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Wireless Advanced Lighting Controls Retrofit Demonstration:

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Energy Technologies Area

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Prepared for the General Services Administration
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Principal Investigator: Francis Rubinstein

GPG
Green Proving Ground Program

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 90.1-2007	ASHRAE – published Energy Standard for Buildings (except low-rise residential); the national standard for commercial building energy codes in the U.S.
BAS	Building Automation System
CBP	Commercial Buildings Partnership initiative of the U.S. Department of Energy
CEC	California Energy Commission
CRI	Color Rendering Index; measure of the ability of a light source to reproduce colors accurately.
DOE	U.S. Department of Energy
EIA	Energy Information Administration
EUI	Energy usage intensity; a metric for characterizing energy use 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 the U.S. General Services Administration
GSA	U.S. General Services Administration
GWE	Global warming effect; a metric for characterizing greenhouse gas emissions, a product of GHG emissions and their specific time-dependent global warming potentials (g $CO_{2,eq}$ /kWh electricity generated, kg $CO_{2,eq}/ft^2$/year).
HVAC	Heating, ventilation, and air conditioning systems in buildings
kWh	Kilowatt-hours; unit of electric energy
LBNL	Lawrence Berkeley National Laboratory
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); unit of light source efficacy in converting electric energy to visible light
MWh	Megawatt-hours; unit of electric energy
NPV	Net present value; 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 more than 9,600 federally and privately owned buildings.

R_a	The general CRI, calculated as an average of the CRIs R1 – R8, covering relatively low saturated covers evenly distributed over the complete range of hues.
R_9	The CRI related to strong red tones. R9 is an important additional CRI to consider as strong reds are prevalent in skin tones and indicates whether the light source will be perceived as warm.
RF	Radio frequency
SIR	Savings to investment ratio; cost-effectiveness ratio of life-cycle savings from an energy improvement to the initial investment cost. If greater than 1, 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 nm).
SPP	Simple payback period; cost-effectiveness metric that characterizes the length of time required to recover the cost of an investment, and defined as the cost of project over the energy savings at the site per year.
Tlm-hr	Teralumen-hour, unit of lighting service defined as the product of a light level (lumen) and the annual hours of operation
TWh	Terawatt-hours; unit of electric energy

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I. Executive Summary

A. INTRODUCTION

Awareness of the economic costs and environmental consequences of electric energy use in buildings is steadily growing. Implementing energy efficiency measures for reducing energy consumption in buildings can be an effective strategy for managing these impacts. Within commercial buildings in the United States, electricity use for lighting accounts for 26% (around 346 TWh in 2010) and represents a large potential energy savings source. Significant lighting energy savings have already been achieved through the widespread adoption of efficient fluorescent lamps and ballasts in the past several decades. Looking towards efficient lighting operations' innovations, wireless advanced lighting controls technology represents an increasingly viable option for capturing the next major level of lighting energy savings in new construction and building retrofits. Fundamentally, lighting is the most amenable building end use load for producing deep energy savings because of its dynamic controllability.

Advanced lighting controls encompass control strategies from occupancy sensing to continuous dimming, institutional tuning and daylight harvesting. These strategies offer greater flexibility and higher granularity of control than traditional basic control methods. Historically, advanced control systems have required extensive control wiring, which has driven system costs. However, recently developed wireless lighting controls systems can be used to network lighting components, while potentially minimizing installation time and labor costs during retrofit in comparison to wired control systems.

Lighting Control Systems Market Trend

- In an effort to reduce overall system first costs significantly, lighting control system manufacturers are partnering with fixture manufacturers to embed their sensors, communication and control componentry directly into fixtures to eliminate the labor costs associated with installing these separate devices in the field at electrician rates.
- NOTE: This project report is based on an earlier technology approach, whereby the sensors and communication components are installed in the field, which forms the basis of the economic analysis contained later in the report.

In FY 2011, GSA buildings used approximately 700,000 MWh of lighting electricity. As it is still very uncommon to find wireless advanced lighting controls in GSA buildings, considerable lighting energy savings potential may be possible through implementing this technology. This Green Proving Ground (GPG) program study examines whether and how wireless advanced lighting controls can play a role in decreasing energy consumption in existing commercial buildings while upgrading the efficiency, management and quality of a lighting system.

B. PROJECT AND TECHNOLOGY OVERVIEW

This GPG program study evaluates the energy savings, cost-effectiveness, photometric performance, and occupant satisfaction associated with implementing wireless advanced lighting controls. Wireless advanced lighting controls were installed on existing fluorescent light fixtures in one study location and were installed with new LED fixtures replacing fluorescent fixtures in another location.

WIRELESS ADVANCED LIGHTING CONTROLS

Traditional lighting systems use manual switches or simple controls features such as automated on/off scheduling to control large fixture groups or entire office floors. Even where standard occupancy sensors are installed, the switching generally occurs only in small private offices and, less commonly, across large zones of fixtures within a building. Advanced lighting control systems, by comparison, employ a variety of design and control approaches to better match lighting conditions to occupant needs while avoiding wasting energy where lighting is unneeded, and do so at much higher spatial and temporal resolution. Advanced controls include a multitude of control strategies; this study focuses on features such as institutional tuning, occupancy sensing and daylight harvesting.

Despite significant energy savings potential, advanced lighting controls adoption has been slow due to a number of barriers; one of the biggest being high installation costs. Advanced wireless lighting control systems currently available are meant to simplify the installation process for lighting controls, potentially reducing material and labor costs by negating the need for long runs of controls and communication wiring. Wireless mesh networks are comprised of a number of devices that can repeat messages and route communication via multiple paths to network lighting components effectively into one coherent and centrally controllable system. However, wireless advanced lighting controls systems are still fairly new to the market, with unfamiliarity with the technology tending to drive up installation time and costs.

LED FIXTURES AND WIRELESS ADVANCED LIGHTING CONTROLS

LEDs are becoming a promising light source for use in the general illumination marketplace. There has been an immense ongoing research and development effort focused on improving the performance of white-light LEDs in terms of efficacy (lumens per watt), light output, color quality, lifetime, control, and optical design for general illumination purposes. LED products currently on the market to replace linear fluorescent fixtures include T8 LED replacement lamps for fluorescent T8 lamps that go into existing fluorescent fixtures, LED retrofit kits installed in existing fluorescent fixtures that also replace fixture optics assembly and electrical components and fully integrated LED fixtures that replace fluorescent fixtures entirely. LED lighting is evolving in technical readiness in parallel with advanced wireless controls for enhanced and more energy-efficient lighting operation. LED technology is well-suited for advanced wireless controls strategies as the fixtures are easy to dim, which is essential for advanced controls strategies like institutional tuning and daylight harvesting. Also, the LED light source is less susceptible to shortened lifetimes due to on/off cycling that occurs with aggressive occupancy sensor control, which can cause fluorescent lamps to fail early.

LED fixture lighting performance, user satisfaction and cost-effectiveness is not the focus of this study, which instead is concerned with wireless advanced lighting controls implementation and operation, how occupants respond to these systems, and under what circumstances they are cost effective. However, as the lighting market is increasingly filled with LED lighting options for commercial building spaces, installation of advanced wireless controls with LED fixtures will be more common in the future—one of the study locations included LED fixtures and wireless advanced lighting controls.

PROJECT OBJECTIVES

This study focused on the following key objectives for each demonstration:

- Quantify and understand the energy savings, light condition changes, light maintenance improvements, and occupant satisfaction changes associated with the wireless advanced lighting controls retrofit;
- Evaluate the retrofit cost-effectiveness, taking into consideration future cost estimates for delayed deployments (in five years); and
- Evaluate implementation, commissioning and operation, and demonstrate whether wireless advanced lighting controls can be installed in a turnkey fashion with reliable performance.

DEMONSTRATIONS LOCATIONS

GSA chose two buildings for advanced, wireless lighting control GPG program demonstrations. The first site, the 16-story, Appraisers Federal Building in San Francisco, CA, was chosen for an LED fixture retrofit combined with wireless advanced lighting controls, while in the second site, the Moss Federal Building in Sacramento, CA, a wireless advanced lighting controls retrofit on existing fluorescent fixtures was implemented.

The 6,800 square foot Appraisers Federal Building study area consisted of mostly open office areas with some private offices, reception and other rooms. Existing lighting controls at the location included both occupancy sensors and manual switches.

The Moss Federal Building is an eight-story high-rise located in Sacramento, CA. Wireless advanced lighting controls were installed on the existing fluorescent lighting fixtures throughout the 4th and 6th floors. The sites are located in the northwest portion of the 4th floor (M4NW), along the south wall of the 4th floor (M4S), and along the south wall of the 6th floor (M6S). Ballasts were retrofitted with dimming ballasts for compatibility with the advanced lighting system. Sites predominantly included open office plan areas, private offices, corridors and conference rooms. Existing controls varied from location to location, including manual switches or occupancy sensors, or both, and in some cases, automated lighting schedulers that turn lighting circuits on and off based on fixed, programmed schedules.

To control the fixtures in both test sites, each dimmable fluorescent ballast or LED driver was connected to a wireless adapter. At Appraisers, wireless fixture adapters were installed at the most granular level, one per fixture, while at Moss, where possible, multiple fixtures were wired to a single wireless adapter; a so-called “zonal” installation approach. Installing wireless adapters on each fixture allows for maximum flexibility in programming and reconfiguring the behavior of individual fixtures or fixture groups, but is more costly in terms of materials than installing wireless adapters in a zonal fashion, with each adapter controlling multiple fixtures. At both locations, fixtures were configured into groups or zones in the controls software such that multiple fixtures (typically four to six) are programmed to operate the same way based on sensor and switch inputs. A photosensor was installed in each of the zones located along the perimeter of the buildings.

Wireless occupancy sensors were installed such that there was at least one occupancy sensor per control zone. Controls installed in private offices typically included an occupancy sensor, a dimming switch and a photosensor, if the office had a window. The entire advanced wireless control system at each location was backhauled to an internet server that can be accessed, monitored and programmed via a web-interface.

MEASUREMENT AND VERIFICATION

During the pre- and post-retrofit study periods, site characterization visits, energy monitoring activities, photometric characterizations, and occupant satisfaction surveys were conducted to analyze the effectiveness of the installed technology. The wireless controls performance also was measured and verified at test-bench level at LBNL during the study period.

Electric energy used by the lighting circuits serving the study areas at Appraisers and Moss were monitored during pre- and post-retrofit periods, which varied in length due to retrofit schedules and site access timing. The wireless advanced lighting controls system interface also can be used to trend controls commands and fixture behavior. One month of systems data was trended for three fixture groups (one in Appraisers and two in Moss). This data was used to calculate average lighting power density and annual energy usage. To compare lighting energy usage from the controls data to baseline lighting usage and to disaggregate savings from different controls strategies, parallel datasets were produced to represent various lighting controls scenarios.

Photometric measurements were conducted for both open office and private office workspaces to characterize electric light levels (illuminance) and color characteristics, including spectral power distributions and color rendering (CRI). Desktop illuminance measurements were taken at the primary work area. Finally, occupant satisfaction surveys were administered. The survey contained 17 multiple choice questions and 3 free response boxes 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.

C. PROJECT RESULTS AND FINDINGS

ENERGY SAVINGS

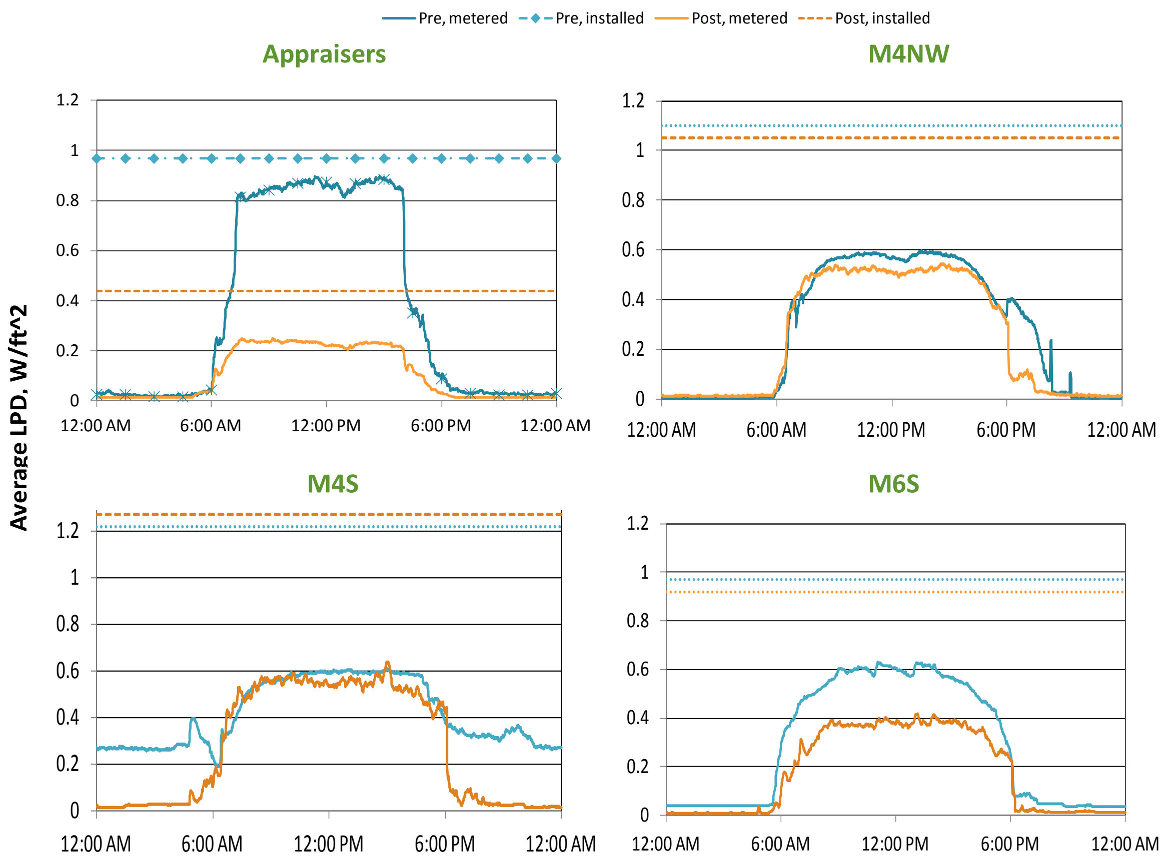
Table 1 summarizes annual lighting energy results at the study locations, extrapolated from the measured pre- and post-retrofit lighting energy usage. The energy savings achieved at Appraisers from the advanced wireless lighting were estimated at 32.3%. At Moss, average energy savings for the three study sites was 32.8%. For site M4NW, modest energy savings of 9% were realized after the retrofit, mostly due to reducing after-hours lighting operation. Counteracting energy savings was system programming to keep fixtures on at a dimmed, 20% “intensity” setting during the workday in areas where no occupants were present, whereas previous occupancy sensors simply turned the fixtures off when no one was present. The wireless controls retrofit at M4S and at M6S had a much greater energy impact, reducing annual energy consumption by 42% to 47%. These savings were brought about by the reduction of after-hours lighting energy use and large reduction in average workday lighting power due to institutional tuning and daylight dimming.

Table 1: Summary pre- and post-retrofit energy use intensities

Site	Appraisers (excluding LED wattage reduction)	Moss (average of three locations)
Pre-retrofit Annual Lighting EUI (kWh/ft^2/year)	2.3	2.2
Post-retrofit Annual Lighting EUI (kWh/ft^2/year)	1.6	1.5
% Savings	**32.3%**	**32.8%**

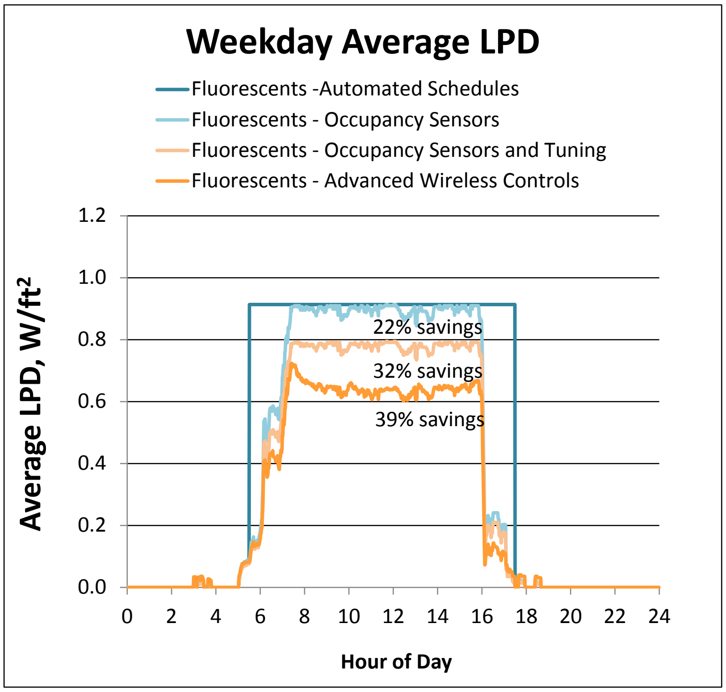
Figure 1 shows how daily lighting power averages changed throughout the day. For Appraisers, the installed lighting power density (LPD) went from 0.97 W/ft^2 to a post-retrofit LPD of 0.44 W/ft^2, a decrease of 55% due to the switch from fluorescents to LED fixtures. Including the LED wattage reduction and operational savings from the advanced wireless controls, energy savings at Appraisers totaled around 69%. The installed retrofit LPD in the three Moss study locations was similar to the pre-retrofit condition (both were fluorescent lighting systems), varying by only 5% - 7% per location. These small differences in LPDs are simply attributable to slight changes in ballast and lamp efficiency.

