing perhaps one of the LED fixture groups to turn on. Remember that the LED fixtures are organized into large groups during commissioning so that the lighting environment appears more uniform to individual occupants. This can result in many lights switching on, even if only to the background level, just to serve the lighting needs of one or a few occupants. In the baseline case, it is likely that the same occupants were arriving early, but perhaps were not using the overhead lighting zones, choosing instead to work with desk lamps or other task lighting options.

For the private offices, conference rooms, and other enclosed spaces, the retrofit caused the daily lighting power curve to shrink noticeably as well; the amplitude is about 39% lower than the pre-retrofit case. The pre- and post-retrofit patterns show roughly the same schedule of operation, with lighting power ramping up from 4:30 to 6:45 AM, and tapering off from 4:00 to 7:00 PM.

Figure 18: Summit average workday lighting power density



*The pre-retrofit metering period included 28 weekdays, 12 weekend days, and 2 holidays. The post-retrofit metering period included 123 weekdays, 53 weekend days, and 6 holidays. Pre- and post-retrofit annual EUIs were calculated assuming 251 weekdays, 104 weekend days, and 10 holidays.

Based on measured lighting energy usage over time at the study location, annual energy savings were calculated for the retrofit of the fluorescent lighting system to the LED fixtures with integrated sensors and controls. Pre- and post-retrofit lighting energy usage over workdays, weekends, and holidays was averaged and multiplied by the annual total days of each type. For this study location, the baseline EUI was 1.78 kWh/ft^2/year. After the retrofit, that value dropped 40.2% to 1.06 kWh/ft^2/year. Though this savings percentage is significant, the baseline EUI is very low compared to GSA and national average office lighting energy usage, so less lighting energy savings were on the table than would be expected at a more typical site.

Table 14: Summit lighting energy usage intensities

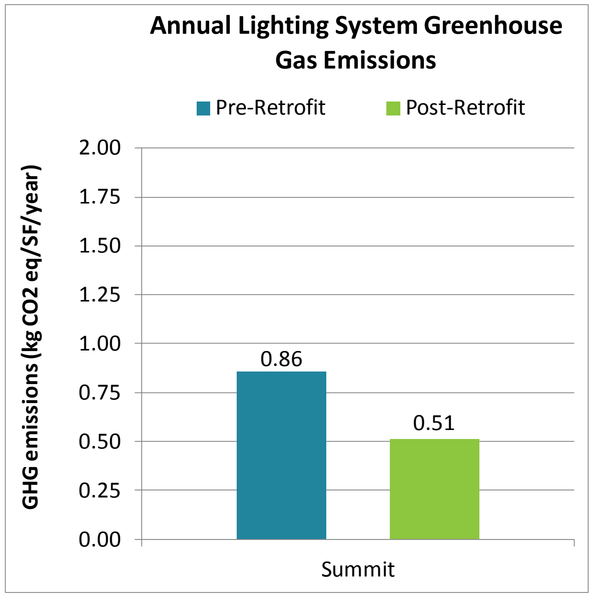
	Weekday EUI ($Wh/ft^2/day$)	Weekend EUI ($Wh/ft^2/day$)	Holiday EUI ($Wh/ft^2/day$)	Annual EUI ($kWh/ft^2/year$)
Pre-retrofit	6.45	1.48	0.62	1.78
Post-retrofit	3.78	1.01	1.11	1.06
% Savings	41.4%	32.1%	-79.8%	40.2%

For Summit, it appears that lighting operation in the demonstration space was already highly efficient even before the lighting retrofit. The LED lighting system with integrated sensors and controls saved energy mostly due to the change-out to the more efficient LED fixtures. The LED fixtures save around 21% lighting power compared to the 2-lamp fluorescent fixtures, and save an additional 12% when institutionally tuned to the medium power setting. Including the benefits of occupancy sensor dimming and shut off and daylight dimming only increases savings by around 7%. To summarize, of the total lighting energy savings at the site of 40%, around 19% of those savings are estimated to come from the controls features, including institutional tuning.

A GREENHOUSE GAS EMISSIONS

Greenhouse gas emissions from the lighting system energy usage were calculated based on the annual energy consumption estimates under pre- and post-retrofit conditions. With energy savings from the LED fixtures and integrated controls at 40.2%, a reduction in lighting energy greenhouse gas emissions of approximately 0.35 kg CO_2/ft^2/year was estimated. This rate is based on Georgia's average electricity generation fuel mix and emissions rate of 481.7 g CO_2 eq/kWh electricity generated.

Figure 19: Summit lighting energy greenhouse gas emissions



POWER QUALITY

Input wattage, PF, and THD were measured on a test bench at LBNL for the pre-retrofit ballasts at Metcalfe and Summit and for the post-retrofit LED fixtures in order to assess power quality implications of replacing the baseline fluorescent fixtures with the LED fixtures and integrated sensors and controls. The LED fixture power quality values were measured at various power level settings, from full power to medium and lower power levels, using the infrared commission remote supplied by the fixture vendor for controls commissioning.

Table 15 Power quality measurements for fluorescent ballasts and LED fixture

Lighting Equipment	Voltage, and Location (if applicable)	Input Power, W	PF	THD
2'X 4' two lamp fluorescent	277V, Summit	58.3	0.98	15.8%
2'X 2' two lamp fluorescent	277V, Summit	57.3	0.99	16.1%
2'X 4' with three lamps working	120V, Metcalfe	84.2	0.99	5.6%
2'X 4' with two lamps working	120V, Metcalfe	63.6	0.99	8.2%
2'X 4' with one lamp working	120V, Metcalfe	38.6	0.97	20.2%
LED fixture (tuned to medium power)	277V	41.8	0.90	25.8%
LED fixture (roughly 50% power)	277V	25.1	.80	32.0%

Lighting Equipment	Voltage, and Location (if applicable)	Input Power, W	PF	THD
LED fixture (tuned to medium power)	120V	41.6	0.99	16.0%
LED fixture (roughly 50% power)	120V	24.2	0.97	21.5%

The LED fixture with integrated sensors and controls met the PF and THD guideline when tested at the tuned medium power setting at 120V, the voltage at the Metcalfe location. When dimmed to the 50% setting, THD was just above the 20% limit. At 277V, the voltage at the Summit location, the LED fixture THD results are slightly above the 20% threshold at the tuned medium setting and over 30% when dimmed to the 50% setting. Overall, there were increases in THD levels corresponding as LED fixture power was dimmed to lower levels. However, the reduction in power and current draw from the lower-wattage LED fixtures relative to the fluorescent baselines roughly balanced the increase in THD. Overall current draw from harmonic distortion is expected to be similar or less with the LED fixtures and controls system than with the baseline fixture ballasts. There should not be substantial changes in power quality for the building utilities with the adoption of the LED fixtures.[9]

B. PHOTOMETRIC PERFORMANCE

GSA's *Facilities Standards for the Public Buildings Service*, known as P-100, establishes design standards and criteria for new buildings, major and minor alterations, and works in historic structures.[10] GSA's lighting requirements in P-100 refer to the Illuminating Engineering Society (IES) recommended light levels for office spaces. IES defines appropriate light levels to be above 300 lux, or approximately 30 fc, for the types of office environments studied here.

Light level measurements at each site, before and after the retrofits, are compared against the P-100 requirement. CRI and other color characteristics of the lighting system are also reviewed. In considering color rendering quality of a light source, GSA considers CRIs higher than 82 to be appropriate. Photographs of the pre- and post-retrofit system were taken with a digital single-lens reflex camera to provide some qualitative basis for comparison.

[9] For example, assume that the fluorescent fixtures were drawing 20A of current on a circuit. Under normal load conditions, the fluorescent total harmonic current at Summit (277V) would be around 16%, or 3.2A, of current, all of which must flow through the neutral conductor. With the LED fixtures at 277V and the medium setting, the wattage is around 28% lower and current draw on the same hypothetical circuit would be around 14.5A. With the LED THD value of 26%, a total harmonic contribution of 3.7A current would be expected, slightly higher than that of the fluorescent fixtures. However, in most cases some of the LED fixtures on the circuit will be further dimmed due to occupancy patterns and available daylight, further reducing current draw and harmonic load. The LED fixture was tested when dimmed to 25W as well, saving about 57% power and current and resulting in current draw of 8.7A and total harmonic contribution of 2.8A on the neutral line. Even with THD increases at dimmed LED settings, the total value of additional current load resulting from harmonic distortion decreases because the total current draw is lower at the dimmed state.

[10] P-100 was updated in 2014, and its lighting requirements now rely entirely on the Illuminating Engineering Society (IES) Lighting Handbook, 10th edition, which recommends office work surface light levels of 300 lux or greater (30 foot-candles in Imperial Units) in most cases.

CHICAGO METCALFE

For a qualitative representation of the lighting system performance before and after the retrofit, Figure 20 presents photographs of the Metcalfe ceiling grid with overhead light fixtures illuminated. The frames were not controlled for identical exposure characteristics (*e.g.,* shutter speed, aperture, and white balance) and are meant to merely portray the general look of the lighting systems. Note that, in the pre-retrofit photograph, many of the lamps in the fluorescent fixtures are extinguished, which is consistent with the appearance of the lighting system throughout the space before the retrofit.

Figure 20: Pre (top) and post (bottom) retrofit ceiling photographs at Metcalfe

A. ILLUMINANCE LEVELS

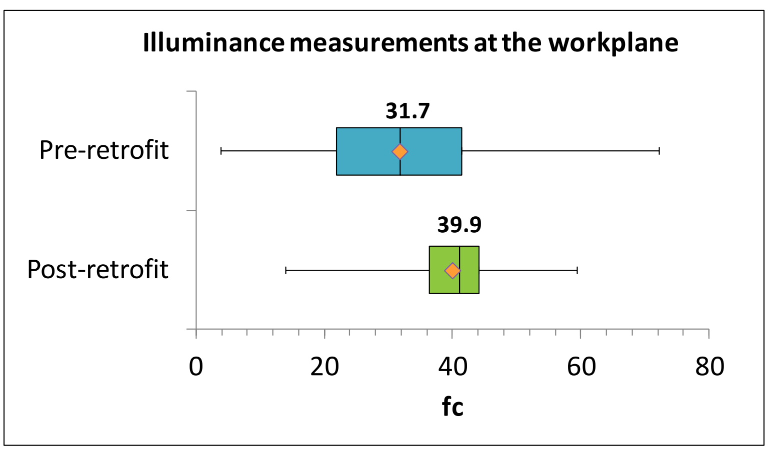
Average illuminance at the work plane was found to be within the P-100 guidance under both the baseline fluorescent system and the retrofit LED system. The fluorescent system even met the average illuminance guidance with the high number of lamp outages found at the site; however, as Table 16 shows, light levels pre-retrofit range widely, likely due to the varying distribution of extinguished lamps throughout the space. The LED system tuned to the medium output setting provided significantly higher average illuminance than the baseline (+26%), and at a much narrower distribution of illuminance values, with the 25th and 75th percentile values within around 10% of the mean.

Table 16: Metcalfe illuminance results

	Pre-retrofit work plane illuminance, fc	Post-retrofit work plane illuminance, fc
Minimum	3.8	13.9
Quartile 1	21.9	36.3
Median	31.7	40.9
Quartile 3	41.4	44.1
Maximum	72.1	59.4
Mean	31.7	39.9

*Pre-retrofit results were based on measurements at 105 workspaces. Post-retrofit results were based on measurements at 106 workspaces.

Figure 21: Measured illuminance levels at Metcalfe



B. COLOR RENDERING, COLOR TEMPERATURE, AND SPECTRAL POWER DISTRIBUTION

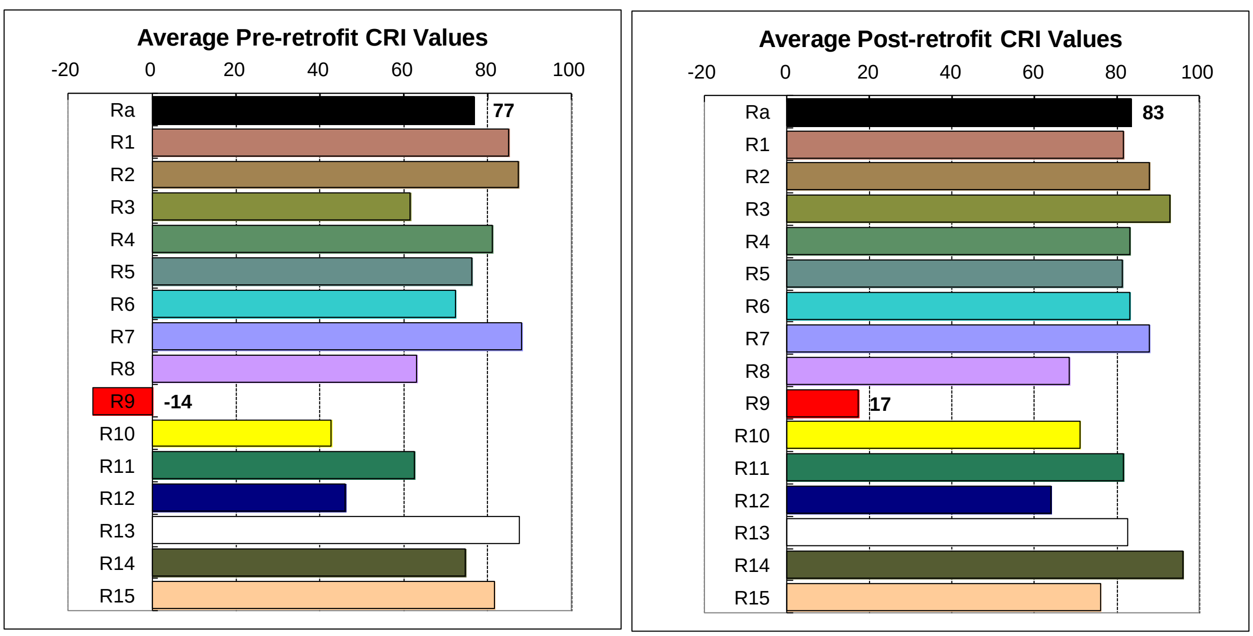
The photometric comparison also examined the general Color Rendering Index (CRI), an average of the color rending across eight color samples, R1-R8, and R9, which is not factored into general CRI, but represents the color rendering quality of a light source for strong red tones. Values closer to 100 represent higher quality, more accurate rendering of a color or colors, relative to a reference light source with exceptional color rendering, such as an incandescent bulb. The pre-retrofit fluorescent fixtures resulted in an average Ra of 77 and R9 of -14. The low R9 indicates that the pre-retrofit fluorescent fixtures did not render strong red tones well. The post-retrofit LED fixtures resulted in a modest improvement in the general CRI, and a more significant improvement in the R9 value, although the level is still quite low.