Figure 1: Summary pre- and post-retrofit average workday lighting power density



An analysis of one month of data from the advanced lighting controls system user interface helped disaggregate the lighting energy savings attributable to the various controls features. Based on the lighting usage patterns evident in the controls system data, a few alternative controls scenarios were established for comparison with the advanced wireless system (as illustrated in Figure 2); from simple automated scheduling to only occupancy sensors and to occupancy sensors with institutional tuning. Comparing these options for a group of fixtures in the Appraisers location, savings from occupancy sensors relative to automated schedules were found to be around 22%, with an additional 10% coming from institutional tuning, and another 7% from daylight harvesting (even though daylighting was only implemented on about one-third of the fixtures in the study group). In total, from the controls system one-month data analysis, advanced wireless controls were found to save around 39% lighting energy relative to an automated scheduling baseline.

Figure 2: Controls data analysis of energy savings per controls strategy



Overall this study found that implementing advanced wireless control systems can save significant lighting energy, but savings are not guaranteed. They are heavily dependent on the baseline controls conditions. Total savings were high in the Moss sixth floor private offices with abundant daylighting. Similar controls savings were found in mixed perimeter and interior offices at Appraisers. However, in some locations that already had occupancy sensor controls, such as on the fourth floor of Moss, the advanced controls actually increased energy usage at times. Overall, the results indicate that advanced wireless controls can save substantial energy in situations where simple on/off switching by wall switches and automated schedules is the norm. If the lighting system already employs occupancy sensors, there will need to be significant daylight harvesting and institutional tuning opportunities for advanced controls to have a large energy impact.

In general, institutional tuning opportunities will be highest in locations where the baseline condition is considered overlit. With continuously dimmable light sources and advanced wireless controls, lighting power and output can be finely tuned to provide desired light levels without wasting energy or creating an uncomfortable environment. However, institutional tuning may not have realized full energy savings potential in the study sites due to discrepancies between settings in the controls system and fixture dimming response. For example, after initial commissioning, it was found through lighting circuit energy measurements that the fixture tuned power levels were higher than expected throughout the day and the controls settings needed to be adjusted to achieve the intended dimming response. This underscores the need for controls vendors and system implementers to know precisely how dimmable fixtures respond to dimming control signals to implement dimming strategies effectively.

In cases where LED fixture retrofits and advanced wireless controls are being considered, the relative costs and benefits of the equipment options installed separately and in combination should be considered. The

LED fixtures installed at Appraisers saved significant energy on their own, due to an over 50% reduction in lighting wattage. Installing wireless advanced lighting controls on existing fixtures would have saved around 32% energy. The highest savings, however, are achieved when installing both options.

PHOTOMETRICS

At Appraisers, the pre-retrofit fluorescent system provided an average work plane illuminance level of 57.2 fc, while the post-retrofit LED and advanced controls system provided an average illuminance of 37.0 fc. While the retrofit lowered light levels, they remained above the 30 fc standard for the type of work performed by this site's occupants, as recommended by GSA's Facilities Standard P-100 (discussed later). Average illuminance levels at Moss were fairly similar pre- and post-retrofit.

Table 2: Summary photometric results

	Appraisers		Moss: M4NW		Moss: M4S		Moss: M6S	
	Pre-retrofit	Post-retrofit	Pre-retrofit	Post-retrofit	Pre-retrofit	Post-retrofit	Pre-retrofit	Post-retrofit
Mean fc	57.2	37.0	32.6	34.9	32.0	29.0	34.7	34.6

OCCUPANT SATISFACTION

For lighting controls to be implemented effectively over the long-term, users must understand and accept the system and its implementation in their workspace. Occupant satisfaction was assessed here through the administering occupant surveys both pre- and post-retrofit to determine how occupants felt about their existing lighting and lighting controls systems and how they responded to the retrofit systems.

Lessons

- Clear communication of design intent is essential for successful installation.
- Prior to installation, an agreement on commissioning process needs to be reached between the vendor, contractor, and property manager.
- Engage controls vendor early to address occupant complaints.
- Identify and communicate dissatisfaction clearly and early so that technical issues can be appropriately addressed. Avoid blaming old equipment failures on new technology (e.g., legacy occupancy sensors, improperly conditioned lamps).

At Appraisers, occupants responded considerably more favorably regarding the lighting service and performance from the advanced wireless controls. Overall comfort level with the light levels doubled from pre- to post-retrofit condition (even with the reduction in average illuminance), with more occupants also feeling like work surfaces were evenly lit. With respect to the functioning of the lighting controls, more occupants expressed satisfaction with the retrofit system as well.

In the case of the Moss lighting controls retrofit, responses were slightly less favorable regarding the lighting service and performance after the controls retrofit. There were decreases in favorable responses with regard to workspace comfort level, illumination of workspace surfaces and controls functioning. There was a slight increase in favorability regarding uniformity of work surface illumination. The occupants did appear to understand that the new controls provide daylight dimming response and adjustable light levels, but dissatisfaction was expressed by a few regarding the way the occupancy and dimming controls work. Possibly influencing these results, after the retrofit, the site experienced some lamp failures due to the use of fluorescent lamps that had not been seasoned for dimming controls (which was later addressed by installing new lamps conditioned for dimming). Also, legacy occupancy sensors were used in some locations, possibly forcing old zoning schemes onto new work station and controls layouts. These issues coupled with commissioning errors appear to have led to dissatisfaction amongst some tenants, which is being addressed by the controls vendor at this time.

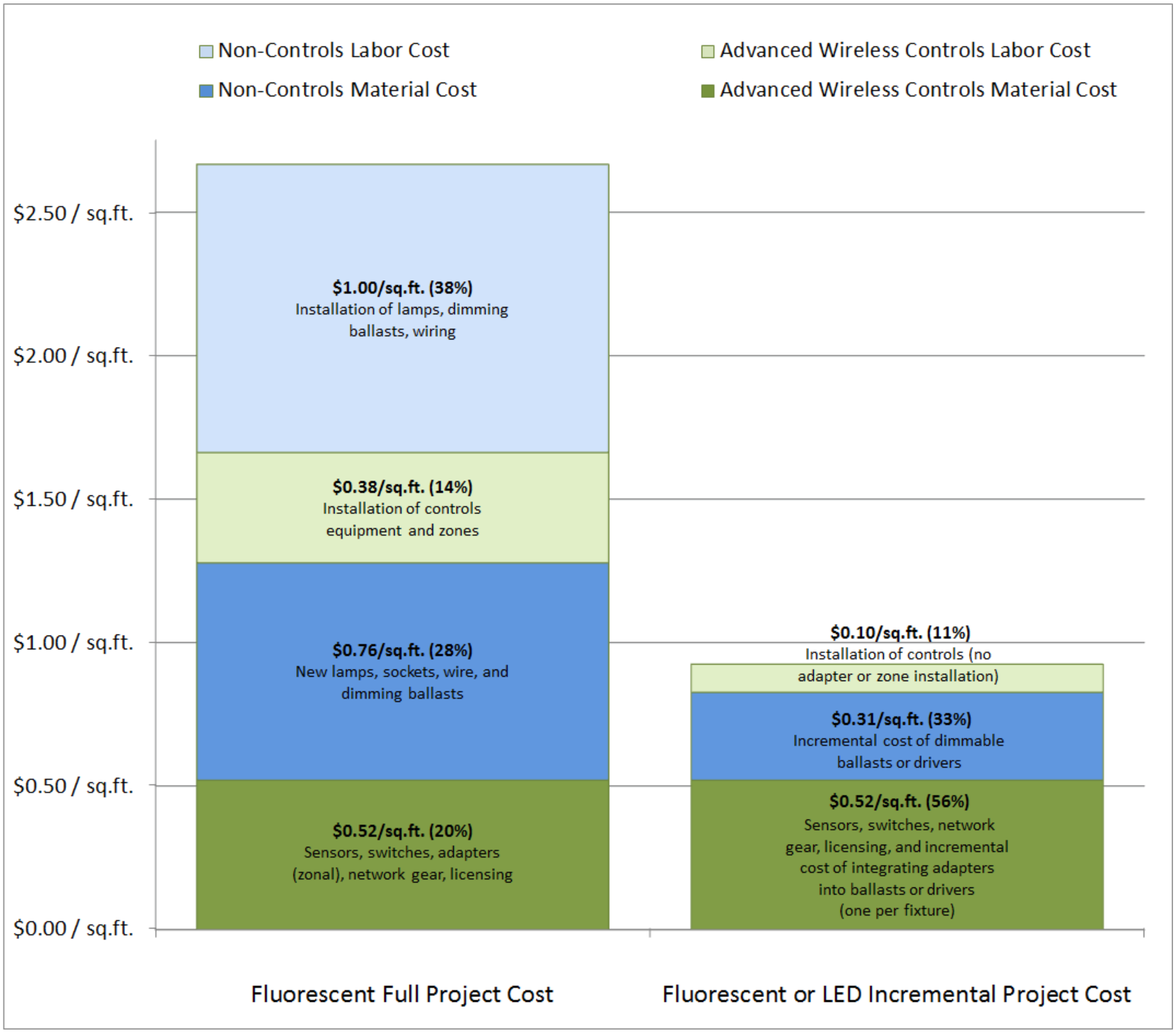
Though the Appraisers survey results are very encouraging and show good acceptance of the new controls system, the Moss survey results indicate possible missteps in the system installation that have negatively impacted occupants. Feedback provided by occupants in the surveys should be addressed by continued system design and commissioning improvements, including aligning occupancy sensor locations with occupant location so that occupant detection and lighting response is optimal.

COST-EFFECTIVENESS

Normalized costs and savings scenarios for wireless advanced lighting controls retrofits and new construction or major renovation installations were prepared for cost-effectiveness analyses. The normalized costs and savings scenarios are intended to represent realistic installed costs for present and future projects at larger scales than the experimental installations evaluated in this study, and including anticipated costs with typical project processes such as competitive bidding. Costs per square foot are based on real-world material and labor costs from a large project (over 200,000 ft^2) in 2012 with controls equipment costs updated to 2014, as well as the latest equipment cost estimates for the controls as provided by the technology vendor, and assuming the zonal installation approach in which multiple fixtures are wired to a single wireless adapter. Costs are projected to decrease with technology maturation, increased sales volume and the embedding of sensors and controls directly into fixtures. Energy savings for normalized costs and savings are based on comparing the weighted average post-retrofit lighting energy usage at the project locations to baseline lighting energy usage equal to a GSA building average (discussed later) and a national commercial building average as well for comparison. Energy cost savings are valued according to a national average electricity rate of $0.10/kWh.

Figure 3 below illustrates the estimated costs per square foot of the materials and labor to install wireless advanced lighting controls. A full project cost scenario for retrofits on existing lighting systems (typically fluorescent) includes the labor and material costs of the advanced controls, as well as the fixture equipment upgrades and labor necessary to enable the technology (new lamps, dimmable ballasts). Electrician labor costs are estimated at $75/hr. An incremental project cost scenario for new construction and major renovation projects also is presented. This scenario applies to fluorescent or LED lighting projects in which the lighting equipment costs and associated labor are already budgeted and the only costs considered are those associated with adding the advanced wireless controls to the project scope.[1]

Figure 3 Project cost estimates for retrofit and new construction scenarios



[1] In the incremental cost and savings approach for new construction or major renovation, the baseline lighting energy usage against which energy savings are valued is held equal to the GSA and national building average lighting energy usage values. This is a simplification since new lighting systems may include lower power demands than the baseline systems already installed in "typical" buildings. In reality energy savings will be achieved by lower-wattage lighting systems as well as energy – efficient wireless advanced lighting controls. The approach here is to consider the controls energy savings first and solely, since lighting controls operations and savings are the focus of this study. Wattage reductions and resultant energy savings from new lighting systems (fluorescent or LED) are outside of the scope of this analysis.

Figure 4 below illustrates the sensitivity of simple payback to 1) installed cost of wireless advanced lighting controls for 2) GSA and national average baseline lighting energy usage scenarios at 3) higher and lower utility rates. Payback contours for utility rates of $0.08/kWh and $0.12/kWh are graphed for the GSA and national average lighting energy baselines. The shaded area between the two contour lines for each scenario encompasses the payback range for rates between those values, including the national average utility rate of $0.10/kWh.

Lighting Control Systems Payback Issues

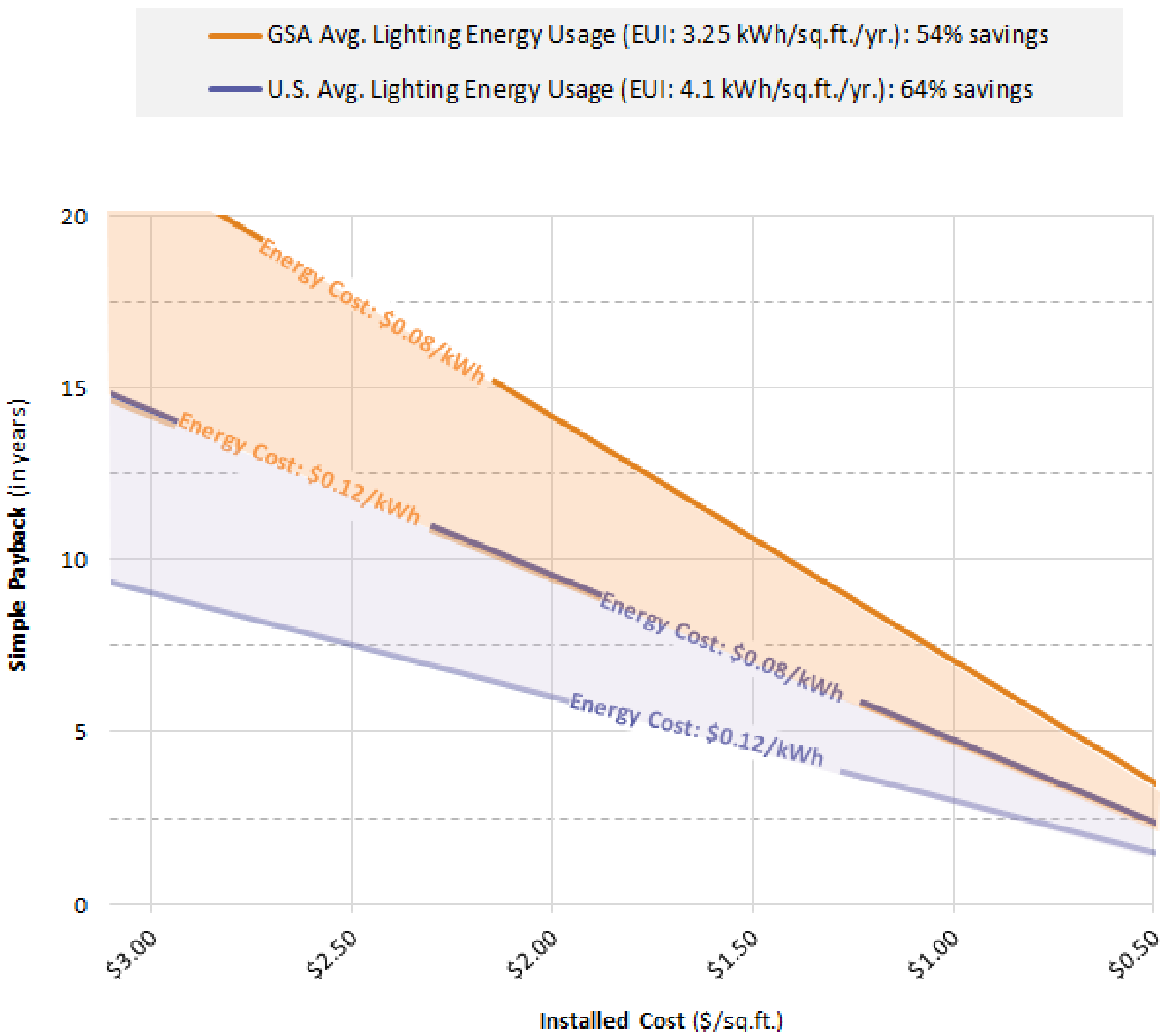
- Simple Payback Period (SPP) calculation looks at first year costs divided by first year savings to provide a rough metric commonly used by market stakeholders.
- A full-fledged financial analysis that produces net present value (NPV), internal rate of return (IRR), and other investment metrics not calculated here includes the investment horizon (i.e., is it a 5-, 10-, or 20-year investment period); ongoing operations and maintenance (O&M) savings; demand response (DR) incentives; escalation or electricity rate changes due to real-time pricing; potential carbon credits or tax treatments; integrated HVAC savings; and other non-energy benefits.
- Other considerations include whether or not the space is owner-occupied, or leased; and who owns the lighting system, etc.
- Due to these other factors, SPP simply acts as a guidepost. It does not encompass the features of a full financial investment analysis typically used for investment decisions associated with construction projects and may omit some of the true investment value over time.

Project cost estimates per square foot are indicated on the graph for advanced wireless controls installations. The estimated full project cost for retrofit on existing lighting system (typically fluorescent) is graphed, as well as the incremental project cost estimate of adding advanced controls to fluorescent or LED lighting project scopes in new construction or major renovations. The incremental costs are assumed to be roughly the same regardless of lamp technology (LED or fluorescent), including only the wireless controls materials, the associated labor and the incremental cost of dimmable ballasts or drivers over static options.

It is clear from the analysis that baseline lighting energy usage is a critical component in advanced lighting controls' cost-effectiveness. For the higher, national average lighting energy baseline, energy savings are greater and their value is reflected in lower paybacks. Paybacks are around two to six years lower over the entire range of illustrated project costs for projects in buildings with U.S. average baseline lighting energy usage, compared to projects in building with the lower GSA average lighting energy baseline. For fluorescent retrofits today, projects with GSA average baseline lighting energy usage reach paybacks of 13 - 19 years for the range of utility rates illustrated, while those with national average baseline lighting energy usage reach payback in 8 - 13 years. Paybacks are significantly better (lower) at the higher utility rate of $0.12/kWh than at the $0.08/kWh rate. At a utility rate of $0.12/kWh, fluorescent retrofits should achieve paybacks in less than 13 years in average GSA buildings, and around 8 years for the national average baseline. In certain areas that experience even higher rate structures associated with real-time pricing or peak-day pricing, the payback is further accelerated.

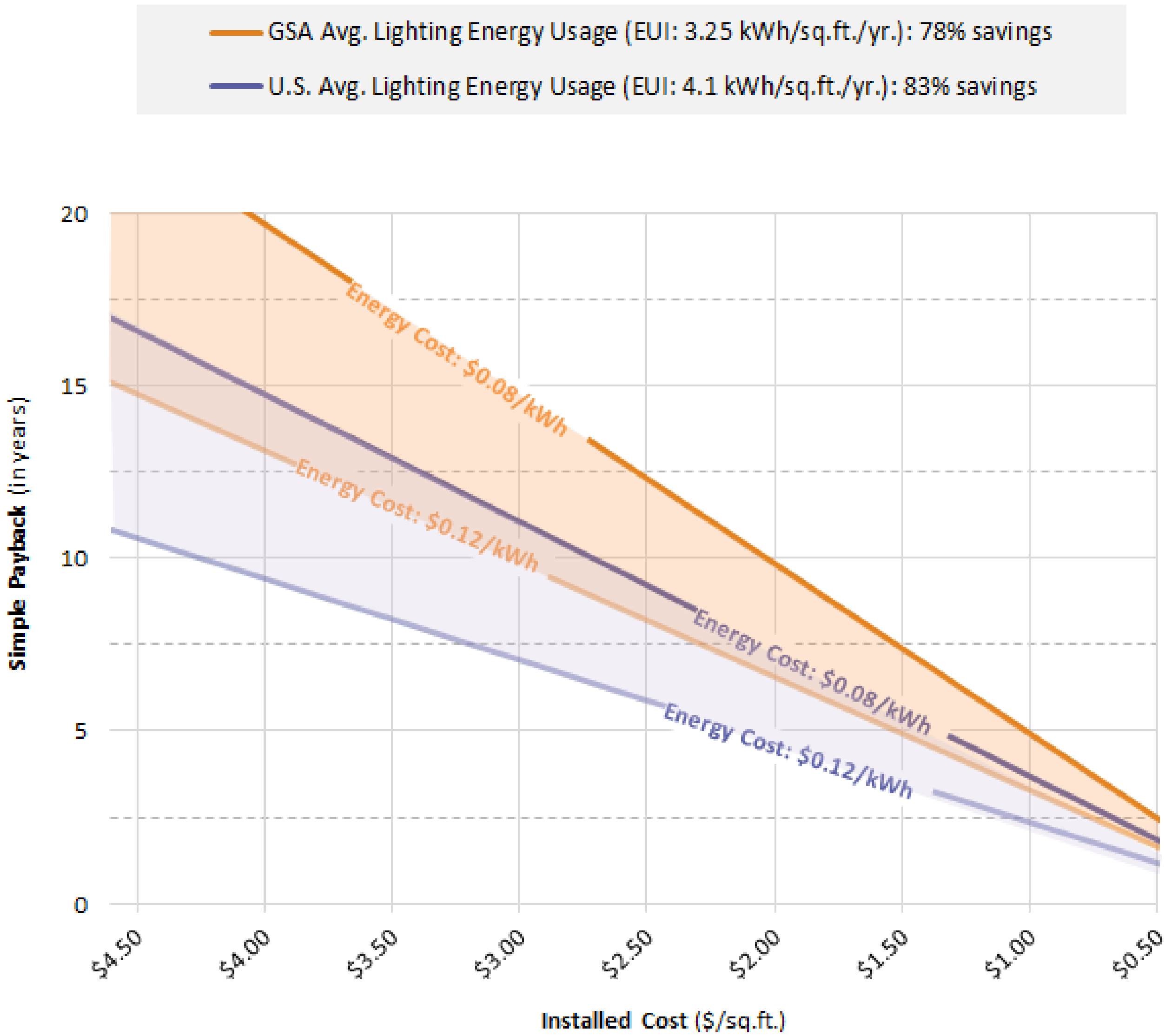
The project cost impacts can be seen moving from left to right along the X-axis. Paybacks continually improve as installation costs per square foot go down. For locations with GSA-average lighting energy usage, installed costs would need to reach a target of $2.00/ft^2 at an electric rate of $0.12/kWh to hit retrofit paybacks in the 10-year range. At the average utility rate of $0.10/kWh, the retrofit cost would need to be closer to $1.75/ft^2 to reach the 10-year payback mark for GSA buildings. **Cost-effectiveness results for new construction and major renovation scenarios, with the much lower incremental installed project costs (close to $1/ft^2), are much better. With paybacks ranging from 3 to 6 years, adding wireless advanced lighting controls to lighting projects is a compelling opportunity in new construction and major renovation**. A key issue in these scenarios is that retrofit project costs are unburdened by the entire advanced lighting control system cost, but instead are simply the cost differential between the code-compliant system and the proposed system. This lower incremental cost drives the investment attractiveness as represented by the values at the lower right side of Figure 4, below.

Figure 4: Sensitivity of wireless advanced controls simple payback to installed cost, EUI, and utility rate



Energy savings increase between 19% and 24% when savings from LED lighting and wireless advanced lighting controls are combined. Installed costs, on the other hand, will be higher when replacing existing lighting with LEDs. Bottom line, LEDs will cost more money initially but save more in the long term. Figure 5 below illustrates the sensitivity of simple payback for wireless advanced lighting controls combined with LED. For locations with GSA-average lighting energy usage, installed costs would need to reach a target of $3.00/ft^2 at an electric rate of $0.12/kWh to hit retrofit paybacks in the 10-year range.

Figure 5: Sensitivity of wireless advanced controls with LED simple payback to installed cost, EUI, and utility rate



D. CONCLUSIONS AND RECOMMENDATIONS

Energy savings potential for wireless advanced lighting controls is clear, but savings are heavily dependent on the baseline controls condition. Advanced controls will be most cost-effective in situations where only very basic lighting controls are in place, such as simple on/off switching by automated schedules. Local utility rates also influence project cost-effectiveness, with locations paying high electric rates being better candidates for advanced controls retrofits. Increasing project scale, continued technology maturation, and competitive project bidding will likely lower project costs and improve cost-effectiveness going forward. Along with energy savings potential, operational efficiencies and benefits from the wireless advanced lighting controls may be appealing to building owners, operators and tenants. The controls enable more active monitoring and management of the lighting system, including reporting issues and outages with light fixtures, a web-based controls interface, and other features. Any economic impact of these features is not quantified or included in the cost-effectiveness analysis.

Some occupant dissatisfaction with the advanced wireless controls was evident in post-retrofit survey results for Moss, likely resulting from specific implementation issues at this location. These included lamp failures due to the use of fluorescent lamps not seasoned for dimming, as well as the use of legacy occupancy sensors forcing old zoning schemes onto new work station and controls layouts. These types of issues are not necessarily reflective of shortcomings in the technology itself but are important "lessons learned" during the installation, commissioning, and early operation of the system (highlighted in the Occupant Satisfaction section), including engaging the controls vendor early to address occupant complaints, and identifying and addressing technical issues early to allay dissatisfaction, while avoiding blaming failures of old equipment on the new technology. The vendor has worked with building management representatives at Moss to improve system performance and increase occupant satisfaction, which should be the priority of any controls system installation. Continued system improvements at this location, and in future installations, are imperative for the technology to be a success. These issues point to the importance of prioritizing effective system design and implementation up-front to facilitate long-term lighting controls system acceptance and viability.

During the advanced wireless controls design, installation, and commissioning process, clear communication of design intent is essential for a successful retrofit. For example, verifying how fixtures should be zoned such that they corresponded with how occupants actually use the space is critical. The details of what constitutes final commissioning must be agreed to by the vendor, contractor, and property manager so that the final, commissioned system is effective, energy-efficient, and satisfactory from the tenants' perspective. In specifying wireless advanced lighting controls, product quality also should be emphasized, including robust product warranties that help ensure system performance for the longer term. Other aspects of system performance and quality assurance, such as reliable communication between the network's components and system hosting, also should be stressed during product specification, though more detailed quality specifications of this nature are beyond the scope of this study.

GSA manages over 370 million square feet of building space and could roll out wireless advanced lighting controls on a vast scale. Cost reductions and efficiencies at such a scale would surely follow, but undertaking a broad retrofit program would only make sense if the energy savings and other performance benefits justified the cost. Again, baseline lighting system operation and energy usage is fundamental in determining whether advanced lighting controls make economic sense, so a good understanding of the existing lighting systems in candidate buildings is imperative. Finally, though cost-effectiveness is an important factor in deciding whether energy-savings advanced lighting controls projects will move forward, other motivations also may play a role, such as regulatory requirements on energy efficiency, GSA's energy and environmental objectives, and non-energy operational benefits associated with centrally managed wirelessly networked lighting systems.

II. Introduction

A. PROBLEM STATEMENT

Awareness of the economic costs and environmental consequences of electric energy use in buildings is steadily growing. Effective energy-efficiency measures for reducing energy consumption in buildings are becoming increasingly important strategies for managing these impacts. In the United States, commercial buildings are responsible for over a third of the total end-use electricity consumed (U.S. Energy Information Administration, 2012a). Within commercial buildings in the United States, lighting accounts for 26% of the electricity used, representing a large potential source of energy savings (Navigant Consulting Inc., 2012a; U.S. Department of Energy, 2012). Some lighting energy savings have been achieved through the wide proliferation of efficient fluorescent lamps and ballasts in the past several decades. However, as the search for greater reductions in energy consumption continues, advanced wireless lighting controls are increasingly being implemented in new and retrofit building designs to save energy.

Advanced lighting controls reduce energy consumption by providing the necessary light levels when and where needed. Although building energy codes, such as the longtime standard ASHRAE 90.1-2007, have specifications for lighting controls, these are generally for large-scale scheduling and occupancy sensor requirements only for large groups of fixtures in certain space types.[2] The 2010 ASHRAE 90.1 revision has gone even further, however, including automatic lighting shut-off for all building sizes, more occupancy sensor requirements, and various multi-level or dimming controls and daylighting requirements.

Currently available advanced lighting controls include continuous dimming, institutional tuning, occupancy sensing, and daylight harvesting, among others. These control strategies offer greater flexibility and higher granularity of control, which gives operators the ability to modify the lighting system configuration in response to building policies, occupancy patterns, daylight availability, and personal preferences, allowing for greater energy savings. Advanced lighting controls also provide lighting systems with the ability to modify energy use dynamically in response to grid demands, which may result in added cost benefits from demand response programs. Wireless advanced lighting controls that use radio frequency communications to relay controls commands rather than line- or low-voltage wiring have the potential benefit of reducing installation time and labor costs during a retrofit in comparison to wired control systems, due to eliminating the need for long wire runs and minimizing work above the ceiling. Wireless lighting controls protocols also can provide more redundant communication pathways (such as mesh networking) and some systems include two-way communication between light fixtures and a system server to help operators monitor and trend lighting operation and identify operational issues through software such as web browser interfaces. Additionally, controls manufacturers are developing strategic partnerships with fixture manufacturers to embed their sensors, controls and communications componentry directly into the luminaires at the factory at a much lower cost than previously experienced through field installations using higher priced electricians. This trend can further drive down overall advanced lighting controls system cost and accelerate technology adoption.

[2] ASHRAE 90.1-2007 requires some form of automatic lighting shut off in buildings > 5,000 ft^2; and installation of an occupancy sensor or a time switch that turns lighting off 30 minutes after the last occupant leaves the space for certain classrooms, conference and meeting rooms, and employee lunch and break rooms (section 9.4.1).

Despite these benefits, and the increasing availability of advanced lighting controls and wireless controls options, wide deployment has not occurred to date. Only 2% of commercial buildings in the U.S. even employ photosensors for daylighting control and only 1% have installed energy management and lighting control systems (Williams, *et al.*, 2011). Some of the advanced lighting controls adoption barriers are unfamiliarity with the technology and higher complexity relative to standard controls options, as well as higher initial costs. As technology innovations are made, pushed by government investments, code and standards development, and other market drivers, wireless advanced lighting controls are expected to see a decline in retail prices concurrent with improvements in technology performance.

B. OPPORTUNITY

This Green Proving Ground (GPG) program study examines whether and how wireless advanced lighting controls can play a role in decreasing energy consumption in existing commercial buildings, while upgrading the efficiency, management, and quality of a lighting system. In response to executive orders and other mandates, GSA continues to identify and utilize sustainable technologies that will reduce the energy and carbon footprint of Federal buildings throughout the U.S. The GSA Public Buildings Service (PBS) has jurisdiction, custody or control over more than 9,600 assets and is responsible for managing an inventory of diverse building types, totaling more than 370 million square feet of building space for over one million federal employees. Due to its wide influence, GSA recognizes the leadership role it plays in encouraging the implementation of "innovative, cost-effective, and sustainable solutions for federal agencies" (U.S. General Services Administration, 2013). As part of these efforts, GSA is mandated to meet ambitious energy targets by 2015 and greenhouse gas reductions by 2020. Since the large majority of GSA's buildings consist of office space, the GPG program has identified cost-effective, energy-efficient lighting solutions as a priority focus area for its 2012 program.

As stated previously, a large opportunity exists to reduce the United States' electricity consumption by upgrading lighting systems within the commercial buildings sector. Of the estimated total U.S. site electricity consumption of 3,500 terawatt-hours (TWh) in 2010, the Energy Information Administration (EIA) estimated that lighting technologies in the commercial sector were responsible for 346 TWh, or approximately 50% of all lighting electricity consumption, across 81.2 billion square feet of floor space. Taking into consideration efficacies, wattages, and operating hours, the commercial building sector lighting inventory provides 17,370 Teralumen-hour (Tlm-hr) of lighting service, defined as the product of a light level (lumen) and the annual hours of operation. As a result of comparatively high annual operating hours, the commercial building sector accounts for approximately 60% of a total of 29,000 Tlm-hr of lighting service from all sectors in 2010 (Navigant Consulting, Inc., 2012b). Installing advanced lighting controls has previously been found to deliver 30% or greater lighting energy savings compared to the national office average of 4.1 $kWh/ft^2/year$, with an installation cost of around $\$7.00/ft^2$. To achieve a successful cost-effective installation, new lighting controls will need to increase energy savings up to 80%, and reduce installation costs to $\$2.00/ft^2$ by 2020 (Rubinstein, 2012).