The correlated color temperature (CCT) of the light source, in degrees Kelvin, is more analogous to the color of the light itself, rather than how it renders colors of objects. Color temperatures in the 2,500K to 3,200K CCT range typically appear warmer and softer; temperature of 4,200K and higher result in a cooler, sharper appearance. There is no specific CCT value required for the office environments studied; the important implication of the pre- and post-retrofit measurements for this space is that the LED system CCT is very similar to that of the fluorescents, so the occupants are not likely to be impacted for better or worse with respect to color temperature performance of the new system.

Table 17: Metcalfe CRI and CCT results

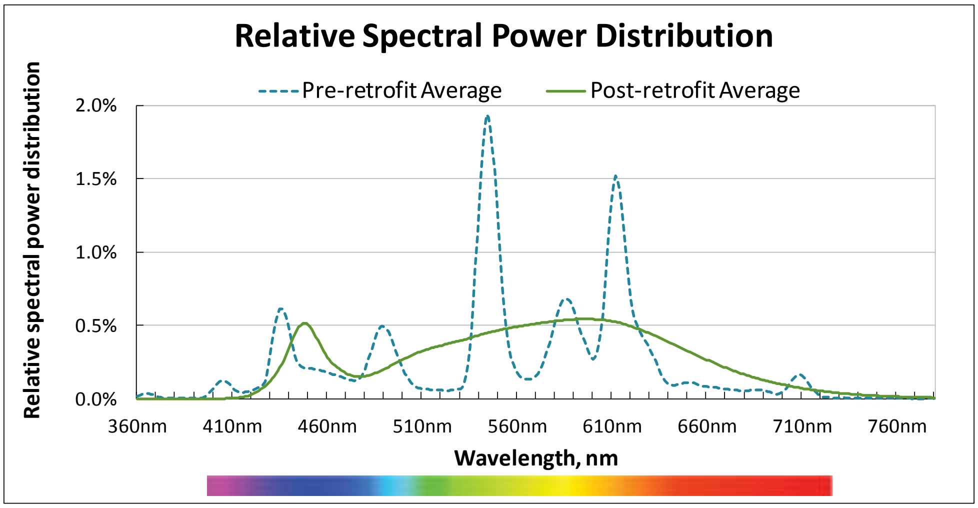
Phase	General CRI, R_a	Red tone CRI, R_9	Color temperature (K)
Pre-retrofit	77	-14	3771
Post-retrofit	83	17	3891

Figure 22: Average measured CRI at Metcalfe



The pre- and post-retrofit relative spectral power distributions indicated that the post-retrofit LED fixtures had a more even power distribution across the visible light spectrum than the pre-retrofit fluorescent fixtures. The pre-retrofit fluorescent fixtures produced a different mixture of light spectra, with large spikes positioned around 440 nm (blue-violet), 490 nm (cyan-blue), 550 nm (green), 590 nm (yellow), and 620 nm (orange). The pre-retrofit fluorescent fixtures emitted barely any light at wavelengths greater than 630 nm, correlating with the red tones. The post-retrofit LED fixtures exhibited a more even distribution of irradiance across the entire visible spectrum, characteristic of a more purely white light source, with maxima occurring around 460 nm (blue) and 610 nm (red) with a noticeable trough at 490 nm (cyan-blue). The graph below presents results of relative-and not absolute-spectral power distribution; the area underneath both SPD curves is equivalent.

Figure 23: Lighting system spectral power distribution at Metcalfe



ATLANTA SUMMIT

The photographs of the Summit ceiling grid with overhead light fixtures illuminated shown in Figure 24 below, provide a qualitative representation of the lighting system performance before and after the retrofit. Again, the frames were not controlled for identical exposure characteristics (*e.g.,* shutter speed, aperture, and white balance) and are meant merely to portray the general look of the lighting systems.

Figure 24: Pre (left) and post (right) retrofit ceiling photographs at Summit

A. ILLUMINANCE LEVELS

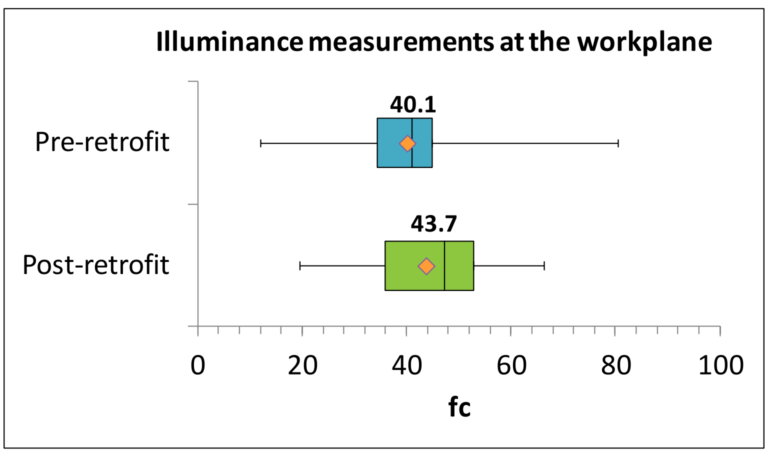
For the Summit study location, average illuminance at the work plane was also found to be within the P-100 guidance under the baseline fluorescent system and the retrofit LED system. In fact, average light levels were considerably higher than the required minimum under both conditions, as shown in Table 18. Similar to the Metcalfe location, the fluorescent system showed higher variability in illuminance levels than the LED system. Post-retrofit, with even the 25th percentile illuminance values several foot-candles higher than required, it is probably safe to say that the LED system could be tuned to the low power setting to save more energy and still meet P-100 guidance.

Table 18: Summit illuminance results

	Pre-retrofit work plane illuminance, fc	Post-retrofit work plane illuminance, fc
Minimum	12.1	19.4
Quartile 1	34.4	35.7
Median	40.9	47.1
Quartile 3	44.9	52.7
Maximum	80.4	66.2
Mean	40.1	43.7

*Pre-retrofit results were based on measurements at 36 workspaces. Post-retrofit results were based on measurements at 29 workspaces.

Figure 25: Measured illuminance levels at Summit



B. COLOR RENDERING, COLOR TEMPERATURE, AND SPECTRAL POWER DISTRIBUTION

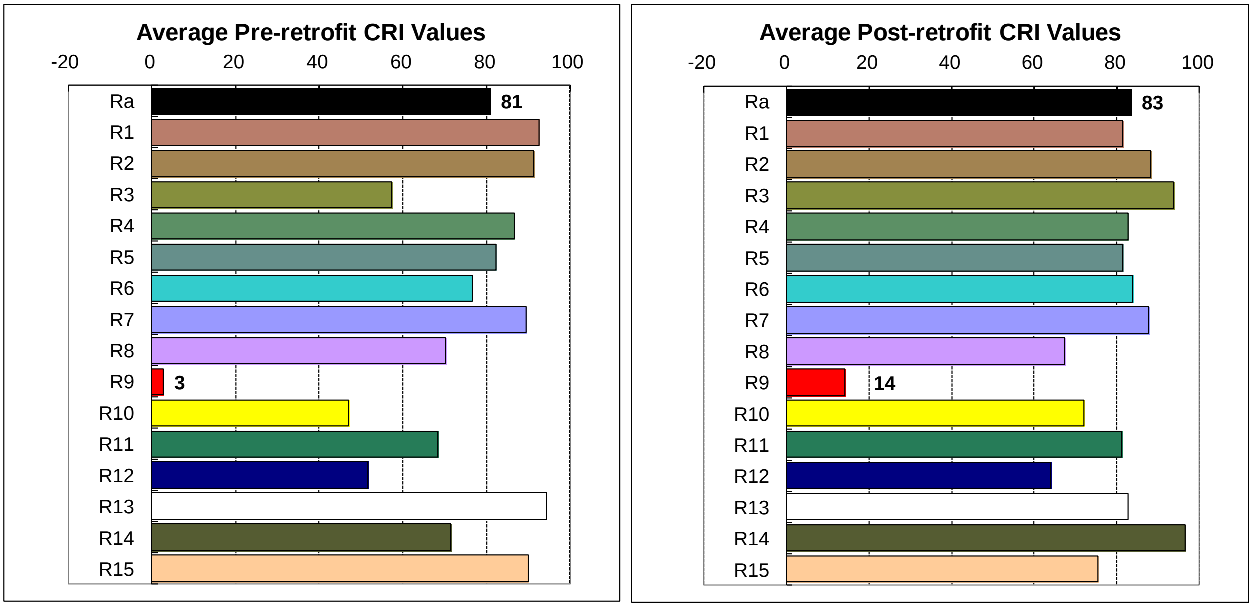
The pre-retrofit fluorescent fixtures in the Summit study location resulted in an average Ra of 81 and R9 of 3. The low R9 indicates that the pre-retrofit fluorescent fixtures did not render strong red tones well. The post-retrofit LED fixtures resulted in modest, but not dramatic, improvements in CRI and R9.

Similar to Metcalfe, the CCT of Summit's lighting systems before and after retrofit are very similar, so the occupants are not likely to be impacted for better or worse with respect to color temperature performance of the new system.

Table 19: Summit CRI and CCT results

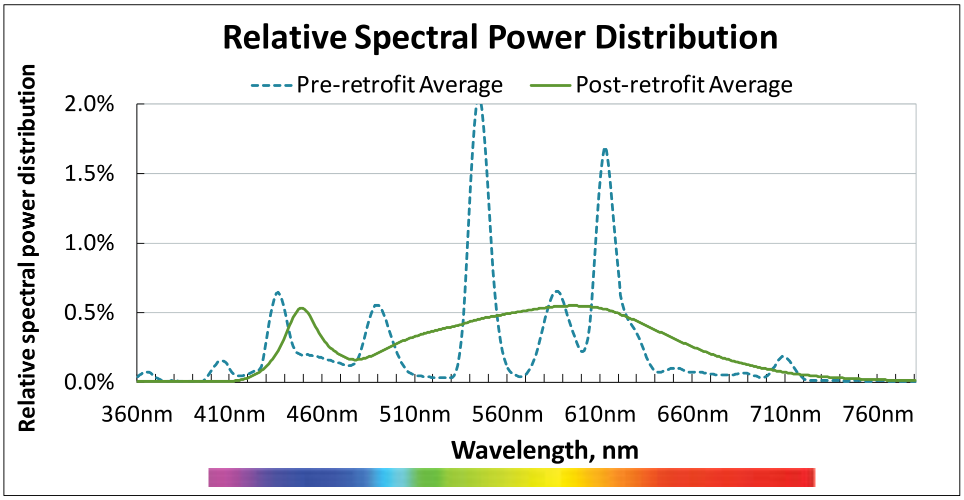
Phase	General CRI, R_a	Red tone CRI, R_9	Color temperature (K)
Pre-retrofit	81	3	3756
Post-retrofit	83	14	3944

Figure 26: Average measured CRI at Summit



The pre- and post-retrofit relative spectral power distributions indicated that the post-retrofit LED fixtures had a more even power distribution across the visible light spectrum than the pre-retrofit fluorescent fixtures. The pre-retrofit fluorescent fixtures produced a mixture of light spectra similar to that of the Metcalfe system, with large spikes positioned around 430 nm (blue-violet), 490 nm (cyan-blue), 540 nm (green), 590 nm (yellow), and 610 nm (orange). Again, the post-retrofit LED fixtures exhibited a more even distribution of irradiance across the entire visible spectrum, essentially the same distribution results as those measured at Metcalfe.

Figure 27: Lighting system spectral power distribution at Summit

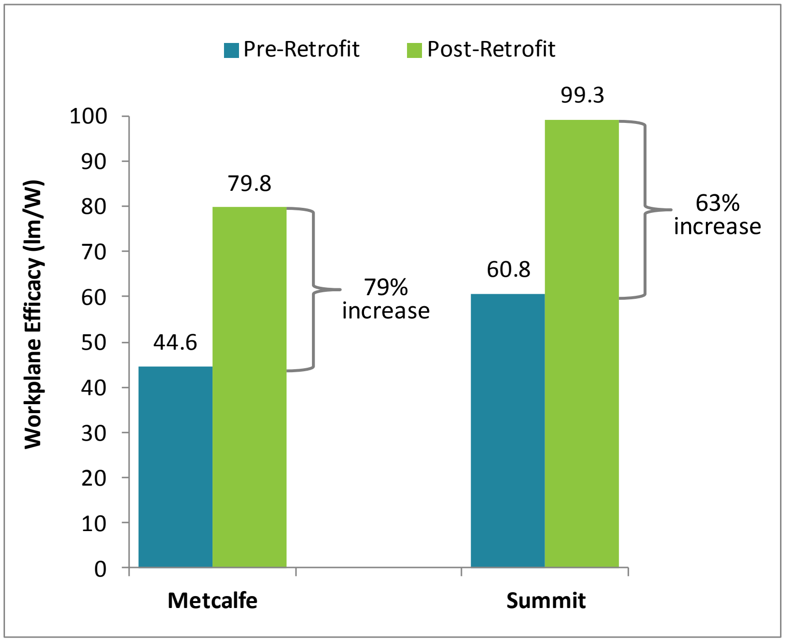


WORKPLANE EFFICACY RESULTS

Based on the pre-retrofit and post-retrofit lighting power densities and average workplane illuminance results, the average workplane efficacy at each location can be calculated. This metric quantifies the lighting available at the surface where visual tasks are performed per unit of electric power required by the lighting system. As such, it portrays the relative energy efficiency of the pre- and post-retrofit lighting systems. In this study, the workplane is taken to be the desk surface. Workplane efficacy (WPE) is calculated in lumens per watt, by dividing the average lumens/ft^2 (foot-candles) by the W/ft^2 measured at each location.