In FY 2011, GSA directly paid building utilities for over 2.7 million megawatt-hours (MWh) of electricity, at a cost of over $300 million and equivalent to emissions of 1.8 million metric tons of carbon dioxide ($CO_{2,eq}$). Assuming that GSA's commercial building lighting energy usage is similar to national averages, lighting comprises 26% of the electricity consumption, or approximately 700,000 MWh. Advanced lighting controls are not implemented on most lighting systems in GSA buildings. There is considerable potential for implementation of advanced lighting controls in these buildings to achieve lighting energy savings. At a very broad level, if advanced lighting controls were widely adopted across the GSA building portfolio and controls-based lighting energy savings of 30% were achieved total annual energy savings would be on the order of 211,000 MWh.

However, in order to accurately predict performance of, and potential savings from advanced controls, it is important to test technologies in real life applications. This GPG study assesses the performance of an wireless advanced lighting controls solution currently on the market. This study also explores the cost and energy savings implications of future deployments of this technology. This report provides results from two demonstration locations; one that assessed advanced wireless controls retrofitted to existing fluorescent fixtures (with new dimmable ballasts added), and one that assessed wireless advanced lighting controls and LED fixtures installed together. Applying the same study methodology and analysis to the sites studied, cross-site comparisons provide insight into how the implemented systems performed and how future implementations might reach the greatest cost and energy savings while achieving occupant satisfaction.

III. Project and Technology Overview

This GPG program study evaluates the energy savings, cost-effectiveness, photometric performance and occupant satisfaction associated with wireless advanced lighting controls. Advanced wireless controls were installed on existing fluorescent light fixtures in one study location and were installed with new LED fixtures replacing fluorescent fixtures in another location. This assessment compares the installation and performance of the advanced lighting controls, with and without the LED retrofit, to the lighting and controls systems in place before the retrofits. Advanced lighting control strategies included institutional tuning, occupancy sensing and daylight harvesting. These strategies will be discussed further in the sections below.

A. TECHNOLOGY DESCRIPTION

WIRELESS ADVANCED LIGHTING CONTROLS

Advanced lighting controls are an effective technology for reducing building energy consumption and increasing lighting system efficiency, giving users greater ability to manage lighting loads and provide appropriate levels where and when needed. Lighting management systems grew from the development of early automated building control systems spurred by the energy crisis in the early 1970s, which initially focused on heating, ventilation, and air conditioning (HVAC) systems (Kastner *et al*., 2005). Since the 1970s, automated systems have expanded to include data acquisition and management services that could be controlled from a central location. Recent building codes, such as California Energy Commission (CEC) Title 24 and ASHRAE/IES 90.1-2010, have placed a greater emphasis on energy savings from lighting technologies and operation, further encouraging the adoption of lighting controls.

Traditional lighting systems use manual switches or simple controls, such as automated on-off scheduling, to control large fixture groups or entire office floors. Even where standard occupancy sensors are installed, the switching generally occurs across large zones of fixtures within a building, rather than at the individual workstation level. Advanced lighting control systems, by comparison, employ a variety of design and control approaches to better match light conditions to occupant needs, while not wasting energy where lighting is not needed and to do so at much higher spatial and temporal resolution than traditional controls. Advanced controls can reduce light when not needed, increase light levels where required, and give users greater control over workplace light levels. Such systems also often provide a centralized means of managing and monitoring lighting usage, set points and schedules.

Advanced controls include a multitude of control strategies. This study focuses on the following specific strategies:

- **Institutional tuning:** Institutional tuning allows building managers and tenants to decrease energy consumption by programming default light levels and ranges within the lighting management system that reflect area or building policies, or both. Energy savings can be generated by setting default light levels as well as maximum allowable levels below full output across each zone.

- **Occupancy sensing:** Occupancy sensors reduce electrical consumption by lowering light levels or turning lights off in an area when occupants leave a control zone. Electrical demand can be reduced by taking advantage of variable occupancy patterns within individual zones throughout an office or building.

- **Daylight harvesting:** Daylight harvesting allows lighting systems to reduce lighting energy by taking advantage of the available natural light. Photosensors detect the level of natural illumination in the area and adjust the electric light output level to achieve a target lighting level.

Several past studies have evaluated the impact of advanced lighting controls on energy use and occupant satisfaction. A meta-analysis of energy savings in commercial buildings presented in current literature conducted by Williams and others assessed the effects of various lighting controls strategies: occupancy sensing, daylight sensing, personal tuning, and institutional tuning (Williams *et al*., 2011). It was found that on average, employing each control technique independently and in combination produced energy savings of 36% for institutional tuning, 24% for occupancy sensors, 31% for personal dimming control, 28% for daylighting controls, and 38% when control strategies are combined.

Despite energy saving potential, the adoption of advanced lighting controls has been slow due to a number of barriers. One of the biggest barriers is high installation costs for both materials and labor. A previous project conducted in 2012 with GSA under the Commercial Buildings Partnership (CBP) program highlighted this during its investigation of advanced lighting controls retrofits (with institutional tuning, occupancy sensing, and limited personal control) at ten office buildings within California and Nevada. The retrofits achieved an average energy savings of around 1.5 kWh/ft^2/year and calculated annual energy cost savings ranging from 26 - 66%. However, high project costs resulted in only two of the ten installations being found cost-effective (savings-to-investment ratios greater than one). Importantly, these installations replaced the entire lighting systems in the buildings with workstation-specific light fixtures rather than just controls, thereby significantly increasing costs. The wired controls systems implemented also required communication cabling runs between all control points, increasing both labor and material costs (Wei *et al*., 2012).

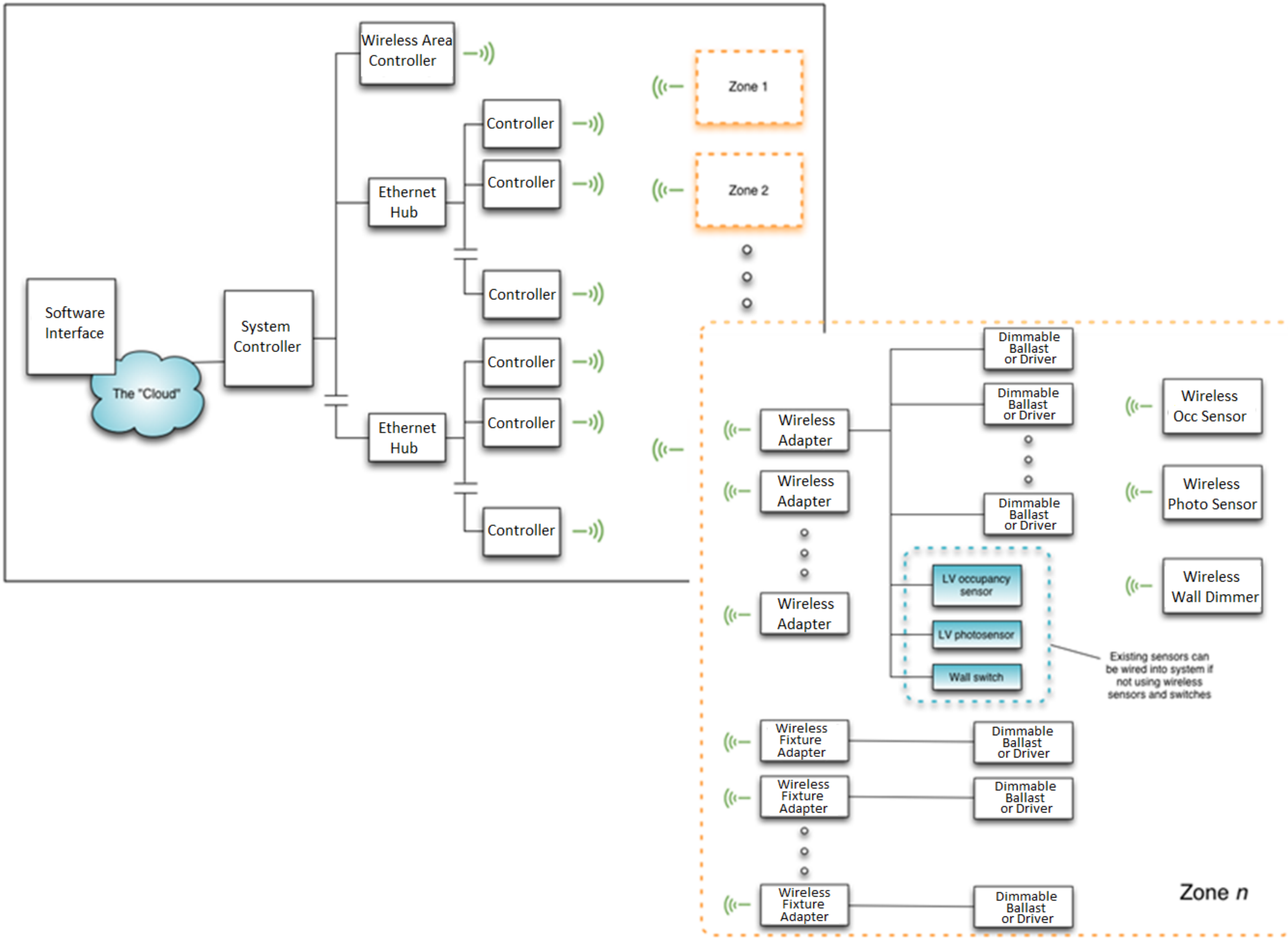
Wireless lighting control systems now available are meant to simplify the installation process and potentially reduce material and labor costs by removing the controls wiring component. Wireless radio frequency (RF) lighting controls were primarily installed in the residential sector until recent improvements in the reliability of radio-based technologies and the development of wireless mesh network standards allowed manufacturers to begin providing commercial applications (Crane, 2013). Wireless mesh networks are comprised of a number of devices that can repeat messages and route communication via multiple paths, typically using the most efficient communication path available. This provides signal redundancy, improved communication range, and lessens signal degradation between devices spread over a large area. Mesh networks also can be programmed to “self-heal”; if any communication point in the network fails, the signal can automatically be re-routed to another point in range. For this reason, a mesh network can be a robust strategy for controlling a system with large numbers of devices and control points, such as commercial lighting systems.

There is a spectrum of lighting controls configurations encompassed by the terms wired and wireless. Wired lighting controls include basic wall switches as well as automated timers or scheduling devices that interrupt mains power to lighting fixtures. Wired controls can also include low voltage relay panels that require low voltage wire runs from switches, sensors, and / or building management system to lighting relay panels that supply and interrupt power to groups of fixtures.

Wireless advanced controls require fixtures that are equipped with dimmable ballasts or drivers. Those ballasts or drivers can have wireless transceivers and on/off relays integrated into the hardware to accept wireless commands from central radios and/or wireless sensors and switches. This is the presumed approach for wireless advanced lighting controls retrofits and new construction projects in the future, as the integrated controller model is expected to become more common in the future. An alternate design approach, common today and the one employed by the technology demonstrated in this study, is to transmit wireless communications to wireless fixture controllers installed in the control space. Typically fixture controllers are powered by the lighting circuits and interrupt mains power to individual fixtures or groups of fixtures with on/off relays that are wirelessly controlled. To transmit dimming commands to the fixtures, the controllers must also be wired via low voltage cabling to nearby ballasts or drivers, either for individual fixtures or small groups of fixtures. For this design approach, the wireless controls system is really a hybrid wired / wireless system, though such systems are usually still termed wireless controls.

The advanced control strategies implemented in the study locations include institutional tuning, occupancy sensing, daylight harvesting, and enhanced personal controls (dimming and on/off switches). A basic schematic of the advanced wireless lighting control system installed for this study can be seen in Figure 6.

Figure 6: Schematic design of the wireless control system studied



Wireless advanced lighting controls systems are still fairly new to the market so specifier/contractor/supplier unfamiliarity tends to drive up installation time and costs. Current installations also typically require a combination of wired and wireless components, which dampens the ease-of-installation benefits provided by an all-wireless system. In the next five years, manufacturers are expected to bundle radio components and controls with the fixture ballast or driver as part of a more complete solution to help reduce installation complexity (Crane, 2013). As advanced wireless lighting systems become more streamlined and the marketplace continues to grow, installers' and users' comfort level with this technology should continue to increase.

LED FIXTURES AND WIRELESS ADVANCED LIGHTING CONTROLS

Since the advent of high-brightness LEDs to provide white-light useful for general lighting around the year 2000, a large amount of research and development has been focused on improving the performance of white-light LEDs in terms of efficacy (lumens per watt), light output, lifetime, control, and optical design. With these advances, LEDs are finally becoming competitive with conventional light sources (Wei & Houser, 2012). LED fixtures have several benefits over conventional general lighting technologies, including greater efficacies, longer lifetimes, improved directionality and adaptability, and higher quality of light. There are currently several types of LED products on the general lighting market to replace linear fluorescent fixtures common in commercial lighting. There are LED lamp options with the same form factor as T8 fluorescent lamps, as well as LED retrofit kits that fit into existing fluorescent fixture housing but replace the original fixture optical assembly. Finally, there are integrated LED fixtures that entirely take the place of fluorescent fixtures (Brodrick, 2013a).

LED lighting for general illumination applications is evolving in technical readiness in parallel with wireless advanced lighting controls for enhanced and more energy-efficient lighting operation. Fortunately, LED technology is well-suited for advanced wireless controls strategies. LEDs are normally operated on direct current and are inherently dimmable as a solid state light source, though a variety of dimming controls approaches are available, so LED compatibility with a given system must be verified. Fluorescent lighting traditionally used in commercial lighting applications is a little more challenging to operate with wireless controls. Standard fluorescent ballasts are not designed for dimming controls. Dimming fluorescent systems must use rapid start ballast technology in which the lamp cathode is always heated at some level to maintain an arc in the tube to allow the lamps to dim. New ballasts and lamps conditioned for dimming normally need to be installed with a dimming controls upgrade. Also, frequent or rapid on/off cycling, which can happen with occupancy sensor control, can cause fluorescent lamps to fail early (though programmed rapid start ballasts can help mitigate this), whereas LEDs are much less sensitive to cycling issues. As such, LED fixtures and advanced wireless controls would seem to be a natural fit technologically. In fact, several leading manufacturers of LED fixtures are now offering integrated sensors and dimming functions in their commercial LED fixture offerings.

B. PROJECT OBJECTIVES

This GPG study on wireless advanced lighting controls technology evaluates the energy savings, cost-effectiveness, photometric performance, and occupant satisfaction associated with advanced wireless controls retrofits on fluorescent fixtures and wireless controls installed in conjunction with LED fixture retrofits. This study compares the baseline lighting and controls systems' performance at the study locations to the retrofit technologies. This study focused on the following key objectives for each demonstration:

- Quantify and understand the energy savings, light condition changes, light maintenance improvements, and occupant satisfaction changes associated with the retrofit;
- Evaluate the cost-effectiveness of the retrofit, taking into consideration cost values for deployments in the future; and
- Evaluate implementation, commissioning, and operation and demonstrate whether wireless advanced lighting controls can be installed in a turnkey fashion with reliable performance.

ENERGY SAVINGS

The purpose of performing an energy savings and cost-effectiveness analysis for an energy-efficiency measure is to determine whether the value of the future energy savings and any other benefits from the measure justifies the expense of implementing it. To carry out this analysis on wireless advanced lighting controls, energy usage and savings were determined by metering lighting circuit energy for the study areas during pre-retrofit and post-retrofit stages. Trend data from the wireless lighting controls system also was processed for a more detailed analysis of energy savings from the various advanced controls strategies.

Energy savings are presented in the form of energy use intensities (EUIs) normalized by project square footage to compare results across studies. Greenhouse gas (GHG) emissions savings also are assessed by calculating the reduction in global warming effect (GWE) due to energy savings at each site, providing insight into the environmental benefits of implementing the efficient lighting controls.

Table 3: Description of metrics used in energy savings analysis of the lighting system

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).
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 or kilowatt-hours per square foot per year.
Workplane Efficacy	A metric for quantifying the lumens available at the surface where visual tasks are performed per unit of power consumed. This metric helps describe the energy efficiency of a fixture and allows for relevant comparison between fixtures with different light output. In this study, the workplane is taken to be the desk surface. WLE is usually calculated in lumens per watt.
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 (in foot-candles) and color characteristics for an office lighting environment, illuminance, spectral distributions, and color rendering indices (CRIs) from the pre- and post-retrofit systems were measured (Table 4). Appropriate light levels at the work plane in the study locations are defined to be at or above 30 fc, the Illuminating Engineering Society's (IES) acceptable light level for a typical office space. GSA's latest Facility Standard P-100, newly released in 2014, refers to the IES Handbook for light level requirements.[3] In considering whether the lighting color quality was acceptable, GSA considers CRIs above 80 to be appropriate.

Table 4: Description of metrics used in photometric assessment of the lighting system

Metric	Definition
Illuminance	The density of incident luminous flux 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 8 are pastels (R_1-R_8), the next 4 consist of saturated solids (R_9-R_{12}), and the last 2 represent earth tones (R_{13} and R_{14}). CRI is calculated as an average of the renderings of R_1 – R_8, covering relatively low saturated covers evenly distributed over the complete range of hues. This study focuses on general CRI as well as R_9, associated with strong red tones. R_9 is an important additional CRI to consider as strong reds are prevalent in skin tones and indicates whether the light source will be perceived as warm.
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).

[3] 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 PBS. 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

OCCUPANT SATISFACTION

Measuring energy savings and photometric qualities helps to quantify the technical 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 40% or more was targeted. Anonymity of responses was enforced and free response boxes were provided to encourage a more complete understanding of successes and challenges the occupants experienced with the lighting systems.

COST-EFFECTIVENESS

The cost-effectiveness analysis provides simple payback periods (SPP) and savings to investment ratios (SIRs) for the implementation of the controls and fixture retrofits (Table 5). Costs are normalized by floor area to compare results across studies. The cost-effectiveness analysis also takes into consideration estimated future technology price reductions to gain insight into whether delayed large-scale deployment is recommended.

Table 5: Description of metrics used in lighting system cost-effectiveness analysis

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 savings at the site per year.
Savings to Investment Ratio (SIR)	Characterizes cost-effectiveness by determining the ratio of life-cycle savings from an energy improvement 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.

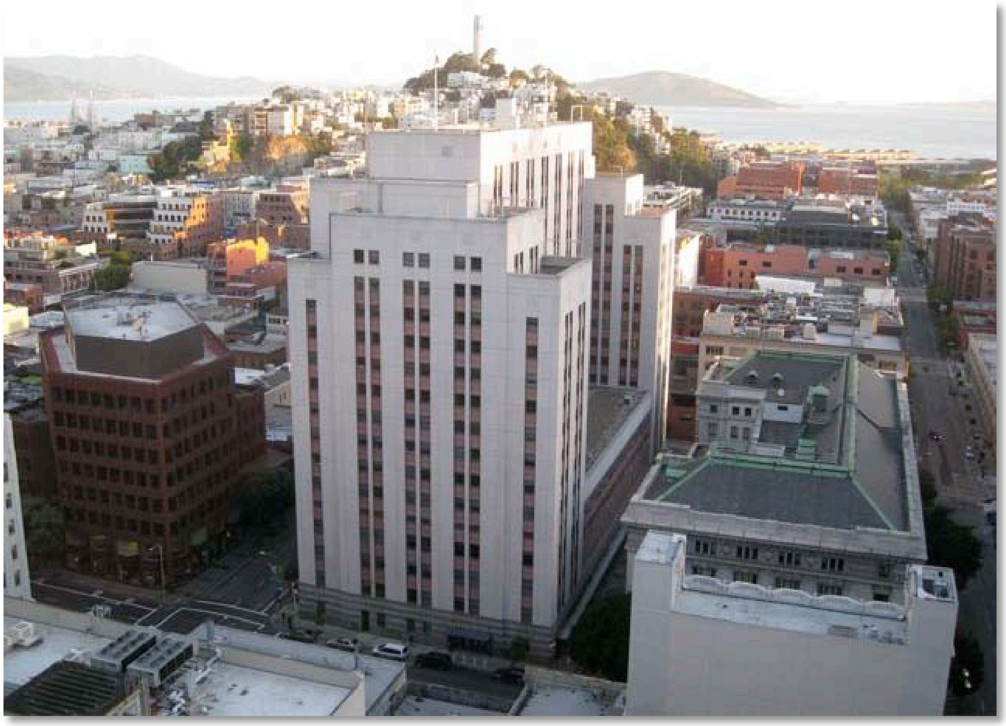
C. DEMONSTRATIONS LOCATIONS

GSA chose two buildings for GPG program demonstrations of wireless advanced lighting controls. The Appraisers Building in San Francisco, CA, was chosen for an advanced wireless lighting control retrofit combined with installation of LED fixtures to replace fluorescent fixtures. A wireless advanced lighting controls retrofit on existing fluorescent fixtures was implemented at the Moss Federal Building in Sacramento, CA.

UNITED STATES IMMIGRATION STATION AND APPRAISERS STORES, SAN FRANCISCO, CA

The United States Immigration Station and Appraisers Stores (commonly referred to as the Appraisers Building) is a 16-story building located in San Francisco, California, and completed in 1944. The exterior of the building is predominantly concrete with long swaths of vertical windows.

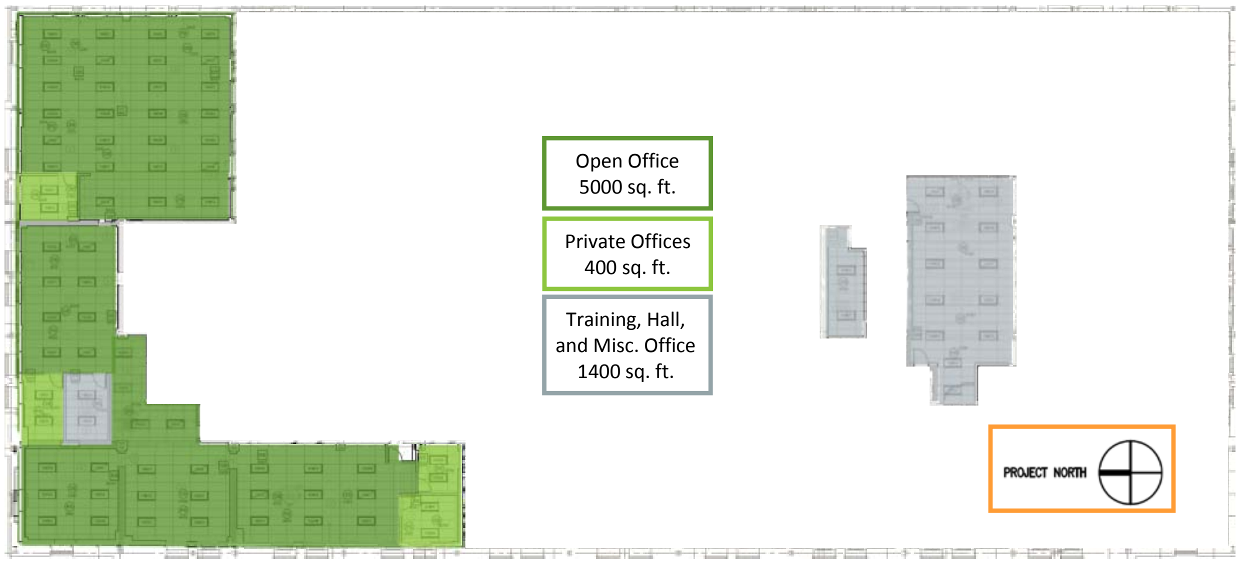
Figure 7: Photo of the exterior of the Appraisers building[4]



The study area consists of five open office areas, three private offices, a reception room, two storage rooms, and corresponding corridors located in the north portion of the third floor, as well as a training room in the interior of the south side. The demonstration area covers approximately 6,800 square feet and includes 33 workstations, with ceiling heights around 9 feet. Occupants perform primarily paperwork and desk/computer work. From GSA communication, typical operating hours were between 6:30 AM and 4:30 PM. During work hours, 60-70% of the workstations were typically occupied.

[4] Photo Credit: Gary Brechin from The Living New Deal website. Accessed 11/14/2012. http://livingnewdeal.berkeley.edu/projects/u-s-appraisers-building-san-francisco-ca/

Figure 8: Appraisers site floor areas and fixture layout



Appraisers' pre-retrofit overhead lighting system was comprised of the following fixtures:

- **Existing lighting fixtures** included 84 recessed 2' x 4' fluorescent fixtures with parabolic louvers dividing the fixture aperture into 18 cells. Fixtures were typically spaced 8' x 10' on center and were designed for 3 F32T8 lamps. Of these fixtures, 14 were emergency fixtures. The pre-retrofit overhead lighting system was found to have an installed LPD of 0.97 W/ft^2, accounting for the effect of two lamps that were found to not be functioning during a pre-retrofit visit. With those lamps functioning, the installed LPD would have increased slightly to 0.98 W/ft^2.

- **Existing lighting controls** included both occupancy sensors and manual switches. Occupancy switches were located throughout the open office area with timeouts of approximately 5 minutes. The open office area in the northeast section was operated with manual switches as the occupancy sensors were not working properly. Private offices were controlled via manual switches with built-in occupancy sensors. There was no scheduler or building automation system (BAS) that controlled the lighting and no fixtures had dimming capabilities.

- **Windows** for the floor are 5 feet wide by 7 feet tall and are located in pairs along the perimeter, approximately 23 feet apart on center, providing significant opportunity for daylight harvesting in the north and west sections of the study area. Buildings adjacent to the Appraisers Building obstruct the majority of the daylight on the lower floors along the east perimeter.

JOHN E. MOSS FEDERAL BUILDING, SACRAMENTO, CA

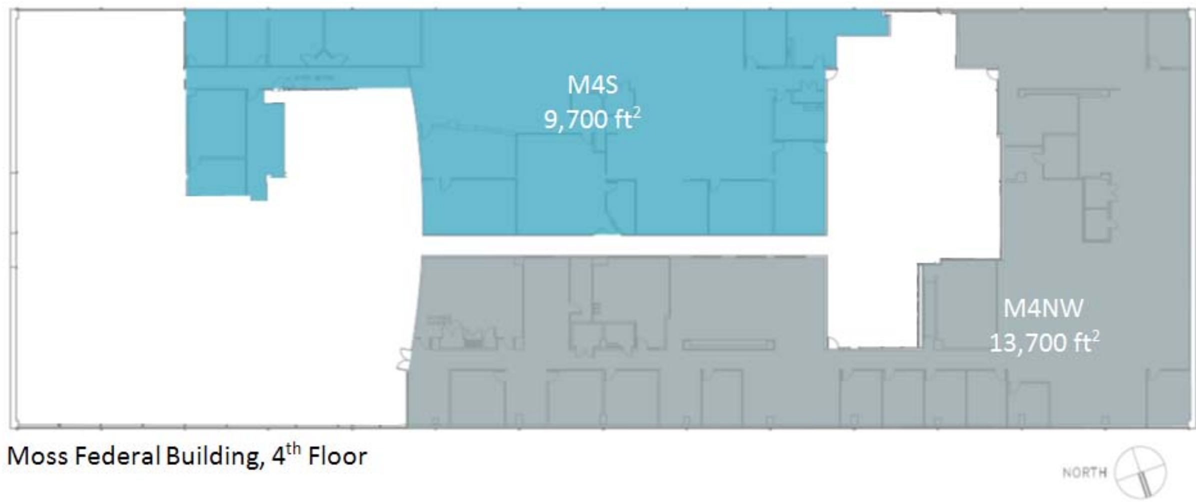
The John E. Moss Federal Building (Moss) was completed in 1961 and is an eight-story high-rise located in Sacramento, CA. The concrete building has a long rectangular footprint with the long axis oriented east-west (Figure 9). Horizontal swaths of windows dominate the north and south walls, while the east and west walls are windowless. Wireless lighting controls were installed throughout the 4th and 6th floors of Moss on the existing fluorescent lighting fixtures. Ballasts were retrofitted to dimming ballasts for compatibility with the advanced lighting system.

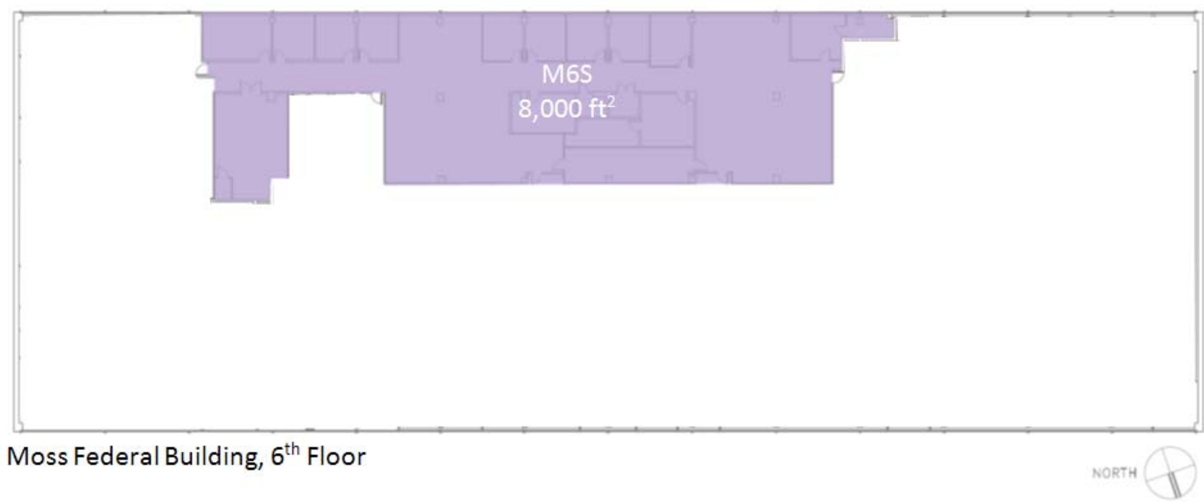
Figure 9: Photo of the exterior of the Moss Federal Building[5]

The advanced wireless controls studied here were installed throughout the 4th and 6th floors of Moss. However, this study focused on three sites on the 4th and 6th floor areas based on accessibility and tenant acceptance of the study activities. As a federal building, Moss hosts various different federal agencies as tenants on each floor. This study defines the sites at this location as agency-specific sections of the building that occupy a large portion of a floor, with each site housing a different agency. The sites are located in the northwest portion of the 4th floor (M4NW), along the south wall of the 4th floor (M4S), and along the south wall of the 6th floor (M6S) (Figure 10).

[5] Photo Credit: Foursquare website. Accessed 6/01/2014. https://foursquare.com/v/john-e-moss-federal-building/4bbb8f90e45295217dda54a4

Figure 10: Moss site locations





Sites predominately included open office plan areas, private offices, corridors, and conference rooms. However, other space types such as break rooms, storage and transition spaces, were sometimes included. Table 6 summarizes key characteristics for each site.

Table 6: Moss site characteristics

Site	Approximate floor area (ft^2)	Description of work spaces	Schedule
Moss FB, 4th Floor, NW section (M4NW)	13,700	Large open office area with 11 private offices, reception room, conference rooms, and 57 active workstations.	6 AM to 6 PM
Moss FB, 4th Floor, S section (M4S)	9,690	Large open office area with a few private offices and several misc. areas, training and conference rooms, and 23 active workstations.	6 AM to 6 PM
Moss FB, 6th Floor, S section (M4S)	8,020	12 private perimeter offices with a few small open office areas. 10 active workstations, a conference room, a break room, and a few storage areas.	7 AM to 4:30 PM

The LPDs for each site were calculated based on the square footage of the locations and the number of fixtures and operating lamps found during site visits. If all ballasts and lamps were functional, the installed LPD was slightly altered. Table 7 lists the pre-retrofit installed LPD of the sites as found, and the installed LPD if all ballasts and lamps had been properly functioning.

Table 7: Moss pre-retrofit installed LPD

Site	Installed LPD as-found (W/ft^2)	Installed LPD with all lamps functioning (W/ft^2)
M4NW	1.01	1.10
M4S	1.21	1.22
M6S	0.90	0.97

Pre-retrofit overhead lighting and controls varied across the Moss sites. In general, the existing pre-retrofit lighting systems consisted of recessed fluorescent fixtures that were regularly spaced in open areas and large rooms or distributed based on layout in private offices. There were no dimmable ballasts or photocells in use at any of the study areas prior to the retrofits. Typical linear fluorescent lamps were 3500K, 32 watts, and rated around 2800 lumens. All three demonstration locations already employed some occupancy sensors, typically in private offices and other enclosed areas, and two of the three locations also employed occupancy sensors in open office areas. Two of the sites maintained scheduled shutoffs or sweeps in the evening to turn off lights after operating hours. Task lighting varied from site to site and was not included in monitoring and analysis, as task lighting did not change during the retrofits.