Workplane efficacy results for both the Metcalfe and Summit study locations are very favorable for the new LED fixtures, with 79% and 63% improvements in WPE, respectively. As illustrated in Figure 28, the LED systems with integrated sensors and controls are clearly more efficient at delivering lumens to the workplane than the pre-retrofit fluorescent systems.

Figure 28: Workplane efficacy results for Metcalfe and Summit



C. OCCUPANT SATISFACTION

Occupant satisfaction surveys were circulated before and after the lighting retrofits at both sites. Results of the survey response analysis are provided below. Percentages are calculated out of the number of occupants who responded to a given question and may not add to 100%, due to rounding. Responding to questions was voluntary, and not all survey takers responded to every question. To provide statistically significant results, the target response rate for the surveys was at least 30% of occupants in the study areas, with the desired number of respondents totaling at least 30.

CHICAGO METCALFE

The pre-retrofit survey link was emailed to 108 occupants, 59 of whom responded between November 14 and December 16, 2013, for a response rate of 55%. The post-retrofit survey link was emailed to 111 occupants, 40 of whom responded between March 20 and June 16, 2014, for a response rate of 36%. Response rates for both the pre- and post-retrofit surveys exceeded the study target response rate of 30%, and the number of respondents for both surveys was above the desired total of at least 30. Based on the response numbers and rates, there is good statistical confidence that the results are accurate and representative of the occupant population in the study space.

Occupants at Metcalfe expressed similar overall comfort level under the retrofitted LED lighting system as under the pre-retrofit fluorescent lighting system. The same low percentage of respondents (13%) felt that the fluorescent and LED lighting systems produced unnatural appearing skin tones. More respondents found the LED lighting system to provide pleasant brightness and well lit room surfaces, and nearly twice the fraction of respondents found that the LED system creates a good image for their organization. All in all, it is clear from the survey results that occupants are as satisfied or more satisfied with the LED lighting with integrated controls compared to the baseline fluorescent system.

Figure 29: Metcalfe occupant responses on overall comfort level with lighting system

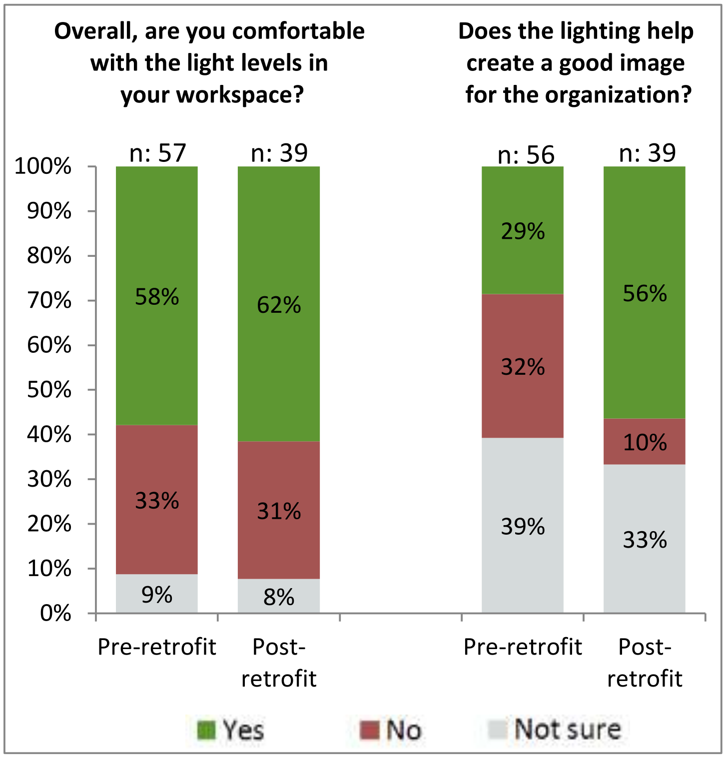
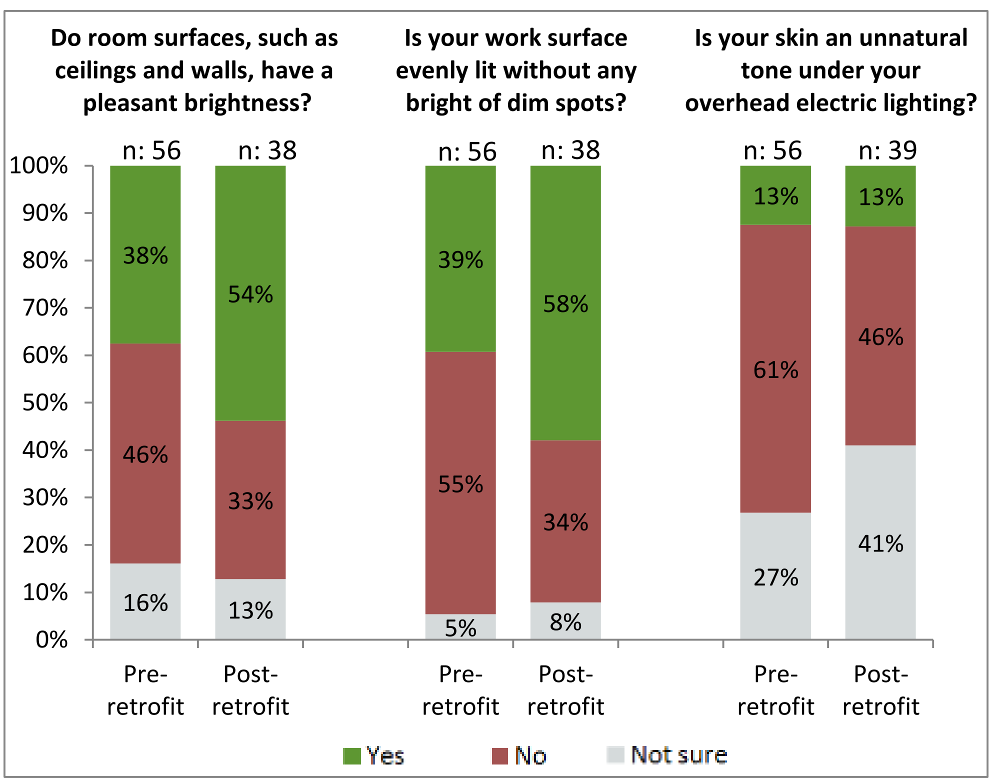
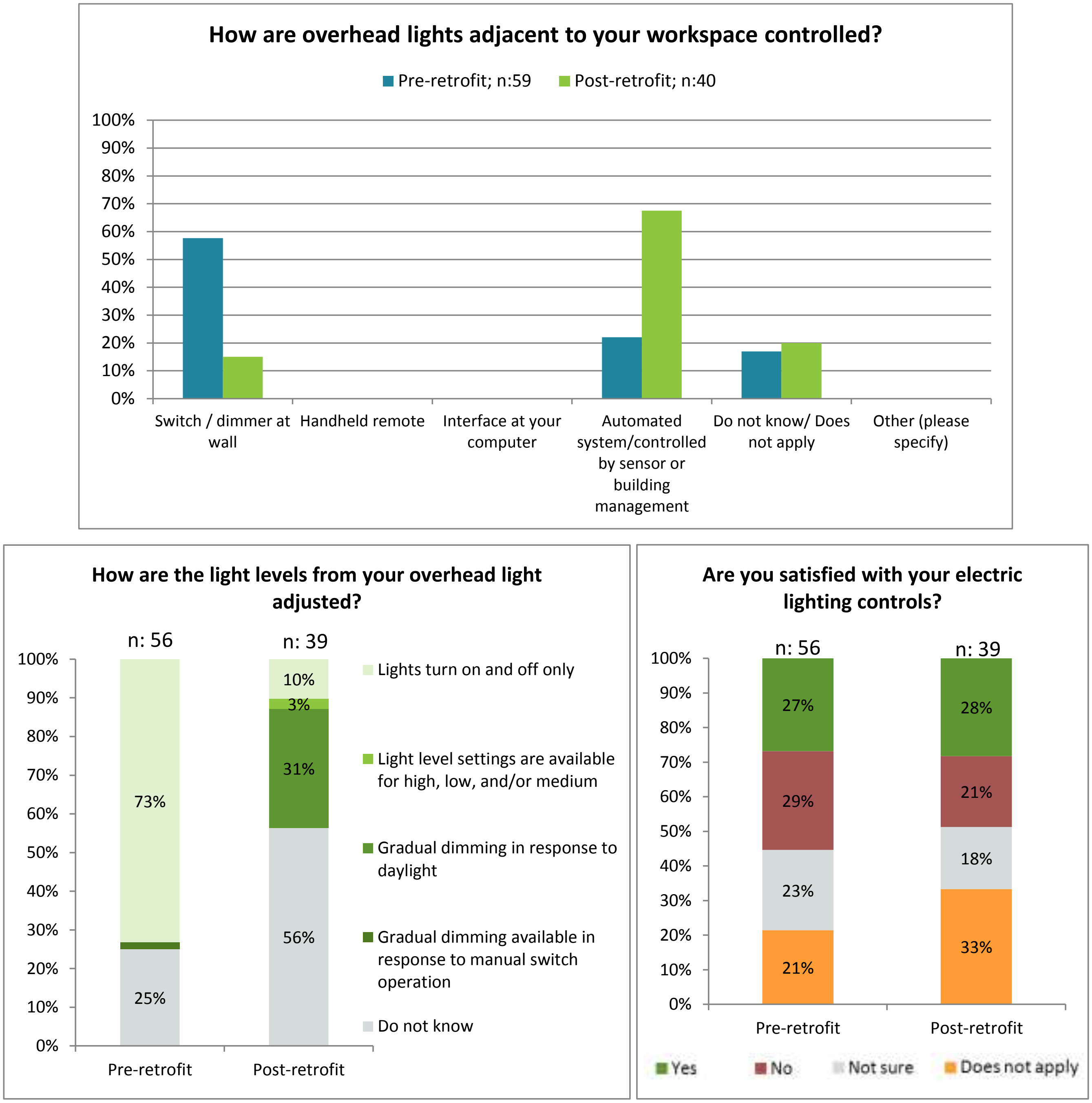


Figure 30: Occupant impressions of lighting at Metcalfe on surroundings, work surfaces, and skin tone



With respect to the lighting controls, almost 60% of respondents understood that the pre-retrofit lighting system was controlled by wall switches and over 70% correctly understood that the overhead lights simply turn on and off and are not dimming. Nearly 70% of respondents understood that the new retrofit lighting controls system was automated and used sensors or central management to provide lighting control. This indicates that, in general, the occupants understood the basics of the pre- and post-retrofit controls systems. Some occupants indicated that they understood that gradual dimming based on environmental conditions occurred, but the majority responded that they do not know how light levels were adjusted. Overall satisfaction levels with lighting controls in the space are quite similar before and after the retrofit, with slightly fewer respondents in the post-retrofit case indicating that they were not satisfied with the lighting controls and more responding that the question did not apply.

Figure 31: Occupant satisfaction with and understanding of lighting system controls at Metcalfe



The survey respondents were also offered “free response” comment boxes in which to type their own impressions on issues such as workspace light levels, suggested improvements to the lighting system, and the operation of the lighting controls. This allowed occupants to give specific feedback that may not have been addressed by the other questions. Some of the trends apparent in the pre-retrofit comments were recognition of the patchwork nature of the lighting system with the multiple lamp outages, a desire by some for more uniform lighting, and recognition that the lighting was controlled in large zones and not reactive to actual occupancy patterns and locations. Post-retrofit trends included acknowledgement that the lights were now responsive to occupancy and motion sensing, that the new light levels were brighter and mostly positively received, and some desire that individual fixtures be controllable and dimmable by individual occupants.

ATLANTA SUMMIT

The pre-retrofit survey link was emailed to 29 occupants, 17 of whom responded between November 14, 2013, and December 18, 2013, for a response rate of 59%. The post-retrofit survey link was emailed to 28 occupants, 14 of whom responded between March 19, 2014, and April 28, 2014, for a response rate of 50%. Response rates for both the pre- and post-retrofit surveys exceeded the study target response rate of 30%, but the total number of respondents was below the desired total of at least 30. Based on the response numbers, results do not necessarily provide high statistical confidence, although they may still provide valuable information and feedback to consider along with the other study outcomes.

Overall, occupants at Summit also appeared to be more satisfied with the retrofitted LED lighting system with integrated controls than the pre-retrofit fluorescent lighting system. More respondents found the LED lighting system to be comfortable and provide pleasant brightness on room surfaces and a much higher percentage believed that the LED system reflected well on their organization. A comparable percentage of respondents found the pre- and post-retrofit systems provided an evenly lit work environment and fewer respondents felt that the LED lighting produced unnatural appearing skin tones.