Table 8: Moss site lighting and controls systems

Site	Fixtures	Controls
Moss FB, 4th Floor, NW section (M4NW)	90 recessed 2' x 4' and 27 recessed 2' x 2' parabolic troffers, as well as 47 other fixtures, including recessed can lights and suspended 1' x 4' fixtures	Open office manual switches and occupancy sensors, and a scheduler that turned lights off at 8 PM, with override switches. Private offices had ceiling mounted occupancy sensors and manual switches for bi-level control.
Moss FB, 4th Floor, S section (M4S)	108 recessed 2' x 2' fixtures, as well as 31 other fixtures, including recessed can lights and circular drop fixtures	Open office areas were controlled by manual switches and occupancy sensors. Private offices had manual switches and occupancy sensors. No automated schedulers.
Moss FB, 6th Floor, S section (M4S)	79 recessed 2' x 4' fixtures, as well as 31 can lights	Open office manual switches and scheduled shut off at 6PM, with override switches. Private offices had manual switches and occupancy sensors.

D. TECHNOLOGY DEPLOYMENT

Wireless advanced lighting controls were installed at the Appraisers and Moss locations. Key controls system components are described in Table 9. Advanced wireless controls zones were implemented such that fixtures were typically grouped four to six per zone, with all fixtures in the zone programmed to operate similarly. Designated control strategies for each zone were programmed based on feedback from the property manager. To control the fixtures, each dimmable ballast (fluorescent fixture) or driver (LED fixture) was wired to a wireless adapter. A photosensor was installed in each of the zones that were located on the perimeter of the building. Wireless occupancy sensors were installed such that there was at least one occupancy sensor in each zone.

At the Moss location, where possible, individual zone adapters were installed and wired to control multiple fixtures, essentially creating small wired zones. This "zonal" approach to installation reduces the number of adapters that need to be installed for the system, reducing the material cost of the project. In contrast to the zonal installation approach at Moss, a more granular approach was followed at Appraisers in which a wireless adapter was installed on each fixture in the study space. Individual fixtures adapters were then grouped together in the system software into logical control zones.

Table 9: Wireless lighting controls components of evaluated technology

Name	Description	Power Source
System controller	Standard system controller that communicates with and coordinates the wireless area controllers. The system controller also has the ability to log and store energy usage, system alerts, and event information.	Line voltage wiring
Area controller	Wireless area controller that communicates with sensors, switches, and lighting control devices to provide commissioning, control and management functions.	Low voltage DC powered either from a plug-in transformer or over the Ethernet cord.
Adapter	Plenum rated wireless adapter that enables 0-10V wireless multiple fixture control. Includes a 15A relay to switch ballasts/drivers and circuit. Also supports bi-level and alternate switching.	Line voltage wiring
Fixture adapter	Wireless fixture adapter that enables 0-10V (only) wireless control of fixtures. Includes a 3A relay to switch ballasts/drivers and circuit. This adapter is typically installed within a fixture and is therefore not plenum rated.	Line voltage wiring
Occupancy sensor	Wireless occupancy sensor with included photosensor. Occupancy sensor operates using passive infrared (PIR) sensing technology.	(2) Lithium-thionyl chloride batteries AA 3.6 V
Photosensor	Wireless photosensor that senses between 0.1 - 185.8 foot-candles.	(2) Lithium-thionyl chloride batteries AA 3.6 V
Wall dimmer	Wireless wall dimmer switch that turns lights on or off as well as dim or brighten lights.	(2) AAA 1.5 V batteries

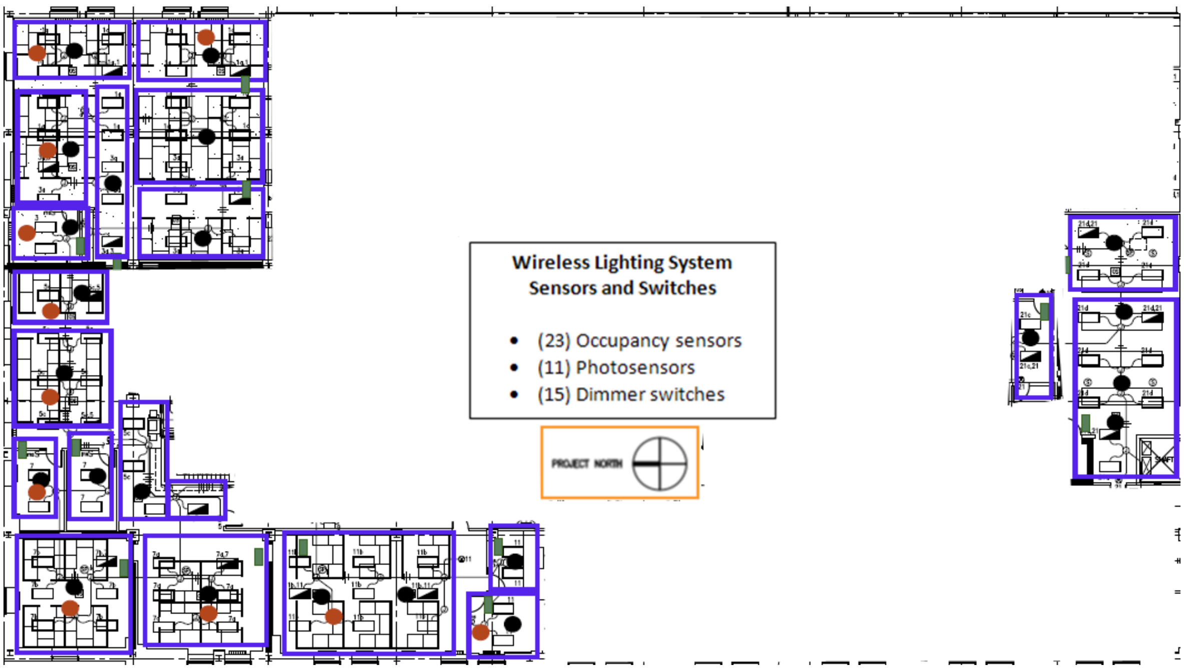
Controls installed in the private offices typically included a photosensor, if adjacent to a window, an occupancy sensor and a dimming switch. Enclosed areas that were neither along the perimeter nor daylit lacked an installed photosensor. In the open office areas, photosensors were distributed along the perimeter, while occupancy sensors and dimming switches were located at the zone level.

It should be noted that although many of the studied system components are wireless there are still key parts that require wiring. For example, Ethernet cables need to connect the area controller either directly to the system controller or to an Ethernet hub that is connected to the system controller, depending on the area controller's distance from the system controller. The fixture controller's low-voltage dimming signal wires also must be wired to the dimmable fluorescent ballast or LED driver.

A APPRAISERS CONTROLS CONFIGURATION

At the Appraisers study location, each fixture was outfitted with a wireless adapter to control on/off and dimming behavior. This one-to-one relationship between fixtures and wireless adapters is the most granular implementation option, allowing for maximum flexibility in configuration of control zones and behaviors, but requiring more hardware than installing single adapters for fixture zones or entire circuits. At Appraisers, fixtures were grouped together in the controls software into zones of two to eight fixtures that behave the same based on location and inputs from switches and sensors. In general, all zones were controlled via input from occupancy sensors and dimmer switches. One photosensor was installed per zone for zones located on the perimeter of the building. Existing occupancy sensors were replaced one-for-one with wireless occupancy sensors. Fixtures turned on and off automatically based on whether occupancy sensors detected occupants.

Figure 11: Appraisers post-retrofit lighting control zones



*Blue rectangles indicate individual control zones, red dots are photosensors, and black dots are occupancy sensors.

Details on the assigned control profiles can be found in Table 10. Strategy definitions outside of operating hours are italicized. Operating hours were defined to be Monday through Friday from 6:30 AM – 5:00 PM. The first commissioning of the controls system was completed in early May 2013. Based on monitoring of the lighting load and controls implementation, it was determined in the summer of 2013 that the controls programming should be fine-tuned to improve performance and energy savings. Fine-tuning of the controls programming was completed in August 2013. Changes to each control profile also are listed in Table 10.

Table 10: Appraisers control profiles

Space type	Preliminary control strategy definition	Configuration changes
Open office areas, private offices and other enclosed areas	• Zonal occupancy sensing turned lights on/off automatically with a 15 minute off delay. Lights turn on at previous on level. • Zonal dimming control with light levels restricted to 0 – 80% "intensity level" • Daylighting enabled if zone located along perimeter of building • Manual override of 60 minutes	• Time delay reduced to 10 minutes • Zonal dimming control maximum "intensity level" reduced to 65% • Manual override reduced to 15 minutes
Hallways	• Zonal occupancy sensing turned lights on/off automatically with a 15 minute off delay. • Occupied light level: 50% "intensity level" • Unoccupied light level at 20% "intensity level" (*0% "intensity level" outside of operating hours*) • Zonal dimming control with light levels restricted to 0 – 80% "intensity level" • Manual override of 60 minutes	• Time delay reduced to 10 minutes *(5 minute time delay outside of operating hours*) • Zonal dimming control maximum "intensity level" reduced to 65% (*raised to 100% light levels outside of operating hours*)

The Appraisers study area underwent a one-for-one replacement of existing fluorescent fixtures with LED fixtures (see Table 11) during the wireless advanced lighting controls study. LED retrofit kits were originally installed at the site, but were replaced with integrated LED fixtures after it was determined that the seismic bracing for the retrofit kits was insufficient. Unlike the retrofit kit, installing the LED fixtures requires the complete removal of the existing fluorescent recessed fixture. Although plenum access is required to install the integrated fixtures, the LED troffers were actually priced lower than the LED retrofit kits and were installed more quickly. The LED fixtures resulted in an installed LPD at the Appraisers location of 0.44 W/ft^2.

Table 11: Rated performance of LED fixture installed at Appraisers

Description	Input Power, W	Fixture Efficacy, lm/W	Photometric Information
2’x4’ fixture with continuous dimming from 100% to 5% with 0-10V DC control protocol	34	90	• Lumen Output: 3100 lumens (emergency backup – 1400 lumens) • Color temperature: 4000° Kelvin • CRI: 90 • Power factor: 0.9 nominal • Total harmonic distortion: <20%

B MOSS CONTROLS CONFIGURATION

Retrofit work at the Moss Federal Building began in February 2013 and extended through late July 2013. The lighting fixture layout and fixture counts were not altered during the retrofit. Lamp burnout issues arose when the new lighting system was installed and implemented. This is because fluorescent lamps that will be dimmed regularly must be conditioned before normal use, and the existing fluorescent lamps had not been conditioned and, as such, were not compatible with dimming strategies. Consequently, the Moss sites underwent a complete re-lamping.

In the Moss study locations, where possible, wireless adapters were installed in a zonal fashion such that one adapter was wired to several fixtures to implement on/off and dimming commands. This zonal implementation strategy requires less hardware and costs less than a more granular approach where one adapter is installed on every fixture, but allows for less flexibility in reconfiguring groups of fixtures later (all fixtures wired to a single adapter will always behave in the same manner). According to the technology vendor, the zonal installation approach is the most common method for installing the advanced wireless controls technology evaluated in this study.

In general, all fixture zones were configured to respond to input from nearby occupancy sensors and dimmer switches. Existing occupancy sensors were either wired to the nearest wireless adapters or replaced with wireless occupancy sensors. Fixtures were programmed to turn on and off or dim (during work hours) automatically based on whether the occupancy sensors detected zonal occupancy. Daylight harvesting was typically enabled if the zone was located along the perimeter of the building (near windows), unless otherwise requested.

Figure 12: Moss post-retrofit lighting control zones

*Blue rectangles indicate individual control zones, red dots are photosensors, and black dots are occupancy sensors.

Details on the assigned control profiles can be found in Table 12. The table lists control strategies for different space types after system commissioning on July 20, 2013. Operating hours were defined as Monday through Friday from 6:00 AM – 6:00 PM. Like Appraisers, after preliminary data analysis, it was determined that controls programming should be fine-tuned to improve performance and energy savings. Fine-tuning took place from September 18 - 30, 2013. Changes to each control profile also are listed. Strategy definitions outside of operating hours are italicized.

Table 12: Moss control profiles

Space type	Preliminary control strategy definition	Configuration changes
Open office areas	• Zonal occupancy sensing turn lights on/off automatically. Time delay of 10 minutes (*5 minutes outside of operating hours*) o Lights turn on to 80% "intensity level" if daylighting is not enabled • Zonal dimming control with light levels restricted to 20 – 80% "intensity level" (*0 - 80% outside of operating hours*) • Daylighting enabled in perimeter zones near windows • Manual override of 60 minutes	• Lights turn on to 65% "intensity level" if daylighting is not enabled (*50% light level outside of operating hours*) • Zonal dimming control for areas where daylighting is enabled restrict light levels to 20 - 65% "intensity level" (*0 - 65% outside of operating hours*)

Private offices	• Zonal occupancy sensing turn lights on/off automatically.
	   o If daylighting is not enabled: lights turn on to previous on level with an off time delay of 20 minutes (*5 minutes outside of operating hours*)
	   o If daylighting is enabled: off time delay of 10 minutes (*5 minutes outside of operating hours*)
	• Zonal dimming control with light levels restricted to 0 – 80% "intensity level"
	• Daylighting enabled in perimeter zones near windows
	• Manual override of 60 minutes
		• Lighting operation was switched to *manual on/auto off outside of operating hours*
		• If daylighting is not enabled: lights turn on to 55% "intensity level" with an off time delay of 10 minutes
		• Zonal dimming control with light levels restricted to 0-65% "intensity level" (*0 - 60% outside of operating hours*)

Conference rooms	• Zonal occupancy sensing turn lights on/off automatically at 80% "intensity level" with an off time delay of 10 minutes (*5 minutes outside of operating hours)* • Zonal dimming control with light levels restricted to 0 – 80% "intensity level" • Manual override of 120 minutes (*60 minutes outside of operating hours*)	• Zonal occupancy sensing turn lights on/off automatically at 60% "intensity level" with an off time delay of 10 minutes (*5 minutes outside of operating hours)* • Zonal dimming control with light levels restricted to 0 – 65% "intensity level" • Manual override of 60 minutes
Hallways	• Zonal occupancy sensing turn lights on/off automatically with a 10 minute off delay (*5 minutes outside of operating hours)* • Occupied light level: 60% "intensity level" • Unoccupied light level at 20% "intensity level" (*0% "dimming level" outside of operating hours*) • Zonal dimming control with light levels restricted to 0 – 100% "intensity level" • Manual override of 60 minutes	• Occupied light level: 40% "intensity level" • Zonal dimming control with light levels restricted to 0-60% "intensity level"

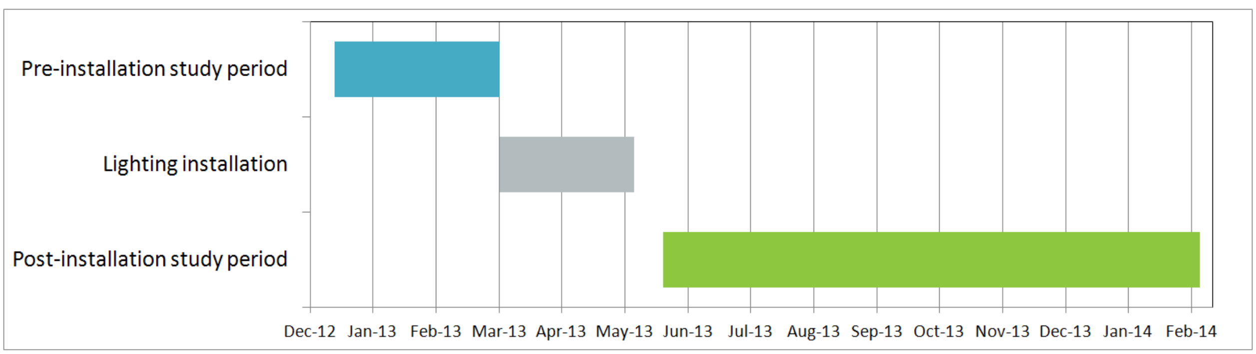
IV. Measurement and Verification Summary

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 installed technology effectiveness. Advanced wireless controls' performance verification also was performed at a test-bench level at LBNL during the study period. Experienced staff from LBNL performed the field work and conducted the assessments necessary for this study.

Appraisers Schedule

This GPG program study took place from December 2012 to February 2014 (Figure 13). The pre-retrofit study period extended until mid-February 2013, when the LED and advanced wireless controls installation occurred. The post-retrofit study period began in May 2013 and extended through February 6, 2014. Because the controls programming was adjusted in August 2013, only post-retrofit energy data from late August 2013 through the end of the study period was analyzed. Also, there are two lighting installation periods to consider because the LED retrofit kits first installed in the space were replaced with integrated LED fixtures in November 2013, due to seismic concerns.