Figure 32: Occupant responses at Summit on overall comfort level with lighting system

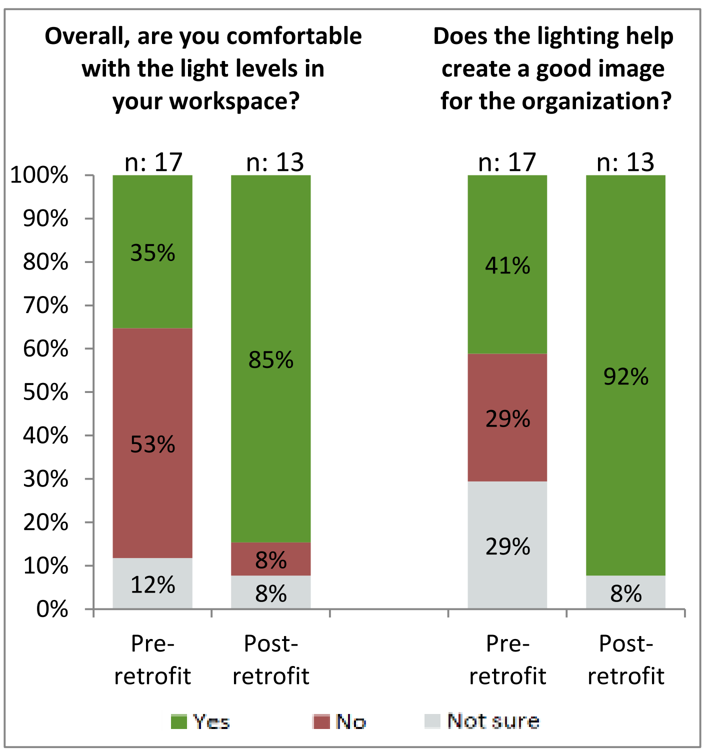
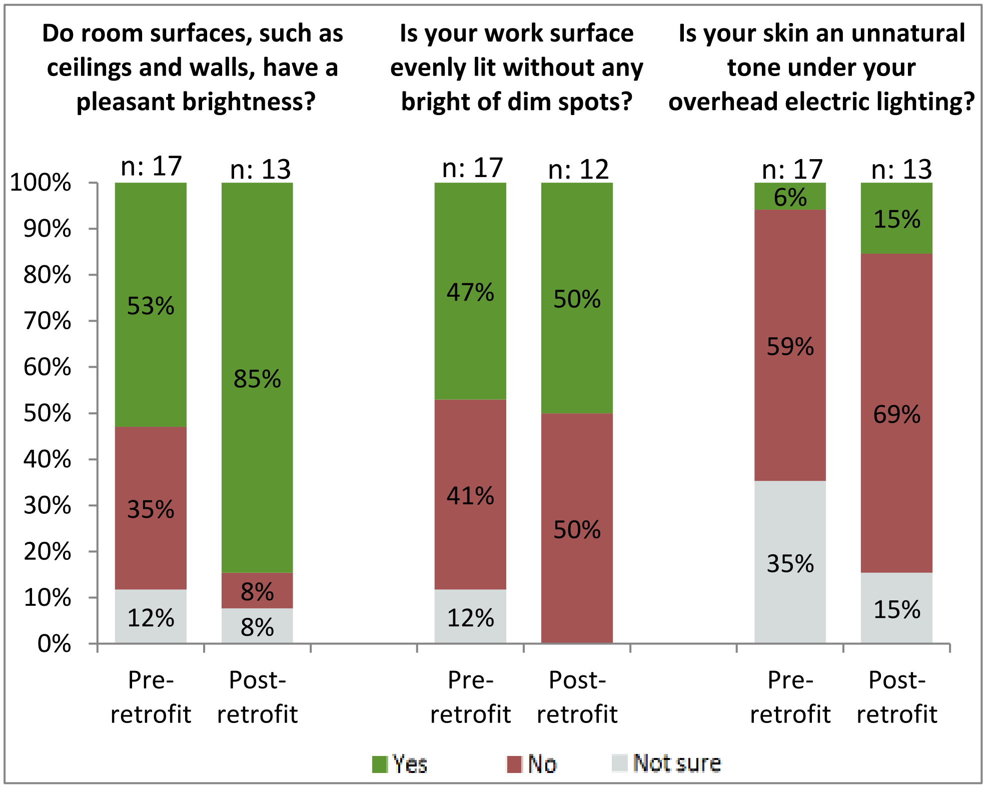
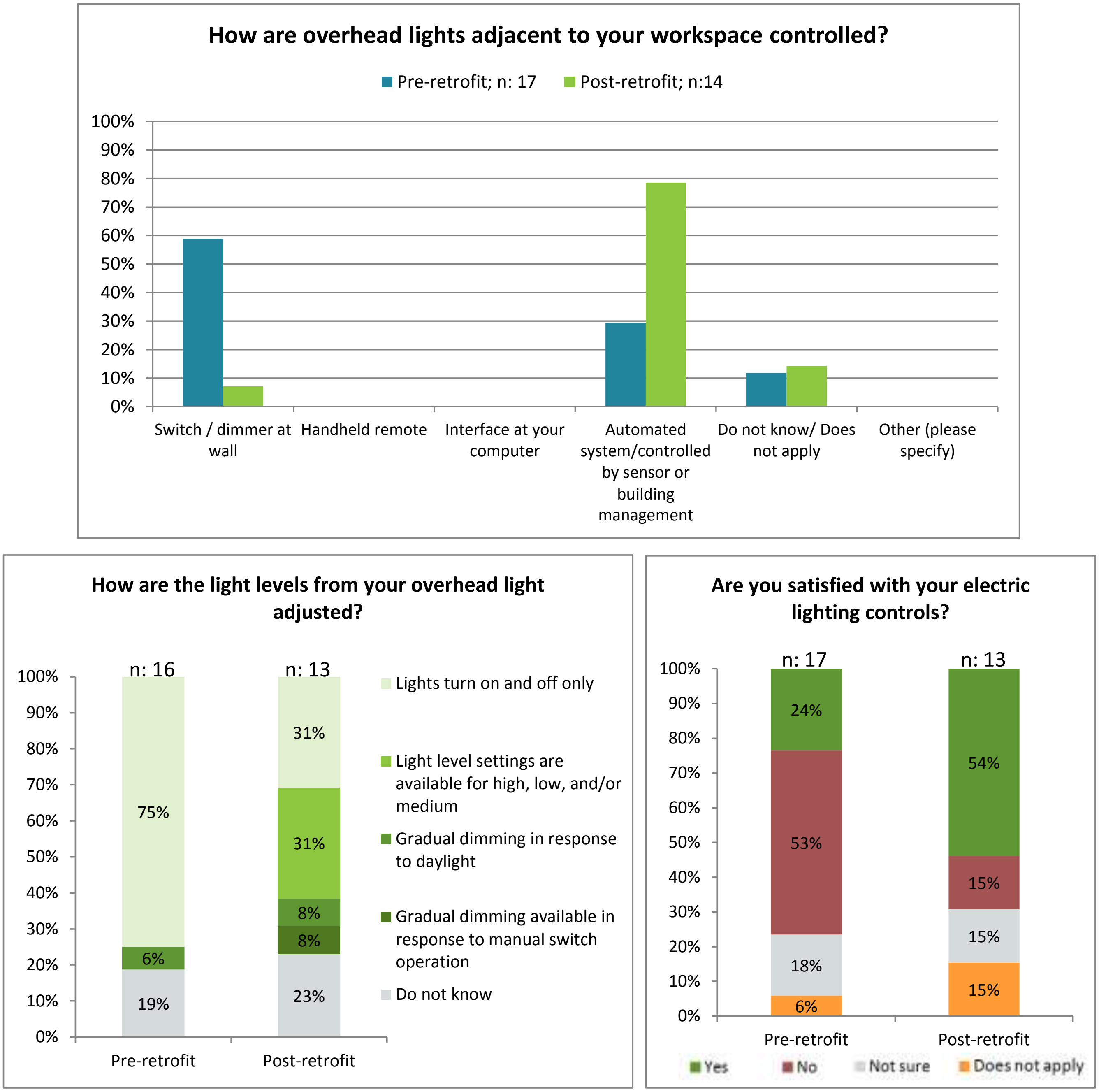


Figure 33: Occupant impressions of lighting at Summit on surroundings, work surfaces, and skin tone



With respect to the lighting controls, many more occupants expressed satisfaction with the retrofit system. Most respondents indicated that they understood that the baseline system was controlled by wall switches and the retrofit system included automated sensor-based control. Some occupants understood that multiple levels of light were available with the new lighting system, but fewer indicated that they understood that the lights were dimming based on daylight availability.

Figure 34: Occupant satisfaction with and understanding of lighting system controls at Summit



The survey respondents at the Summit demonstration location were also provided with the free response option to type impressions and feedback on issues such as workspace light levels, suggested improvements to the lighting system, and the operation of the lighting controls. For whatever reason, no occupants chose to provide free response comments during the pre-retrofit survey (perhaps because there were fewer total occupants and survey responses than at Metcalfe). In the post-retrofit survey, a limited number of comments were entered by respondents. The main theme from post-retrofit free responses was that some occupants would prefer to have more individual control over light level settings. It is clear, however, from the overall survey results that occupants are largely satisfied with the retrofit lighting and controls system, so the free responses should be viewed in this context.

PROJECT IMPLEMENTOR SATISFACTION INTERVIEW

Ease of implementation and commissioning is an important feature of the turnkey retrofit lighting system. To understand whether the system was relatively simple and straightforward to install and implement an informal satisfaction interview was emailed to the primary project implementation contacts at the two demonstration locations. Overall, the contacts indicated satisfaction with the retrofit systems and the process of commissioning the systems for operation. On the process of programming and commissioning the zones of fixtures for occupancy response, the project contact at Metcalfe expressed that after the vendor programmed the first zones to demonstrate the process, it was easy for building staff to program the rest of the zones. The short instruction manual provided was also sufficient and the zone setup instructions were easy to follow. The Summit PM found that instructions and follow-up were adequate, and sufficient documentation was available to maintain, commission, and re-commission the system.

The Metcalfe property manager expressed that more follow-up instruction on re-commissioning of zones would be helpful for building engineering staff so that they would be better prepared when future changes need to be made to the system. The project manager recommended that this happen for future installations. For the Summit project, there was some confusion regarding how the wireless remote provided with the system was used to program zones. When LBNL staff evaluated a fixture and commissioning remote for the system at the lab, they also had some difficulty in programming the tuned setting based on the instructions provided. The remote and accompanying instructions are being refined by the vendor. Overall, it appears that the most effective way for the building staff to learn how to use the controller was by watching the vendor demonstrate the programming steps.

At both locations the system is operating as expected, with stable operations. Regarding staff training, the Metcalfe project manager compiled records of the fixture groups, as programmed, and provided those to the building staff for their records. The project manager recommended that local building staff and engineers be trained on the programming of the zones and change-out or resolve any issues that could arise with the sensors or controls.

The Summit property manager has not received complaints or feedback from occupants on the new system. Some building occupants at Metcalfe complained to the project manager that the LED lights appeared too bright when first installed. For a couple of the desk locations at Metcalfe, the occupancy sensors on-board the fixtures were not detecting occupant motion adequately, so stand-alone motion sensors were installed and connected to the fixtures in question to prevent them from dimming while occupants were present.

D. COST-EFFECTIVENESS

This cost-effectiveness analysis examines whether the value of the future energy savings and other benefits, such as maintenance savings from installing the LED fixtures with integrated sensors and controls, justify the expense of the investment. For results that are more informative to GSA investment choices regarding lighting and lighting controls retrofits and new construction projects, the energy savings and project costs were normalized from the demonstration-specific results to figures applicable to standard GSA buildings and project scales and processes.

NORMALIZED ENERGY SAVINGS

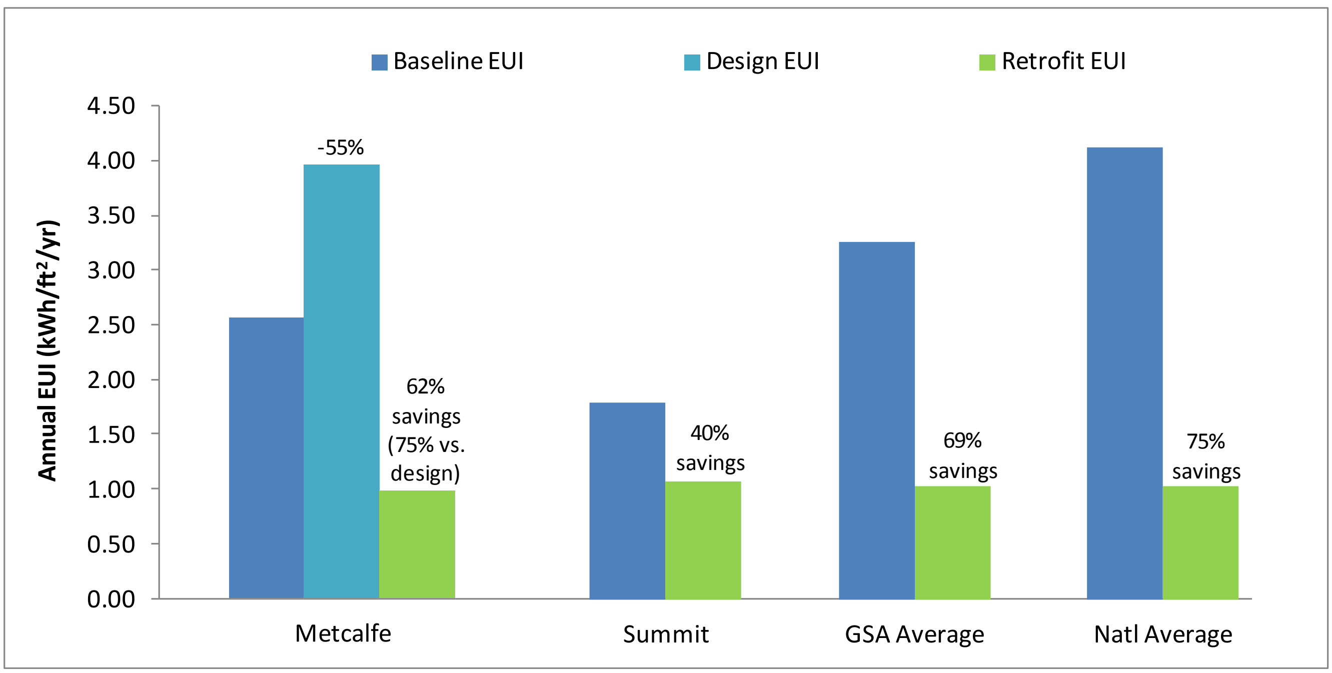
For a normalized energy savings analysis that is more broadly applicable to GSA buildings, the performance of the LED fixtures with integrated controls needs to be compared to typical baseline lighting energy usage at GSA buildings. A baseline lighting energy usage intensity figure was calculated for a sample of 12 GSA buildings located in California, Nevada, Illinois, Indiana, and Missouri. The lighting EUI and LPD averages for the sample were weighted according to the floor area of each site and were found to be 3.25 kWh/ft^2/year at an installed LPD of around 0.95W/ft^2. The average lighting EUI is substantially higher than that of the Summit or Metcalfe demonstration locations, though if the Metcalfe lighting system were operating with all lamps functioning, per design, the estimated lighting energy usage there would have been higher than the GSA average (see Table 20). Cost-effectiveness was also calculated for projects with a lighting energy baseline equal to the national average for commercial buildings, 4.1 kWh/ft^2/year [14, Table 4.21].

The weighted average post-retrofit lighting energy usage for the two demonstration sites, 1.01 kWh/ft^2/year, was compared to the normalized baselines to determine energy savings values used in the cost-effectiveness analyses. Energy cost savings were valued according to a national average electricity rate of $0.10/kWh. The project costs and energy savings are presented in Table 20, below. The energy savings are also illustrated in Figure 35, and both the costs and energy savings for retrofit projects are illustrated in Figure 37. Only the normalized costs and savings figures were used for the cost-effectiveness analysis that follows.

Table 20: Project-specific and normalized costs and energy savings

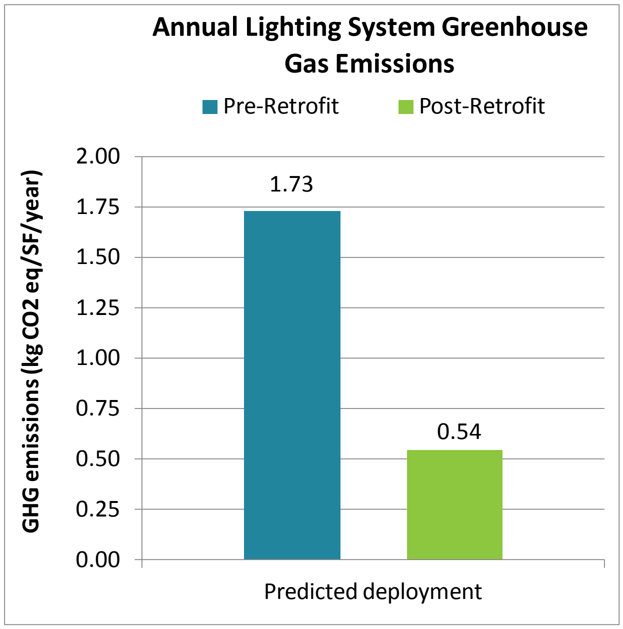
	Baseline Annual EUI (kWh/ft^2/ year)	Retrofit Annual EUI (kWh/ft^2/ year)	Savings (kWh/ft^2/ year, %)	Utility Rate ($/kWh)	Annual Energy Cost Savings/ft^2
Metcalfe, measured	2.56	0.98	**1.58 (62%)**	$0.061	**$0.097**
Metcalfe, design	*3.96*	*0.98*	***2.99 (75%)***	*$0.061*	***$0.183***
Summit	1.78	1.06	**0.71 (40%)**	$0.096	**$0.069**
Normalized lighting energy (GSA average)	3.25	1.01	**2.24 (69%)**	$0.102 (natl. avg.)	**$0.230**
Normalized lighting energy (National average)	4.10	1.01	**3.09 (75%)**	$0.102 (natl. avg.)	**$0.317**

Figure 35: Annual lighting energy usage and savings



GHG emissions savings are not monetized for the cost-effectiveness model due to uncertainties such as carbon market policies and regulations, as well as pricing, taxes, or trading. Nonetheless, as done previously for specific demonstration projects, the estimated GHG savings for the normalized case were calculated for reference. These savings are based on the GSA average office lighting energy usage and measured retrofit lighting energy usage with the LED fixtures and integrated controls. Emissions calculations are based on emissions factors for the national average fuel mix. Estimated performance of the LED fixtures and integrated controls for normalized costs and savings result in a 69% reduction in energy usage and GHG emissions, approximately 1.19 kg CO_2/ft^2/year at the national emissions rate of 531.6 g CO_2 eq/kWh electricity generated.

Figure 36: Normalized costs and savings lighting system greenhouse gas emissions for GSA buildings



ESTIMATED PROJECT COSTS

Labor costs for the demonstration projects were determined by communication with GSA and the technology vendors. Cost totals were provided by each site for the labor required to replace existing fixtures with the LED fixtures with integrated controls. The base labor rates charged for the installations at the two sites ranged from around $30 per hour for electricians to $80 to $100 per hour for job supervisors.[11] The hours of labor associated with the projects ranged from around 1.5 to 2 hours per fixture (including all work in project scopes, not just installation of individual fixtures).

Because the demonstration projects were experimental in nature, the costs per square foot from the specific cases are not expected to be representative of project costs at more typical project scales (larger) and processes (competitive bidding for installation labor). Normalized labor costs were discounted 15% to 20% relative to the weighted average labor costs per fixture from the demonstration locations, presuming that projects at larger "real world" scales will experience efficiencies in project staging, mobilization, and

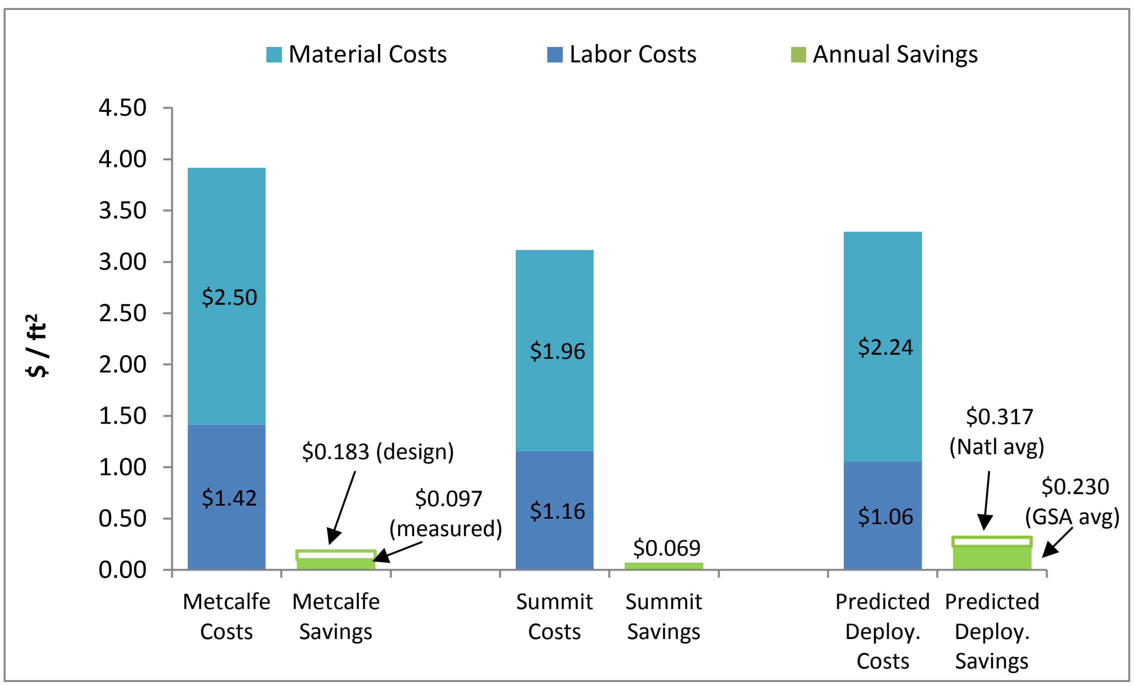
[11] Note that as projects are often awarded "lump sum," a simple calculation of total hours of labor multiplied by labor rates per hour may not equate to total project costs, which may also include mobilization, delivery charges, overhead and profit (O&P), fees, permits, and other costs and expenses not encompassed by hours of labor.

management, and will be subject to more competitive bidding than demonstration-scale projects, which should drive down costs.

For the demonstration locations, material (the LED fixtures with integrated controls) was donated by the vendor so there were effectively no material costs. The vendor provided a GSA - bulk purchase price estimate for the LED fixtures with integrated controls, which was used to estimate project cost totals. For the normalized labor and material pricing, a weighted average fixture density from the two demonstration sites of 85 ft^2 / fixture was used.

Importantly, the turn-key aspect of the integrated sensors and controls system proved to be a major advantage compared to stand-alone advanced lighting controls systems that would be installed separately from fixtures, adding potentially significant labor costs per square foot. For example a previous GPG study on advanced wireless lighting controls found installation labor costs ranging around \$0.40-\$0.50/ft^2 for the controls installation and setup alone [1]. For the technology demonstrated here, the installation labor cost was basically only the cost of replacing one fixture with another. The controls being integrated in the fixtures enabled an advanced controls system to be rolled out at almost no additional labor costs, other than the commissioning of fixture groups, which only took a few hours of labor per site.

Figure 37: Retrofit project costs and energy savings



For retrofit cost-effectiveness, project costs include the full cost of all materials (*e.g.*, fixtures and any other equipment installed in the retrofit) and the labor cost associated with installing and commissioning the system. The analysis is different for new construction situations or major renovations where an existing lighting system has reached the end of its useful life and needs to be replaced anyway. In these cases, the cost of the project is simply the difference in cost between the LED fixtures with integrated sensors and controls and the cost of the lighting and controls system that would have been installed otherwise, such as typically specified code-compliant systems (*e.g.*, traditional fluorescent fixtures and basic code-compliant lighting controls). The cost difference between the LED fixtures with integrated controls option and the alternative is commonly called the project incremental cost.

Comparing the vendor-supplied estimate for the cost of the LED fixture with integrated controls to listed GSA pricing online for various standard fluorescent fixture options, an incremental cost of $70 / fixture was estimated. Cost-effectiveness for new construction and replacements at end-of-useful-life scenarios is, therefore, better than for retrofit scenarios, since there is a lower cost outlay to be made up for by future energy savings and maintenance savings, if included. Table 21 compares the costs of the retrofit and new construction project scenarios.

Table 21: Retrofit and new construction project costs and savings

Project Scenario		Labor Cost/ft²	Material Cost/ft²	Total Project Costs/ft²	Annual Project Energy $ Savings/ft²
Normalized costs and savings (GSA average EUI)	Retrofit (full cost)	$1.06	$2.24	$3.29	$0.230
	New construction or replacement at end of useful life (incr. cost)	$ -	$0.82	$0.82	
Normalized costs and savings (National average EUI)	Retrofit (full cost)	$1.06	$2.24	$3.29	$0.317
	New construction or replacement at end of useful life (incr. cost)	$ -	$0.82	$0.82	

* Figures presented here may not sum to totals due to rounding.

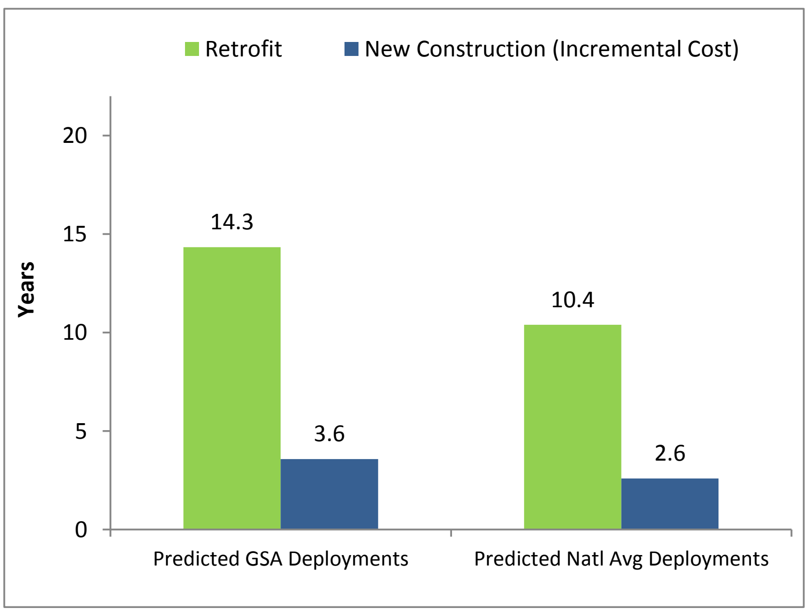
SIMPLE PAYBACK RESULTS

Simple payback is calculated by dividing the cost of an energy savings investment by the annual avoided costs resulting from implementation of the technology. The result is the number of years it would take for the avoided costs resulting from the technology to pay for the initial investment. As the term connotes, it is a relatively simple approach to cost-effectiveness analysis. It does not consider the service life of the technology, nor does it account for time value of future avoided costs. It typically also does not include avoided maintenance costs that would have occurred after the lighting system operating hours reach the lifespans of the different components (fluorescent ballasts and lamps in the case of this study). Even so, it is a relatively ubiquitous metric in the context of energy efficiency investment decision making and provides a quick, first-order snapshot of the attractiveness of an energy efficiency project. The inputs of the payback calculations are provided in Table 22 for the normalized costs and savings scenarios in buildings with GSA's average baseline lighting EUI and the national average baseline lighting EUI. The results are illustrated by the bar graph in Figure 38. Paybacks for the retrofit cases are around 10 to 14 years. In the case of new construction and major renovation projects, paybacks are as low as three to four years, well within the GSA threshold for potential investment.

Table 22: Simple payback results for normalized costs and savings

Project Scenario		Estimated Simple Payback
Normalized costs and savings (GSA average EUI)	Retrofit (full cost)	14.3
	New construction or replacement at end of useful life (incr. cost)	3.6
Normalized costs and savings (National average EUI)	Retrofit (full cost)	10.4
	New construction or replacement at end of useful life (incr. cost)	2.6

Figure 38: Estimated simple paybacks



In the coming year the technology vendor is developing a lower-cost LED fixture option with the same integrated controls technology as that studied here, but at around a 20% lower fixture cost than the cost of the fixtures used in this study. Simple payback was also calculated for the projected lower-cost option, assuming the same energy savings. Retrofit paybacks decrease to around 9 to 12 years and new construction and major renovation paybacks decrease to one to two years. However, photometric performance, fixture energy usage, and occupant satisfaction criteria were not evaluated for any alternate LED fixture models during this study. As such it is not possible to guarantee that performance of or satisfaction with any alternative, such as the proposed lower-cost model, would be equivalent to that of the evaluated fixtures.

SIMPLE PAYBACK ESTIMATES FOR LED FIXTURES WITHOUT INTEGRATED CONTROLS

In the previous project results sections for the Metcalfe and Summit demonstrations, the energy savings from the fluorescent-to-LED fixture switch were compared to additional energy savings captured by the integrated controls. While this study's focus is an integrated lighting and controls system, cost-benefit results from LED fixtures with integrated controls can also be compared to the cost and savings expected from installing LED fixtures without integrated controls.