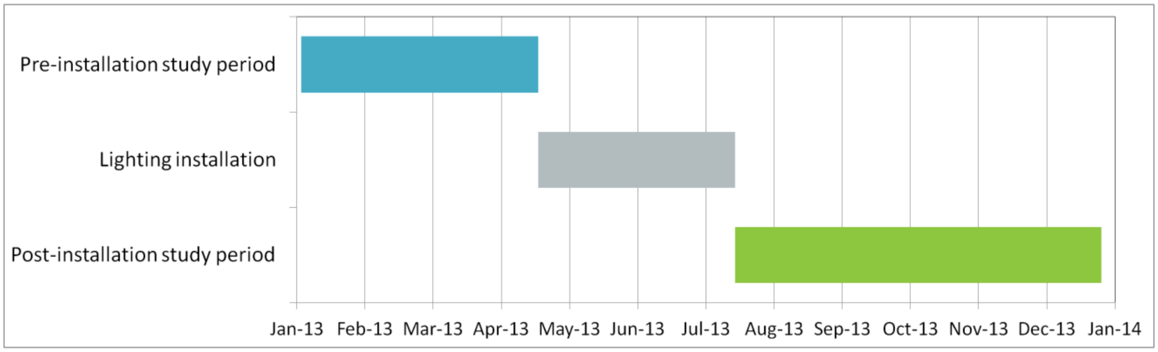
Figure 13: Appraisers wireless advanced lighting controls demonstration project timeline



Moss Schedule

The Moss GPG study took place from January 2013 to December 2013 (Figure 14). The pre-retrofit study period extended until mid-March to late April for the Moss sites depending on when the respective retrofits occurred. The post-retrofit study period began in mid-July and continued through mid-December 2013. Because the controls programming was adjusted in September 2013, only post-retrofit energy data from October 2013 through the end of the study period was analyzed.

Figure 14: Moss wireless advanced lighting controls demonstration project timeline



A. SITE CHARACTERIZATION

Pre- and post-retrofit site visits were performed at Appraisers on December 20, 2012, and June 12, 2013. A second post-retrofit visit was performed in February 2014 because the LED retrofit kits were replaced with integrated LED fixtures in November 2013. Pre- and post-retrofit site visits were performed at the Moss sites on January 30, 2013, and October 23, 2013. During the site visits, light levels and color characteristics were measured throughout the spaces and site characteristics were documented including workstation layout, partition heights, workspace dimensions, task lighting and overhead lighting layout and characteristics. Occupant schedules and work styles were recorded to the extent possible. Changes between pre- and post-retrofit site and occupant conditions also were documented.

B. ENERGY SAVINGS

MEASURED LIGHTING CIRCUIT DATA

To assess the energy savings achieved at each site, lighting energy usage at each site was measured during pre- and post-retrofit periods. The lighting branch circuits serving the study areas at Appraisers and Moss were monitored at the lighting panels. Circuits were traced or identified from as-built drawings. This study used power meters that recorded true power at a one-minute interval per the measurement and verification plan.

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 days included days when daylight savings time began or ended, days with incomplete or unusual power metering data (such as during power outages), days during which site work interfered with typical operation, and the last week of December (12/25/2012-1/2/2013). A government shutdown occurred in October from 10/1/2013 to 10/16/2013 that required occupants to go on furlough at Appraisers and at Moss locations M4S and M6S, so power metering data from these dates was excluded for these sites. The agency in M4NW was considered essential during the shutdown and its tenants continued working through the period, so data was included at M4NW during the government shutdown.

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

APPRAISERS

The original post-retrofit period for analysis began in late May 2013. However, the post-retrofit lighting controls system underwent a re-configuration in mid-August 2013 to improve performance and energy savings. Due to these changes, the final post-retrofit analysis considers metered data from August 26, 2013 on to characterize the energy savings after the control profile changes. Installed LPDs were determined using input watts measured from post-retrofit fixture testing and floor areas used were those areas served by the lighting circuits monitored.

Table 13: Appraisers pre- and post-retrofit power metering periods

Phase	Start Date	End Date	Weekdays	Weekend days	Holidays	Total Days
Pre-retrofit	12/15/2012	3/4/2013	42	22	5	69
Post-retrofit	8/26/2013	2/6/2014	85	41	8	134

MOSS

The pre-retrofit lighting system at the Moss Federal Building consisted of a large number of de-lamped fixtures or fixtures with burnt out lamps that had not been replaced. All fixtures were re-lamped during the retrofit, slightly changing the baseline lighting power density. To account for this change, an adjustment to the pre-retrofit metered power data was made to scale the data to what would have been measured for a fully lamped and functional lighting system. The percent difference between the installed LPD during the pre-characterization visit and the LPD if all lamps were functional was calculated and applied to the power metering data. Post-retrofit energy savings were then determined in relation to this adjusted baseline.

The post-retrofit lighting control system underwent a re-configuration from September 18-30, 2013, to improve performance and energy savings. The system was reconfigured so that fixture dimming for institutional tuning was increased and timeouts for occupancy sensors were shortened, causing the lights to dim or turn off more quickly when occupants vacate a space. Though the post-retrofit period originally started in late July 2013, the energy savings analysis considers metered data beginning in October 2013 to characterize the energy savings from the control profile changes. Due to a government shutdown that affected M4S and M6S (but not M4NW), the post-retrofit period for those sites does not begin until mid-October 2013.

Table 14: Moss pre- and post-retrofit power metering periods

Phase	Site	Start Date	End Date	Week-days	Weekend days	Holidays	Total Days
Pre-retrofit	Moss FB, 4th Floor, NW section	1/7/2013	4/1/2013	50	23	2	75
	Moss FB, 4th Floor, S section	1/7/2013	4/23/2013	64	29	2	95
	Moss FB, 6th Floor, S section	1/7/2013	3/18/2013	41	18	2	61
Post-retrofit	Moss FB, 4th Floor, NW section	10/1/2013	12/19/2013	51	21	4	76
	Moss FB, 4th Floor, S section	10/19/2013	12/19/2013	39	17	3	59
	Moss FB, 6th Floor, S section	10/19/2013	12/22/2013	40	19	3	62

CONTROLS SYSTEM DATA

The evaluated advanced lighting controls system is able to trend controls commands sent to the fixture controllers in each control zone. Compared to lighting circuit energy measurements, which aggregate all fixtures on the circuit into one data record (kWh per circuit, for example), controls information provides more granularity and detail about how fixtures are operating through the day at the smallest zone level. The data from the controls system can be used to analyze how the lighting controls features, such as occupancy sensor time-outs and daylight dimming, work in the study areas.

One month of advanced wireless controls system data was trended for three groups of fixtures (one in Appraisers and two in Moss) and was used to calculate average daily lighting power density and extrapolate to annual energy usage. To compare the lighting energy usage from the controls data to baseline lighting usage possibilities and to disaggregate savings from different controls strategies, parallel datasets were produced to represent various baseline controls scenarios (automated on/off zone schedules, zonal occupancy sensors, zonal occupancy sensors, and institutional tuning).

C. PHOTOMETRIC CHARACTERIZATION

Photometric characterizations were conducted for both open office and private office workspaces in order to characterize electric light levels, resulting in illuminance, spectral power distributions, and CRIs. Desktop illuminance measurements were taken at the assumed primary work area, characterized as the front edge of the main desk's center section. Objects directly obstructing the overhead lights were removed temporarily while the measurement was taken, but otherwise desktop objects and clutter were unmodified.

Task lights were typically turned off during measurements, but some measurements were taken with task lights turned on to approximate task light levels. If task lights were present, measurements were taken at the front, center edge of the primary and secondary workspace with the task lights on and off. The resulting median, quartile, minimum, and maximum pre-retrofit and post-retrofit light levels were compared.

D. OCCUPANT SATISFACTION SURVEY

Surveys were administered either online or by paper form (depending on site restrictions) and occupant responses were recorded anonymously. This survey contained 17 multiple choice questions that addressed satisfaction with lighting levels, lighting control, and lighting quality, including three free response boxes where respondents could provide their own comments. Occupants were asked to respond to qualitative questions about their workspace and overall office light conditions. If necessary, reminder emails were sent out to encourage more occupants to take the survey. Post-retrofit occupant satisfaction surveys were typically distributed 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.

V. Results

A. MEASURED ENERGY SAVINGS

APPRAISERS

Input power for the pre-retrofit and post-retrofit fixtures was measured on a test bench at LBNL. Based on the test bench measurements, the number of fixtures in the study space, and the square footage of the space, the pre-retrofit installed LPD was 0.97 W/ft^2. Based on measurements for the LED fixtures at full power, post-retrofit LPD was determined to be 0.44 W/ft^2. The installed maximum LPD in the study area decreased by 55% due to the switch from fluorescents to LED fixtures.

Table 15: Appraisers installed lighting power

Study Period	Floor area (ft^2)	Installed power (W)	Installed LPD, W/ft^2
Pre-retrofit	6,765	6,593	0.97
Post-retrofit		2,886	0.44

To assess the advanced lighting controls performance at this site, it was possible to exclude savings due to the LED lighting wattage reduction by scaling the post-retrofit energy data up by a factor equal to the pre-retrofit LPD divided by the post-retrofit LPD (0.97 W/ft^2/ 0.44 W/ft^2). The advanced wireless controls retrofit at Appraisers resulted in a significant reduction in lighting energy consumption as measured over time at the lighting circuit level. Annual energy savings from the controls was calculated to be 32.3%.

Table 16: Appraisers pre- and post-retrofit energy use 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	8.8	0.9	0.4	2.3
Post-retrofit	5.7	1.1	2.0	1.6
% Savings	35.3%	-20.8%	-453.7%	32.3%

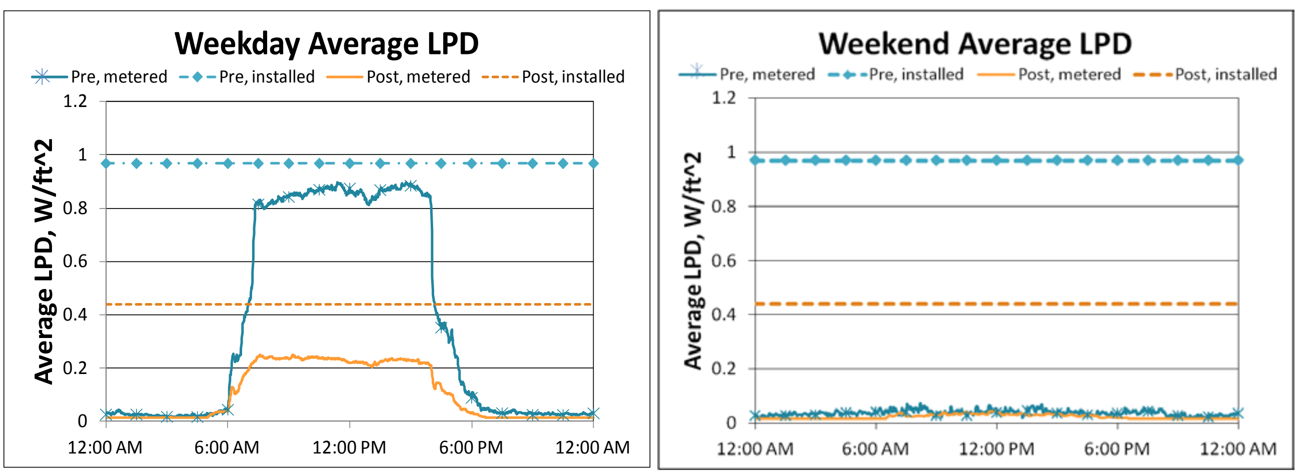
Including the effects of the LED fixture wattage reduction, lighting energy decreased by 69% from a baseline EUI of 2.3 kWh/ft^2/yr to a retrofit EUI of 0.7 kWh/ft^2/yr. Appraisers was already operating fairly efficiently prior to the retrofit, with an EUI significantly lower than the average commercial building lighting EUI of around 4.1 kWh/ ft^2/yr (Rubinstein, 2012). Despite efficient baseline lighting operation, deep savings were still achieved by implementing LED fixtures and advanced wireless controls. Table 17 presents daily and annual pre- and post-retrofit EUI results for the Appraisers study area.

Table 17: Appraisers pre- and post-retrofit energy use intensities, including LED wattage reduction

	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	8.8	0.9	0.4	2.3
Post-retrofit	2.6	0.5	0.9	0.7
% Savings	70.6%	45.2%	-151.2%	69.3%

Figure 15 displays the installed and average LPD for weekdays and weekends for the pre- and post-retrofit study period. During normal weekday operating hours (between 7 AM – 4 PM), the adjusted pre-retrofit lighting condition resulted in an average metered LPD of 0.84 W/ft^2, or 87% of the installed LPD. Post-retrofit lighting conditions resulted in an average metered LPD of 0.23 W/ft^2 during operating hours with a peak average LPD of 0.25 W/ft^2, around 52% of the installed LPD. Pre-retrofit LPDs remained slightly below the pre-retrofit installed LPD largely due to unoccupied private offices and the presence of occupancy sensors that would shut off lights five minutes after vacancy was detected. During the retrofit, existing occupancy sensors were replaced one-for-one with wireless sensors. As a result, occupancy sensor location and zone definitions before and after the retrofit were the same, with the exception of the NE corner where occupancy sensors were not working prior to the retrofit.

Figure 15: Appraisers pre- and post-retrofit installed and average lighting power density



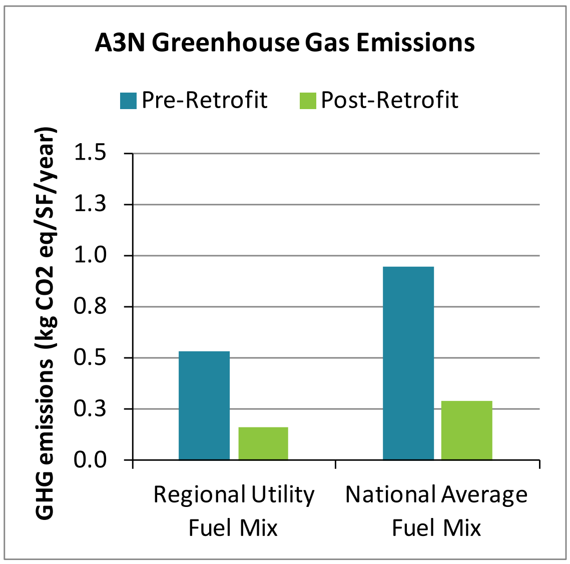
*The pre-retrofit metering period included 42 weekdays, 22 weekend days, and 5 holidays. The post-retrofit metering period included 85 weekdays, 41 weekend days, and 8 holidays. Pre- and post-retrofit annual EUIs were calculated assuming 251 weekdays, 104 weekend days, and 10 holidays.

Maximum occupancy can be seen from the period of around 7:30 AM until 4 PM, with a slight dip at 1:00 PM around lunch. Cleaning at Appraisers occurs during normal work hours, from 10:30 AM to 11:30 AM, so the downward slope of lighting power density from 4:00 PM to 7:00 PM during workdays is due to some occupants occasionally working late. Pre- and post-retrofit after hours lighting use was not zero, but was mostly negligible. There was an emergency fixture on one of the monitored circuits that remained on 24/7 near the main entrance to the site. Additionally, the post-retrofit system requires a small amount of standby power from the wireless fixture adapters.

Weekend energy consumption from lighting was fairly low for pre-retrofit and post-retrofit conditions, respectively. Holiday energy consumption was slightly higher than weekend energy consumption in the post-retrofit period. Although the data suggests that tenants did not come into work on holidays, those dates were not scheduled in the control system as different from normal workdays, resulting in fixtures in hallways turning on to 20% between 6:30 AM and 5:00 PM.

Figure 16 presents results from GHG emission calculations based on calculated annual energy consumption under pre- and post-retrofit conditions at Appraisers. The reduction in energy consumption resulted in a 69% reduction in GHG emissions, saving approximately 0.37 kg CO_2/ft^2/year with Pacific Gas and Electric (PGE)'s fuel mix and 0.65 kg CO_2/ft^2/year with the national average fuel mix.

Figure 16: Appraisers pre- and post-retrofit lighting system greenhouse gas emissions



MOSS

Similar to the Appraisers' lighting equipment tests, input power for the pre- and post-retrofit ballasts was measured on a test bench at LBNL. Based on the measurements, the number of fixtures in the study spaces, and the square footage of the spaces, the installed LPDs before and after were determined for each study space. The pre-retrofit lighting system at Moss (the "as-is" baseline) consisted of a large number of de-lamped fixtures or fixtures with burnt out lamps that had not been replaced. All fixtures were re-lamped during the retrofit, slightly changing the baseline lighting power density. To account for this change, an adjustment to the pre-retrofit metered power data was made to scale the data to the fully lamped and functional lighting system (the "adjusted" baseline).