Energy savings from an LED fixture retrofit without integrated controls can be estimated by comparing the baseline lighting power density of 0.95W/ft^2 (see Normalized Energy Savings above) to the weighted average retrofit lighting power density at the demonstration sites if the LED fixtures were operated at full wattage with no controls-based dimming (0.56W/ft^2). All else equal (no controls or operational changes) the LED wattage reduction alone would have saved an estimated average of 41% in lighting energy. The integrated advanced controls added an estimated 28% energy savings for the average GSA office and 34% energy savings for the national average case.

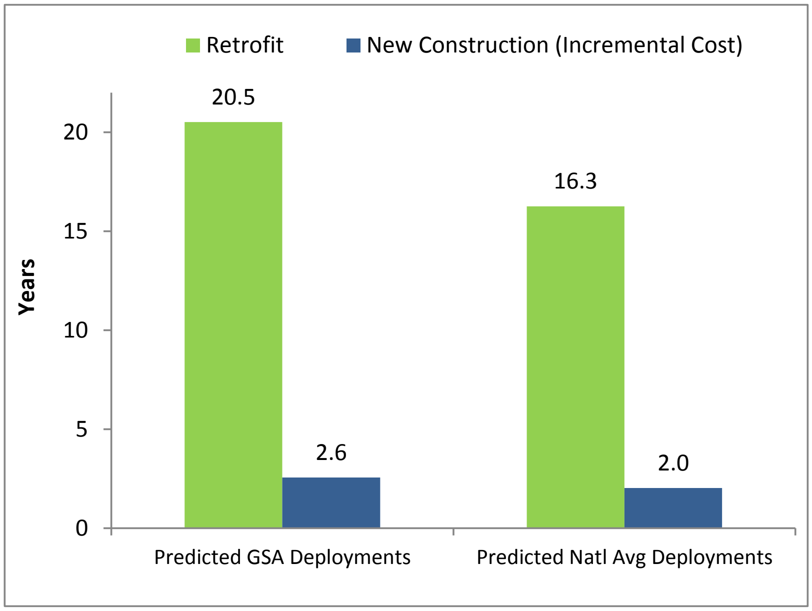
A cost savings of $0.47 per square foot is estimated here for installing LED fixtures without integrated controls compared to LED fixtures with integrated controls, at the normalized fixture density of 85 ft^2 / fixture estimated here. The LED fixture option is essentially a lower cost / lower savings option. The costs and savings for the two options are tabulated in Table 23, below, and the simple payback results for LED fixtures without controls are illustrated in Figure 39.

Table 23: Comparing costs and savings for LED fixtures with and without integrated controls

Project Scenario		With Integrated Controls		Without Integrated Controls	
		Project cost/ft^2	Annual savings/ft^2	Project cost/ft^2	Annual savings/ft^2
Normalized costs and savings (GSA average EUI)	Retrofit (full cost)	$3.29	$0.230	$2.82	$0.138
	New construction or replacement at end of useful life (incr. cost)	$0.82		$0.35	
Normalized costs and savings (National average EUI)	Retrofit (full cost)	$3.29	$0.317	$2.82	$0.174
	New construction or replacement at end of useful life (incr. cost)	$0.82		$0.35	

Paybacks for the retrofit cases with LED fixtures but no integrated controls increase to 16 to over 20 years compared to 10 to 14 years for the LED fixtures with integrated controls. Essentially, the cost savings of selecting fixtures without integrated controls do not make up for the lost energy savings over time. In the case of new construction and major renovation projects, however, paybacks drop to the two to three year range. Because the labor costs are not counted in the incremental cost analysis, the cost savings from selecting fixtures without integrated controls are more influential in the new construction case and paybacks improve by about one year relative to the LEDs with integrated controls.

Figure 39: Estimated simple payback without integrated controls



SIMPLE PAYBACK SENSITIVITY ANALYSIS

Project cost-effectiveness varies considerably based on the values of various inputs, from the estimated energy savings and the utility pricing that translates those into cost savings, to the material and labor cost estimates for the project. A simple payback sensitivity analysis was carried out to see how payback results are affected by changes in energy savings levels, utility pricing, and project costs. The sensitivity analysis results illustrated in Figure 40 show how for the higher energy cost isopleths, project paybacks (on the Y axis) shift downward. Likewise, the higher the projected energy savings are (on the X axis), the better the payback result. The estimated average energy savings per square foot for the average GSA building is indicated by the darker dotted line. At that savings level and the low utility rate of $0.08/kWh, the payback result is more than 17 years for a retrofit project, but fewer than 5 for new construction. At a higher electric rate of $0.12/kWh, the project economics improve to a payback less than 13 years in the retrofit case and around 3 in the new construction case. With even higher energy savings for the national average lighting energy usage baseline, indicated by the lighter dotted line, cost savings result in shorter simple paybacks; around 13 years for the retrofit at the lower utility rate and well under 10 at the higher utility rate.

Figure 40: Normalized retrofit payback sensitivity to energy savings and utility rates

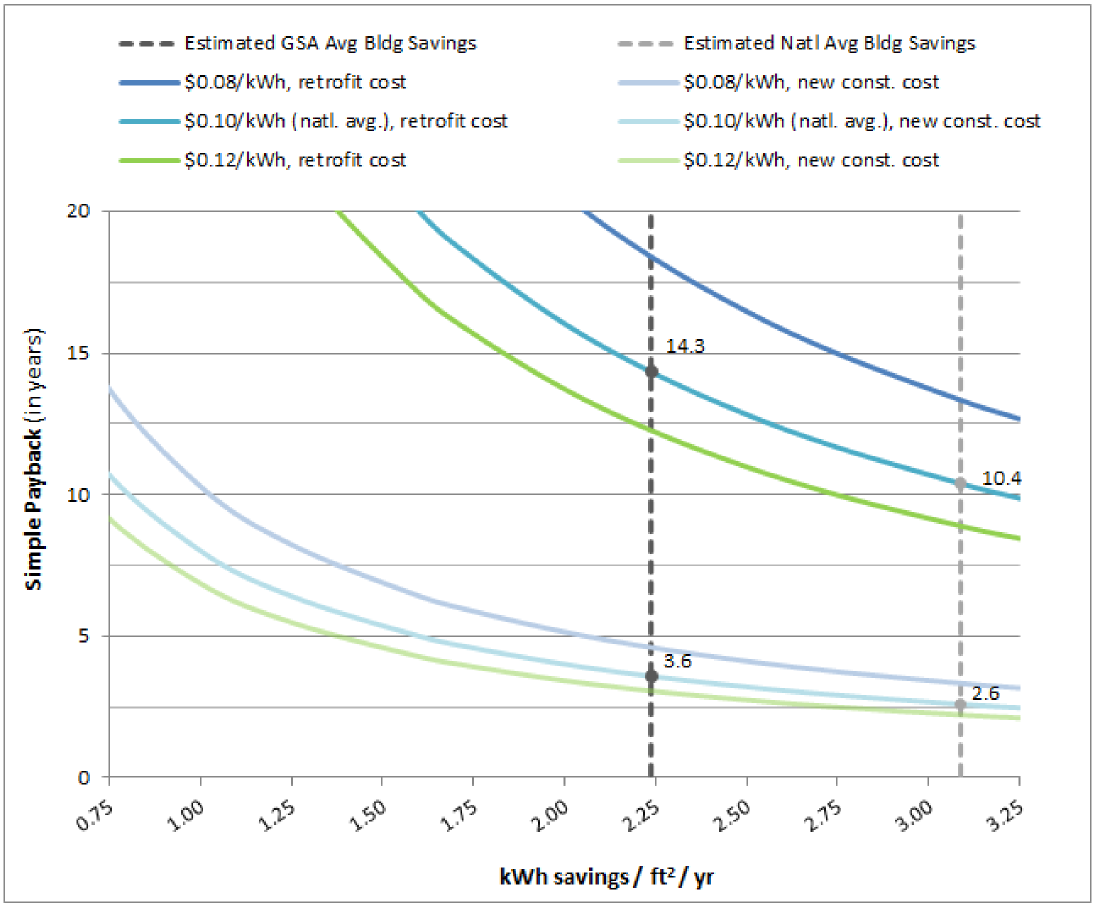
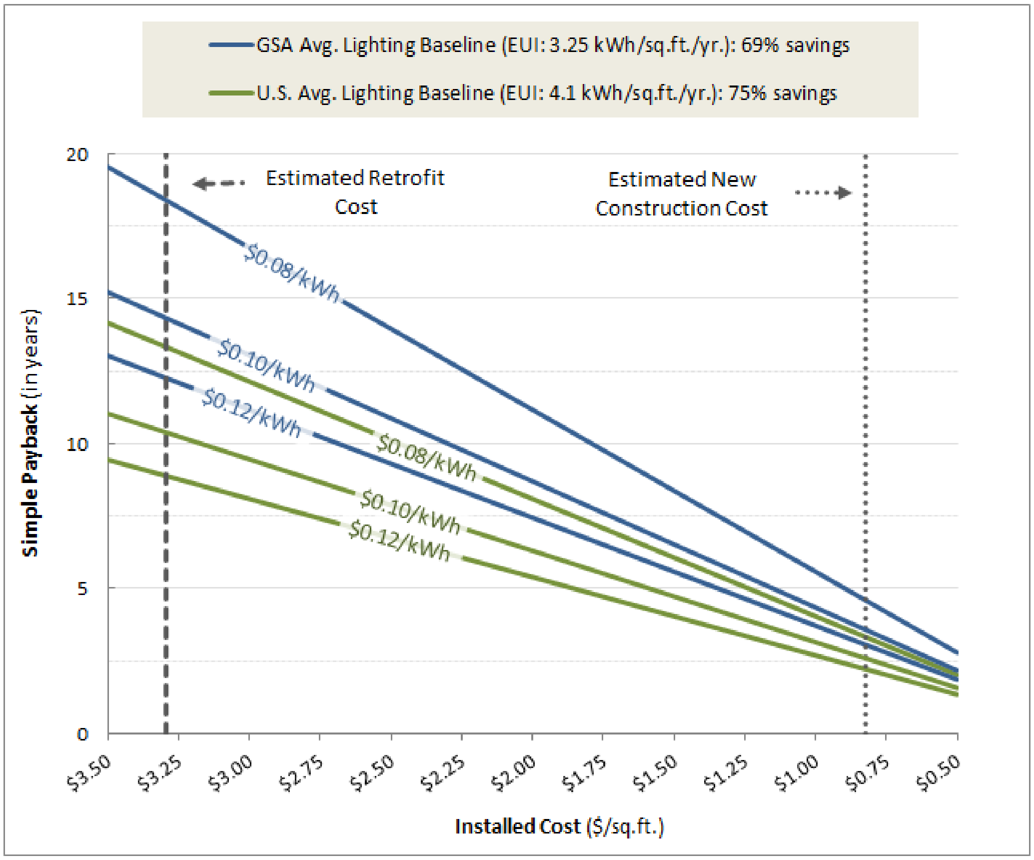


Figure 41 provides another way of looking at the simple payback sensitivity. This time the annual energy savings are held constant at the level predicted by study results relative to the GSA average baseline, as well as relative to the national average baseline (4.1 kWh/ft^2/year) for comparison. Project costs vary on the X axis and payback is shown to decrease steadily as project cost goes down. The dotted lines bound the estimated cost for retrofit projects and new construction projects, obviously showing the positive payback implications of the latter. Isopleths for three electric utility rates are given for the GSA- and national-average lighting energy baselines. The figure illustrates payback ranges for different lighting energy baselines, electric utility rates, and project costs, essentially showing that the higher the electricity rate and lighting energy baseline, the shorter the payback; and the higher the project cost, the longer the payback. The graphic should help any potential implementer of the evaluated technology estimate simple payback at their site if the project costs can be estimated, the utility rate is known, and some characteristics of the building baseline lighting energy usage is known (is it more similar to the average GSA building or the higher national average?).

Figure 41: Normalized simple payback sensitivity to project costs and utility rates



DISCOUNTED LIFE-CYCLE COST ANALYSIS

The discounted life-cycle cost analysis is a more comprehensive method of accounting for the true cost savings resulting from an energy efficiency investment, in this case LED fixtures with integrated sensors and controls. While simple payback merely divides project cost by estimated annual energy savings, the life-cycle approach sums the savings (*i.e.*, avoided costs) that will accrue from the technology over the estimated lifetime of that technology, compared to the system that would be operating in the space otherwise. Because the LED fixtures are a longer-lifetime, lower-maintenance option than standard fluorescent systems, maintenance savings that occur periodically during the system life-cycle can be included. Fluorescent lamps and ballasts need to be replaced every few years, depending on annual operating hours and the rated life of the equipment; the labor and material costs of servicing that equipment are avoided with the LED fixture option. Maintenance savings were not addressed by the simple payback approach, which also does not account for the time-value of future cost savings.

Multiple inputs must be defined for the life-cycle cost model. First, the cost of the investment (material and labor) must be estimated, whether the full cost of the system or the incremental cost relative to installation of an alternative, standard option. The annual energy cost savings, which may include future energy cost escalation, must also be defined, along with the frequency and value of periodic avoided maintenance costs. Annual lighting energy usage, cyclical replacement of burned out fluorescent lamps and ballasts that would be necessary if not for the LED fixtures, and the total estimated lifetime of the LED equipment all depend on the annual operating hours of the system, which must also be defined. Similarly, the time horizon of the investment analysis, typically the projected lifetime of the selected technology, must be selected. This is the total length of time over which discounted avoided energy and maintenance cost savings is summed. Table 24, below, provides the assumptions that go into the life-cycle cost model prepared here. Any changes in these variables affect the results of the life-cycle model.

Table 24: Additional inputs for project Life-cycle economics model

Variable	Value	Notes, Details
Annual Lighting Operating Hours	3,100 (normalized)	Typical operating hours for office space, based on average of estimated operating hours for demonstration locations
Replacement Frequency of Lamps	Every 25,000 hours	Standard fluorescent lamp rated life: ~ 20,000-30,000 hours [15]
Lamp Replacement Cost: labor + material	$25	Based on maintenance cost estimates from project location contacts
Replacement Frequency of Ballasts	Every 50,000 hours	Fluorescent ballast rated life from product cut-sheets
Ballast Replacement Cost: labor + material	$80	Based on maintenance cost estimates from project location contacts
Nominal Discount Rate	2.5%	From U.S. Dept. of Commerce and NIST guidance [16] and Energy Escalation Rate Calculator (EERC2.0-13)[12]
Nominal Energy Escalation Rate	2.2%	
Time horizon for life-cycle cost analysis	15 years	Within timeframe of expected useful life of LED troffers (50,000 hours operation)

The results of the discounted life-cycle cost analysis are tallied in terms of:

A. Net Present Value (NPV) is the sum of initial project cost and the discounted present values of future avoided costs;

B. Savings-to-Investment Ratio (SIR) the ratio of discounted life-cycle avoided cost to the initial investment cost. SIRs greater than one indicate that an investment is cost-effective over the investment's lifetime; and

[12] The Energy Escalation Rate Calculator, developed for the Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy, is available at: http://energy.gov/eere/femp/eerc-download

C. Internal Rate of Return (IRR) the discount rate at which the net present value of an investment would equal zero. Essentially, this is the interest rate earned by the investment.

RETROFIT CASE

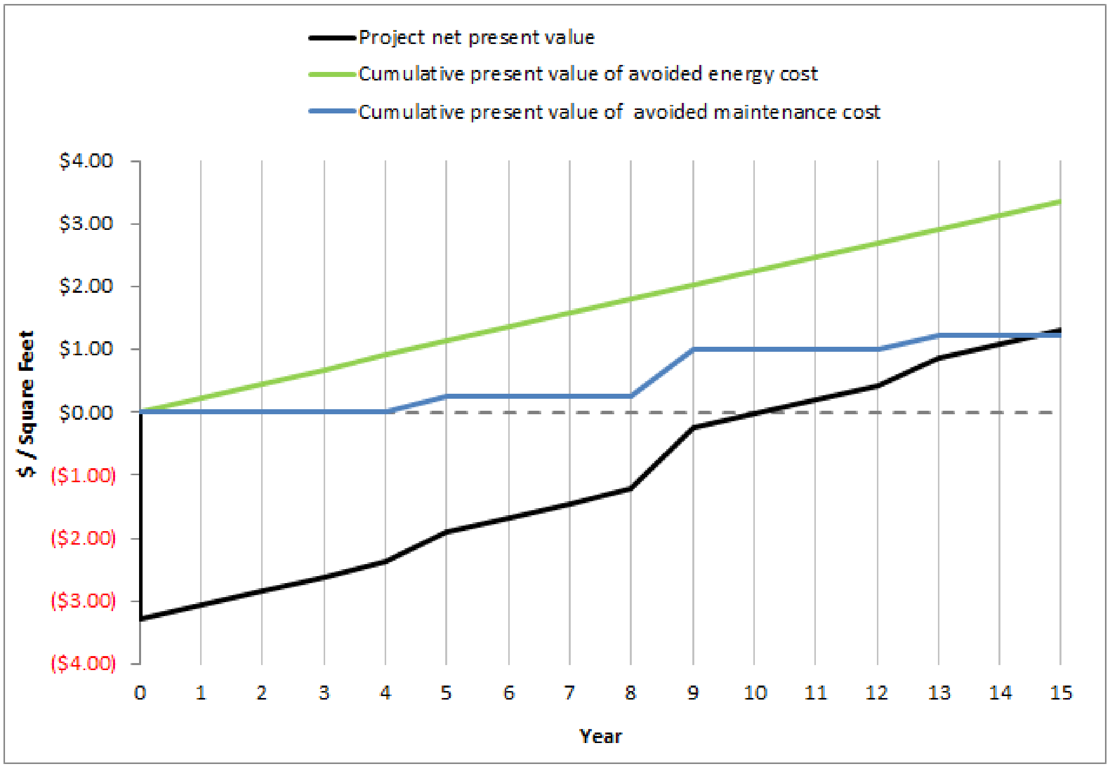
Results are presented in Table 25 and illustrated in Figure 42 for the retrofit case in buildings with GSA-typical baseline lighting EUI. For retrofits of fluorescent troffers and typical baseline controls to the LED fixtures with integrated sensors and controls, the SIR is around 1.4, indicating good future savings from the project relative to the initial investment. The NPV of the discounted future savings minus the initial cost is positive and the rate of return earned by the project is 6.9%, well above the discount rate, indicating a cost-effective investment.

Table 25: Life-cycle cost results for retrofit projects in GSA buildings

Initial Project Cost (\$ / ft^2)	\$3.29
Simple Payback (years)	14.3
Savings to Investment Ratio	1.39
Internal Rate of Return (%)	6.9%
Net Present Value (\$ / ft^2)	\$1.30

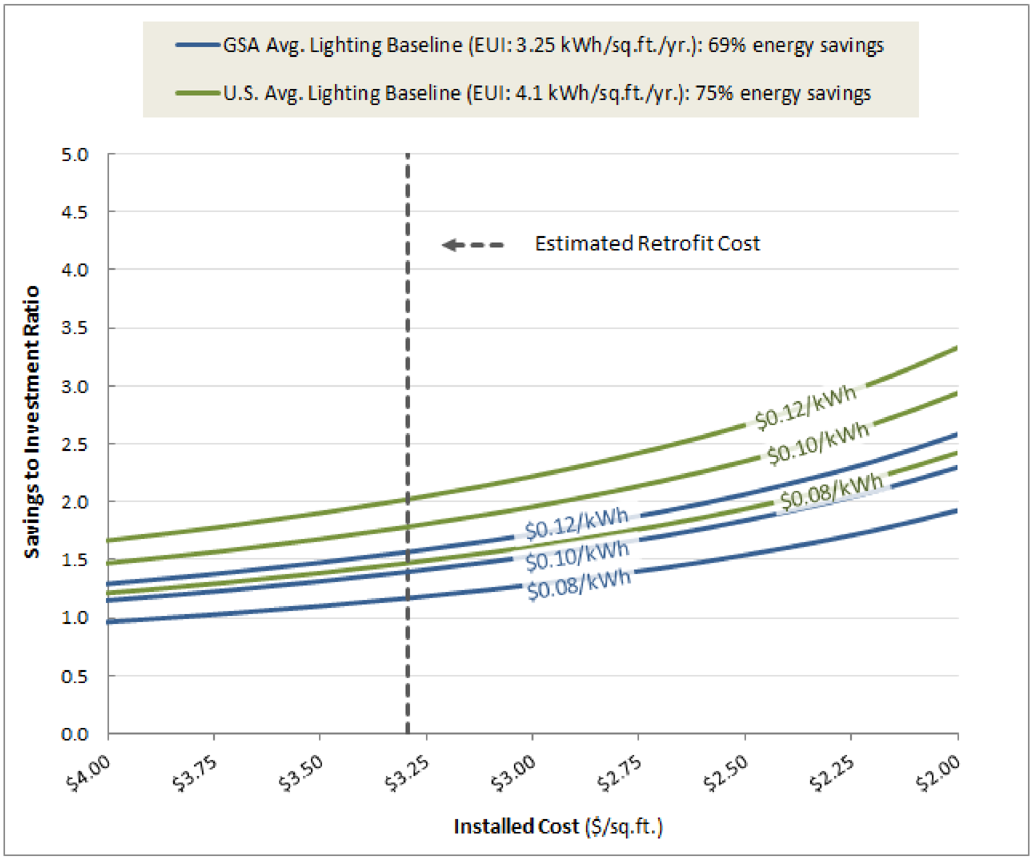
In the Figure 42 plot, the cumulative value of avoided energy costs and avoided maintenance costs are portrayed separately, by the green and blue curves (respectively). The slope of the energy savings curve diminishes slightly over time; although the annual energy savings are not expected to vary, the present value of each year's savings decreases slightly relative to the last according to the annual discount rate. The maintenance savings appear more like a step function with periodic savings due to avoided lamp and ballast replacement costs. The total project value, which is the cost of the installation at year zero and then the cumulative avoided costs going forward, is represented by the black curve. It is clear from the graph that over the 15-year period of analysis, savings from the investment more than make up for the initial cost. Maintenance savings in the life-cycle model are compelling; responsible for around one quarter of the system savings over the 15-year lifetime.

Figure 42: Present value of avoided costs for retrofit projects in GSA buildings



As was done for simple payback calculations, SIR sensitivity to the variables of project cost per square foot, electric utility rate, and energy savings (vary depending on baseline lighting energy usage) was calculated with the lifecycle cost model. Project costs vary on the X axis and SIR is displayed on the Y axis. Figure 43 illustrates retrofit SIR results for different lighting energy baselines, electric utility rates, and project costs, with the dotted line showing the cost for retrofit projects estimated here for normalized projects. The plot clearly shows that SIR improves as total retrofit cost decreases, and is greater at higher energy savings levels and higher energy costs. For virtually the entire range of project costs, savings, and energy costs displayed in the graph the SIR is over 1, indicating an economically sensible investment.

Figure 43: Normalized retrofit SIR sensitivity to project costs and utility rates



NEW CONSTRUCTION CASE

The very best life-cycle economic results not surprisingly come from normalized costs and savings in new construction, major renovation, and replacement at end of useful life cases. The projected initial investment cost is only the difference in cost of the LED fixture and controls package compared to installation of standard fluorescent fixtures at typical GSA pricing. The labor costs are assumed to be equal, as the physical installation of the LED fixtures is not much different than installation of fluorescent fixtures, and with the sensors and controls already integrated there are no additional installation labor costs there. Some programming and commissioning of fixture groups is, of course, required for the LED system, but this was found to be minimal in the demonstrations and is perhaps comparable to or even less than the switch wiring and relay panel configurations that would be necessary for typical controls.

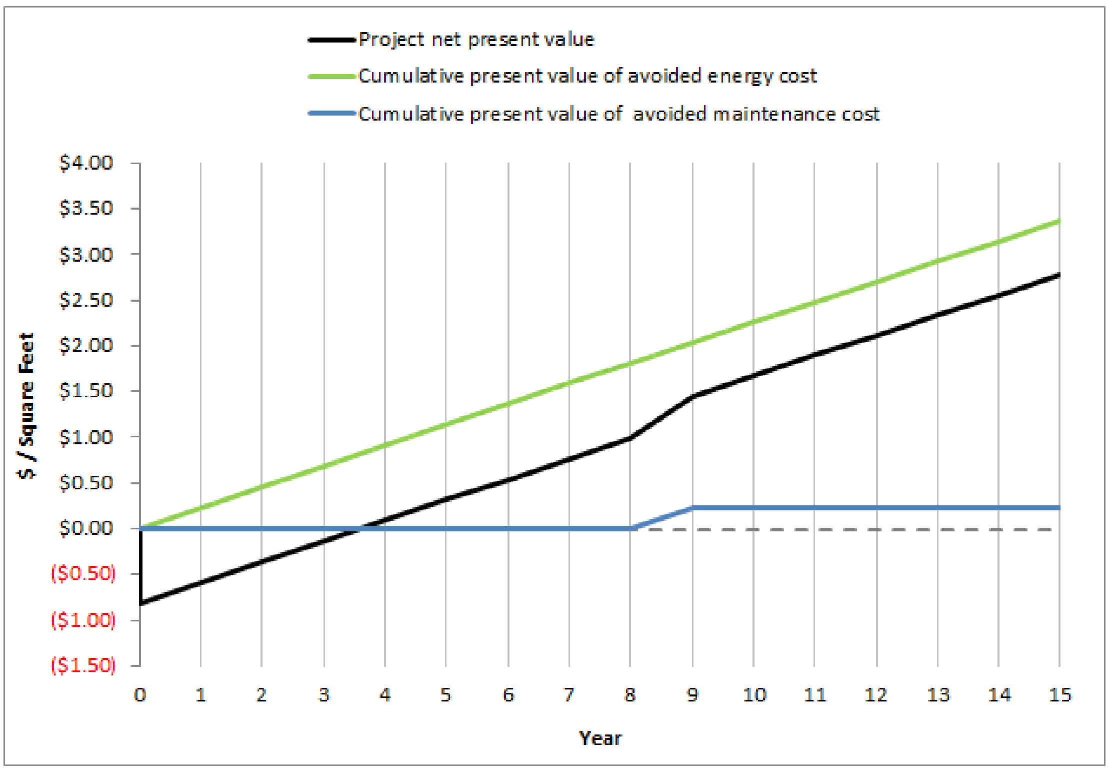
Life-cycle cost results for the new construction and major renovation scenarios are detailed in Table 26 and Figure 44. In the new construction case, the LED system with integrated controls is compared to the alternative of installing a brand new fluorescent system with new lamps and ballasts. There are fewer avoided maintenance cost cycles than for the retrofit case where it was assumed that existing equipment is being replaced, on average, half-way through its useful life. The new electronic ballasts would have a similar rated life to that of the LED fixtures, so only fluorescent lamp burn out and replacement is avoided by the LED system. It is estimated that lamps would be replaced once during the 15-year analysis period, since they have an assumed rated life half that of the LED fixtures (25,000 hours vs. 50,000 hours). Even so, at 4.37, the

SIR is very high for this case, as is the project IRR of around 31%. It is safe to say that under the assumed project costs and savings for this scenario, this investment option is a "slam dunk."

Table 26: Life-cycle cost results for new construction projects in GSA buildings

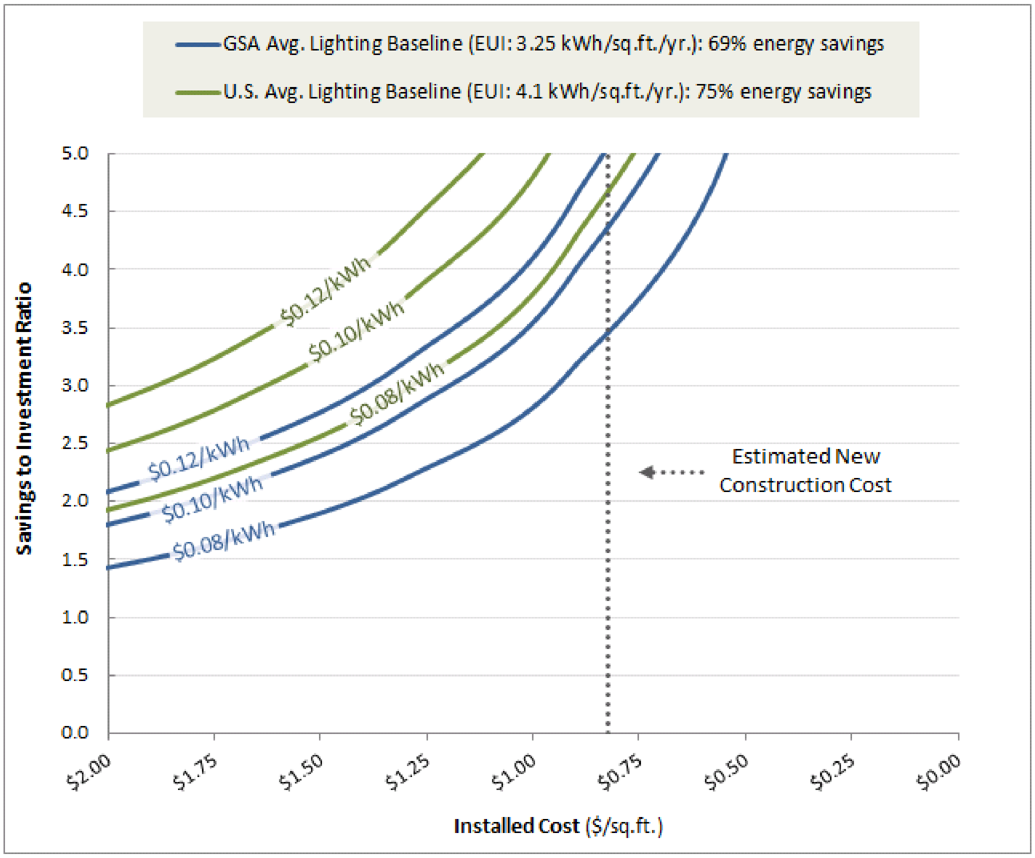
Initial Project Cost ($ / ft^2)	$0.82
Simple Payback (years)	3.6
Savings to Investment Ratio	4.37
Internal Rate of Return (%)	30.9%
Net Present Value ($ / ft^2)	$2.78

Figure 44: Present value of avoided costs for new construction projects in GSA buildings



New construction SIR sensitivity to project cost per square foot, electric utility rate, and energy savings is illustrated in Figure 45 below. For the range of displayed project installation costs and energy costs and savings, SIR is well above the threshold of 1, and is many times that value for most instances, indicating an attractive investment opportunity.

Figure 45: Normalized new construction SIR sensitivity to project costs and utility rates



VI. Conclusion

A. OVERALL TECHNOLOGY ASSESSMENT

Recessed linear fluorescent fixtures are the major lighting technology currently used to illuminate interior commercial spaces, accounting for more than 50% of the installed commercial light fixture base. LED fixtures to replace linear fluorescents are achieving efficacies above those of modern fluorescent lighting systems, have lifetimes well above the expected life of fluorescent lamps, and are easier to control with advanced dimming systems. While installations of indoor LED troffers are on the rise, they still have only a small share of the general illumination market.

At present, most commercial buildings do not include advanced lighting controls systems either, even though energy savings from their implementation have been proven by several studies. Uptake of advanced controls in the commercial market has been hindered by high installation costs, including equipment costs and high labor costs due to factors such as extensive controls wiring and commissioning requirements, system complexity, and laborer unfamiliarity. Though advanced lighting controls retrofits are achieving solid energy savings, high project costs have resulted in many such retrofits not being cost-effective. A turnkey lighting system with efficient fixtures and advanced controls capabilities that can be more easily installed and commissioned to lower the implementation cost barrier would potentially enable more widespread usage and result in energy savings.

This GPG program study evaluated whether market-available LED fixtures with integrated sensors and controls can significantly decrease energy consumption in existing commercial buildings, while maintaining or improving lighting quality and easing implementation of advanced lighting controls features. The study examined energy savings, photometric performance, occupant satisfaction, and cost-effectiveness associated with implementing LED fixtures with integrated controls, with the following summary results.

- **Energy savings**: At the Metcalfe study location, the baseline lighting EUI was 2.56 kWh/ft^2/year, although if the fixtures were operating with all lamps functional, the baseline lighting EUI would have been 3.96 kWh/ft^2/year. The post-retrofit lighting EUI of 0.98 kWh/ft2/year corresponds to energy savings of almost 62%, and more than 75% relative to the design baseline. At Summit, the baseline EUI was 1.78 kWh/ft^2/year with retrofit lighting energy dropping 40.2% to 1.06 kWh/ft^2/year. Both demonstration locations had lower-than-average lighting power densities and annual lighting energy usage compared to GSA and national averages (the Metcalfe site would have had more typical lighting power density and energy usage if not for the widespread lamp outages). Moving from the GSA average lighting EUI baseline of 3.25 kWh/ft^2/year to the average post-retrofit energy use seen at the demonstration sites, energy savings were estimated at around 69%, and relative to the national average lighting EUI baseline of 4.1 kWh/ft^2/year, energy savings of 75% could be expected.

  Generally, lighting wattage reductions due to switching to LEDs should also correspond directly to lighting energy reductions over time. The integrated sensors and controls also enable temporal changes in lighting operation, such as daylight dimming or dimming and turning off when occupants are not present. Those strategies, along with the institutional tuning enabled by the controls, are responsible for energy savings above what would be expected from the LED retrofit alone. At a GSA average lighting power density (around 0.95 W/ft^2), the wattage reduction from the LED retrofit alone would save around 41% in lighting energy. The advanced controls, including institutional tuning, would then add an estimated 28% savings for the GSA average and 34% savings for the national average.

- **Photometric performance**: Both demonstration locations met P-100 average illuminance requirements with the new LED systems and increased light levels relative to pre-retrofit systems. Based on the pre-retrofit and post-retrofit lighting power densities and average workplane illuminance results, the average workplane efficacy, which quantifies the lighting available at the work surface per unit of electric power drawn by the system, was calculated for the demonstration sites. Workplane efficacy results for both the Metcalfe and Summit study locations were very favorable for the new LED fixtures, with 79% and 63% improvements, respectively.

- **Occupant satisfaction**: At Metcalfe, based on the total number of respondents and the survey response rate, there is good statistical confidence in the results. For the Summit location, the total number of respondents was below 30, so results do not provide as high statistical confidence. At both sites, however, there were significant increases in satisfaction with the lighting environment, equivalent to improved satisfaction with controls. Project contacts for each location weighed in on the ease of implementation of the systems. Qualitatively the retrofit system also appeared to deliver on the simple “turnkey” selling point. Overall, both sites’ project contacts indicated that the systems were operating as expected and that the building tenants were satisfied with the results of the retrofit installations. From an ease of implementation standpoint, the technology appears to be an improvement over wired controls systems, as well as systems with individual fixture controllers, stand-alone sensors, and system gateways, servers, and other devices.

- **Cost-effectiveness**: At the average electric rate of $0.10/kWh, new construction paybacks of 3 to 4 years were found, with 10- to 14-year paybacks for retrofit scenarios. Essentially the analysis showed that the higher the electric rate and the higher the baseline lighting energy usage, the shorter the payback will be. The higher the project installation cost, the longer the payback will be. A discounted life-cycle cost analysis was calculated that summed the future avoided costs that would accrue from the technology over the estimated lifetime of that technology, compared to the system that would be operating in the space otherwise. Because the LED fixtures are a longer-lifetime, lower-maintenance option than standard fluorescent systems, maintenance savings that occur periodically during the system life-cycle can also be included in the life-cycle analysis. For typical GSA buildings, the SIR for a retrofit installation was found to be around 1.4 and the NPV of the discounted future savings (minus the initial project cost) was positive with a rate of return for the project of 6.9%. Lastly, maintenance savings were quite compelling when considered in the life-cycle analysis, responsible for around one quarter of the system savings over the 15-year lifetime.

B. LESSONS LEARNED

- Based on informal interviews with project contacts, overall installation went smoothly at both demonstration locations and commissioning of the control zones was straightforward and took little time. Because the fixtures are essentially the same as any standard 2’X 4’ or 2’X 2’ fixture, installation is also more or less the same, so contractors are unlikely to have difficulties with installation.

- Further to the previous point, the turnkey aspect of the integrated sensors and controls system proved to be a major advantage compared to stand-alone advanced lighting controls systems that need to be installed separately from fixtures, often at significant costs per square foot. A previous GPG study on advanced wireless lighting controls found an installation labor cost range of around \$0.40 - \$0.50/ft^2 for the controls alone, for example [1]. For the technology demonstrated here, the installation costs were basically those of replacing one fixture for another; the controls being integrated in the fixtures enabled an advanced controls system to be rolled out at almost no additional labor costs, though there is an incremental cost to the fixtures with controls on-board.

- There were some recommendations from project contacts for more initial training and support from the vendor to the building staff so that maintenance and re-commissioning of the system at later dates is better understood. It also became clear that the commissioning remote, which is only intended to set up fixture grouping during system programming, is not intended for day-to-day switching or dimming of fixtures in the system. At the Summit location, the commissioning remote was unintentionally provided to tenants, who used it to switch fixtures on and off at various times, which led to important commissioning instructions being lost. Once the system was re-programmed and the commissioning controller was retired to the building engineer, this problem was resolved. Essentially, the lighting system is an automated one and not intended for dynamic feedback from occupants, other than by turning fixtures entirely off by the use of manual wall switches.

- In a couple of specific fixture locations at Metcalfe, a lack of fixture responsiveness to occupant presence required that separate stand-alone sensors be installed on the ceiling to cover the space adequately. This appeared to be a rare result, but specified systems should perhaps always include a small number of extra stand-alone occupancy sensors for cases where fixture location or orientation means that the embedded sensor does not provide adequate coverage.

- Occupants of the spaces where the retrofit technology was installed expressed high levels of satisfaction with the retrofit lighting systems, for the most part. Some user preference was expressed, however, for more individual control of fixtures, for those who prefer less or more light than what the tuned system provides.

C. BARRIERS AND FACILITATORS TO ADOPTION

- **Barrier:** LED fixtures tend to be more costly than fluorescent alternatives.
  Facilitator: The higher efficacy LED light source provides more lumens at a lower electric power demand. Though many factors influence fixture choice (*e.g.,* aesthetics, light distribution, and cost), for facilities to invest in the LED option, the higher incremental cost of the LED fixtures may need to be recovered by energy and maintenance cost savings over time. The advanced dimming controls integrated into the retrofit technology also allow for tuning of fixture groups to reduce fixture power to settings that provide more appropriate, tailored levels of light to a given space, while eliminating unnecessary over-lighting and the associated energy usage. Other factors, such as

product lifetime, lighting performance, and aesthetics will also influence what fixture is specified for retrofit and new construction projects.

- **Barrier:** There is also incremental cost associated with the integrated controls compared to a standard static LED fixture option.
  Facilitator: This incremental cost may be recovered by the energy savings from the advanced controls features, but that will depend on how the lights would be operating otherwise. If there are already occupancy sensors at relatively high density in a space that are ensuring that unneeded lights are staying off when occupants are not present, the advanced controls savings would be pretty limited and the incremental cost may not be recouped by energy savings.

- **Barrier:** Low utility rates at some locations, such as the Metcalfe building (annual average of only $0.06/kWh), diminish the economic benefit of energy savings from the retrofit system.
  Facilitator: Locations with higher utility costs will have an easier economic case for LED fixtures with integrated controls.

- **Barrier:** Though advanced lighting controls retrofits have achieved solid energy savings in most studies reviewed, high project costs have often resulted in projects not being cost-effective.
  Facilitator: The turnkey ease-of-implementation emphasis of the technology design evaluated here is meant to reduce that cost barrier, as well as the complexities that have hindered advanced controls uptake in the past. The demonstrated technology enables advanced lighting controls to be rolled out with almost no labor cost beyond that of the fixture installation. The sensors and dimming controls are already integrated into the fixtures and ready to go.

  The longer lifetime of the LED fixtures should also further reduce operation and maintenance costs relative to the existing fluorescent fixtures. The discounted life-cycle cost analysis included avoided maintenance costs estimates. For the retrofit case, maintenance savings were quite compelling, responsible for around one quarter of the system savings over the 15-year lifetime (see Figure 42) and helping achieve the estimated SIR of 1.4 and the rate of return of 6.9%.

D. MARKET POTENTIAL WITHIN THE GSA PORTFOLIO

A recent DOE study estimated that while current annual electricity savings for the installed base of LED troffers was 0.1 TWh in the US, potential energy savings at 100% LED penetration in all troffer applications in the nation would be an impressive 110 TWh [4]. Those energy savings are equivalent to the annual electric energy usage of 10 million U.S. homes. DOE estimates that LED savings in the U.S. troffer market is the most promising of all major lighting categories it has evaluated.

In the case of GSA, its inventory of more than 9,000 federally owned and leased buildings is responsible for nearly 2.6 million MWh of electricity usage annually. If the proportion of electricity for lighting relative to overall building electricity is the same in GSA buildings as the national average (26%), lighting is responsible for around 676,000 MWh per year. Annual lighting energy savings from the LED troffers with integrated controls for typical GSA buildings is estimated at 69% in this study. Conservatively assuming that half of GSA building lighting energy usage is for interior fluorescent fixtures, and if all of those fixtures were replaced with the LED fixtures and integrated controls evaluated here, something on the order of over 230,000 MWh savings per year could be achieved, at annual cost savings of over $23 million (at $0.10/kWh).

Based on the results of this study, it is clear that LED fixtures with integrated controls can reduce lighting energy usage in GSA's commercial buildings. There may be considerable potential for deep energy savings through the retrofit deployment of these technologies within GSA buildings where project cost-effectiveness is likely. This would include buildings with average or high baseline lighting energy usage and electric utility rates at or above the national average of $0.10/kWh. For new construction or major renovation cases where the project cost is only the incremental cost of the LED fixtures with integrated controls relative to standard fluorescent fixtures and simple controls, it appears that cost-effectiveness is almost guaranteed for these systems, so they should be strongly considered in any such project.

II. Appendix

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