The controls retrofit required new dimmable ballasts to be installed and new lamps to be installed at the Moss locations. After the retrofit, the M4NW installed LPD in the metered areas decreased by 5% compared to the adjusted pre-retrofit system. The M4S installed LPD in the metered areas increased by 7%, and the

M6S installed LPD decreased by 5%. These small differences in LPDs are simply attributable to changes in ballast efficiency.

Table 18: Moss installed lighting power

Location	Floor area, ft^2	Pre, As-is Installed LPD, W/ft^2	Pre, Adjusted Installed LPD, W/ft^2	Post Installed LPD, W/ft^2
M4NW	10,543	1.01	1.10	1.05
M4S	6,421	1.18	1.19	1.27
M6S	8,025	0.89	0.97	0.92

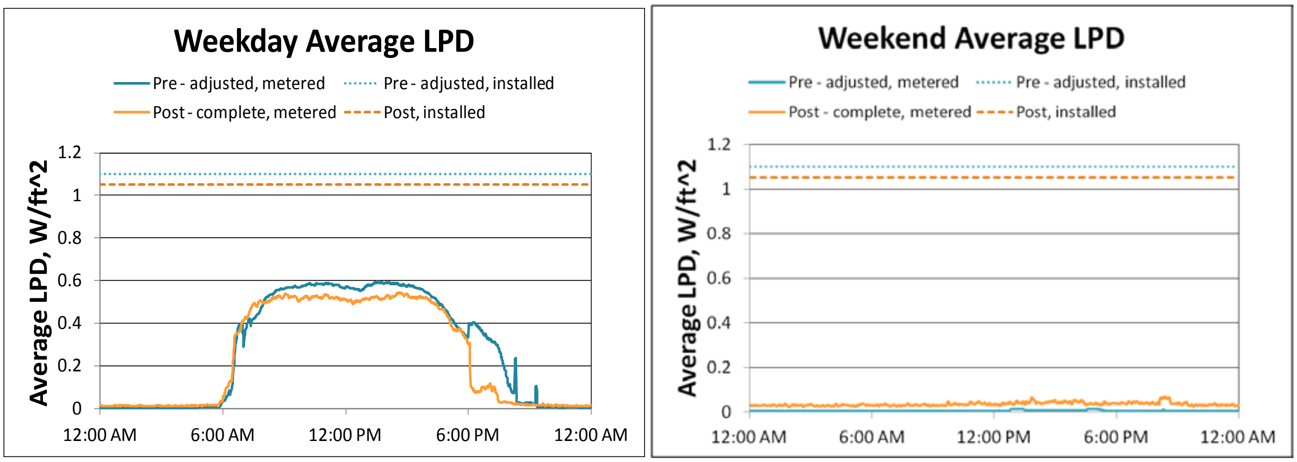
Energy savings post-retrofit for each location are presented in Table 19. Annual energy results also are provided for the combined Moss sites, based on average annual EUI per site, weighted by each site's square footage. The three locations at Moss include a wide variety of space types, from perimeter private offices with significant daylight to interior open office areas with no daylight, as well as miscellaneous copy rooms, conference rooms, and hallways. The pre-retrofit controls also varied, from occupancy sensors and automated schedules in some locations to simple wall switch controls in others, so the weighted average savings for the three locations is really bound by the unique characteristics of each site.

Table 19: Moss pre- and post-retrofit energy use intensities

Location and Square Footage		Weekday EUI (Wh/ft^2/day)	Weekend EUI (Wh/ft^2/day)	Holiday EUI (Wh/ft^2/day)	Annual EUI (kWh/ft^2/year)
M4NW (10,543 ft^2)	Adjusted pre-retrofit	6.8	0.1	0.5	1.73
	Post-retrofit, fine-tuned	6.0	0.4	2.3	1.57
	% Savings	11.8%	-260%	-385%	**8.99%**
M4S (6,421 ft^2)	Adjusted pre-retrofit	10.0	6.2	7.2	3.2
	Post-retrofit, fine-tuned	6.6	0.3	3.1	1.7
	% Savings	34.2%	95.0%	56.9%	**46.9%**
M6S (8,025 ft^2)	Adjusted pre-retrofit	7.0	1.5	1.4	1.9
	Post-retrofit, fine-tuned	4.3	0.3	1.2	1.1
	% Savings	39.0%	78.1%	15.4%	**41.9%**
Combined Areas (24,989 ft^2)	**Adjusted pre-retrofit**				**2.18**
	Post-retrofit, fine-tuned				**1.46**
	% Savings				**32.8%**

The advanced wireless controls retrofit as originally commissioned at M4NW did not result in energy savings, instead increasing energy consumption somewhat compared with the adjusted pre-retrofit baseline. However, after fine-tuning of the controls programming occurred in late September, modest energy savings of 9% were realized. Importantly, pre-retrofit and post-retrofit average LPD was significantly lower than the pre- and post-installed LPD in this space. The study area consists of a significant number of miscellaneous space types, such as the file storage room, mailroom, and conference rooms. These room types see variable use throughout workdays and are never all occupied at the same time. Also, manual switches and occupancy sensors were already located throughout the space at high granularity, significantly limiting controls savings potential.

Figure 17: M4NW pre- and post-retrofit installed and average lighting power density

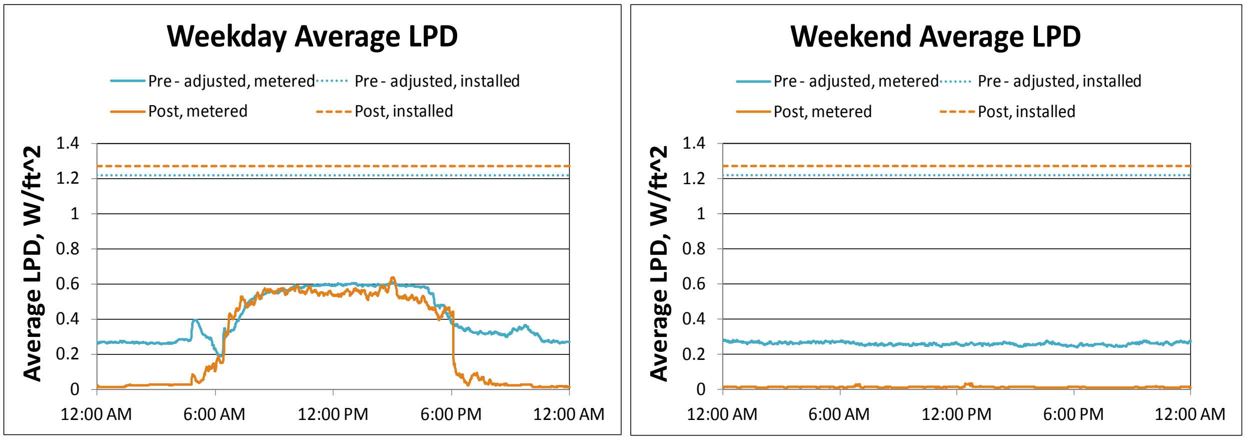


*The pre-retrofit metering period included 50 weekdays, 23 weekend days, and 2 holidays. The post-retrofit metering period, beginning 10/1/2013, included 51 weekdays, 21 weekend days, and 4 holidays. Pre- and post-retrofit annual EUIs were calculated assuming 251 weekdays, 104 weekend days, and 10 holidays.

Some of the M4NW savings are attributable to slightly higher efficiency lamps and ballasts, but the advanced controls strategies also saved energy in this space in a few different ways. Photosensors were installed along the perimeter offices to achieve daylight harvesting savings, though more lights in this study space were interior lights without daylighting controls. Changes in lighting schedules also accounted for some savings. Prior to the retrofit, automated schedules turned off any lights that remained on at 8:00 PM. The wireless system was programmed to turn unoccupied zones completely off from 6:00 PM on. This change, visible in the Figure 17 weekday LPD plot, results in savings in areas where lights previously remained on for one or two hours after occupants had left the building. Counteracting the advanced wireless controls system's savings, the zones in open office areas were programmed to remain on at 20% "intensity level" during unoccupied hours during the workday. This open office dimming strategy promotes important lighting aesthetics considerations, providing more uniform lighting throughout the site during the workday. However, it actually reduces energy savings potential since the lights no longer turn all the way off during the workday, in contrast to the occupancy sensor controls in the pre-retrofit condition.

The wireless controls retrofit at M4S had a much greater energy impact, reducing annual energy consumption by 47%, even with the small increase in installed LPD post-retrofit in this space. These savings were largely brought about by the reduction of after-hours lighting energy use due to retrofit controls strategies. As the average LPD curves in Figure 18 show, after hours and weekend lighting use dropped dramatically post-retrofit. Prior to the retrofit, some lighting load, including in the corridors, remained on outside of operating hours. The installation of occupancy sensors in the corridors with the wireless controls reduced after hours and weekend lighting use to near zero. Savings also were achieved by daylight harvesting in a few zones along the perimeter of the office space.

Figure 18: M4S pre- and post-retrofit installed and average lighting power density

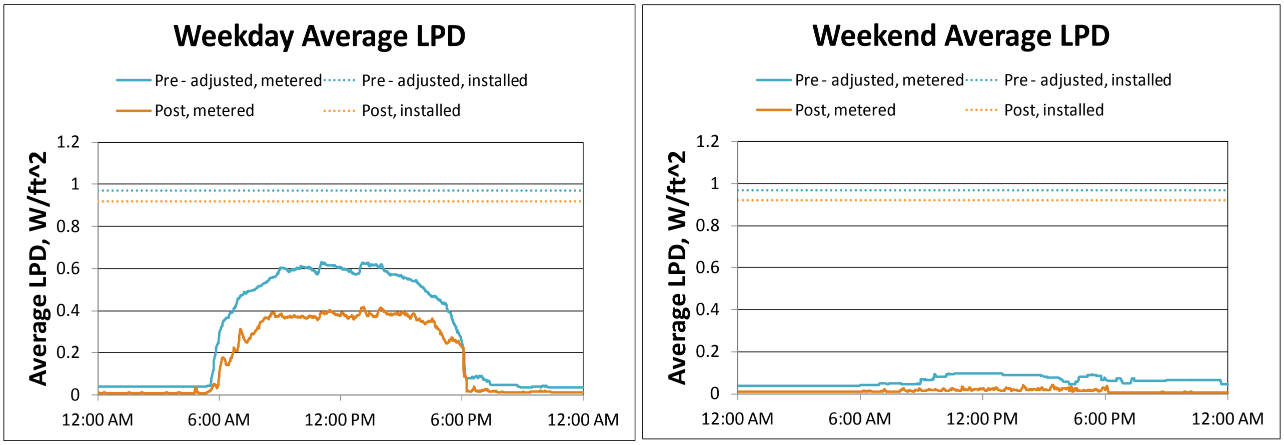


*The pre-retrofit metering period included 64 weekdays, 29 weekend days, and 2 holidays. The complete post-retrofit metering period included 39 weekdays, 17 weekend days, and 3 holidays. Complete pre- and post-retrofit annual EUIs were calculated assuming 251 weekdays, 104 weekend days, and 10 holidays.

Similar to M4NW, the average pre- and post-retrofit LPD was well below the installed LPD. This was due to private office areas (two of which were locked and completely unoccupied) and miscellaneous rooms (conference rooms, a break room, and various training rooms) that saw variable use throughout the day and were typically never all on at the same time. However, in the open office areas, lighting power before and after the controls retrofit approach the installed LPD during operating hours. This indicates high utilization of the open offices during the workday, limiting any occupancy sensors savings during work hours.

The wireless controls retrofit at M6S reduced lighting energy consumption by 42%. Unlike the other Moss areas, much of the savings here was achieved by a large reduction in average workday LPD. This reduction was brought about in several ways. In the perimeter area, where there were already occupancy sensors pre-retrofit, daily lighting energy usage was reduced by institutional tuning and daylight dimming, which was highly effective in these south-facing offices. In the interior open offices areas, the lights were turned off by an automated schedule at 6:00 PM pre-retrofit, but there were no occupancy sensors. Savings in those areas was likely due to institutional tuning and the advent of occupancy sensors, allowing lower lighting power levels in unoccupied zones during the daytime.

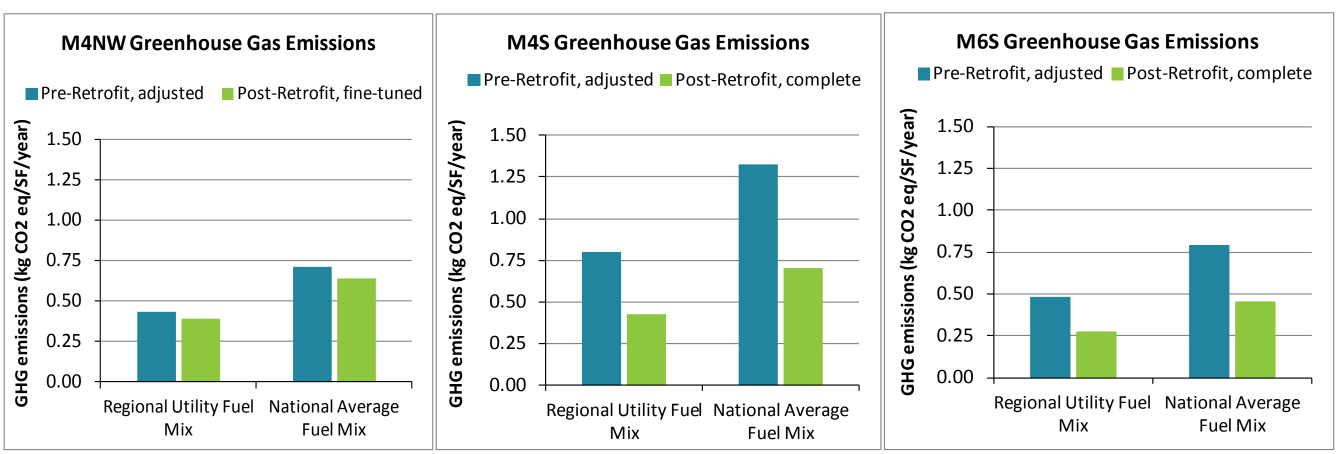
Figure 19: M6S pre- and post-retrofit installed and average lighting power density



*The pre-retrofit metering period included 41 weekdays, 18 weekend days, and 2 holidays. The complete post-retrofit metering period included 40 weekdays, 19 weekend days, and 3 holidays. Complete pre- and post-retrofit annual EUIs were calculated assuming 251 weekdays, 104 weekend days, and 10 holidays.

Figure 20 presents results GHG emission savings based on annual energy consumption under pre- and post-retrofit conditions. Energy savings at M4NW resulted in a 9.5% decrease in GHG emissions, approximately 0.04 kg CO_2/ft^2/year savings with local utility Sacramento Municipal Utility District (SMUD)'s fuel mix and 0.07 kg CO_2/ft^2/year with the national average fuel mix. The reduction in energy consumption at M4S resulted in a 47% reduction in GHG emissions, approximately 0.38 kg CO_2/ft^2/year with local utility SMUD's fuel mix and 0.62 kg CO_2/ft^2/year with the national average fuel mix. Finally, the energy reduction at M6S resulted in a 42% reduction in GHG emissions, approximately 0.2 kg CO_2/ft^2/year with SMUD's fuel mix and 0.34 kg CO_2/ft^2/year with the national average fuel mix.

Figure 20: Moss pre- and post-retrofit lighting system greenhouse gas emissions



B. CONTROLS SYSTEM DATA ANALYSIS

The pre- and post- retrofit lighting circuit data collected over many months allows accurate comparison of total lighting energy usage at the study locations. However, lighting circuits typically serve 10, 20 or more fixtures that may be spread across a combination of spaces, from perimeter and interior offices to open and private offices and sometimes even other space types, such as storage, copy rooms, and bathrooms. The resolution of data measured at the circuit level is, therefore, too coarse to see how lighting levels change through a day on individual fixtures or in single offices or smaller control zones. On the other hand, the zones configured in the advanced controls system are at much finer resolution, with each zone encompassing only around two to six fixtures.

The controls system web interface offers a reporting feature that allows the user to trend "intensity" data (reported in terms of percentage, from 0% - 100%) for each lighting zone, which can be used to derive lighting power trends over time for a given study period. One month of controls-based data was analyzed for three groups of fixtures (one in Appraisers and two in Moss) to calculate average daily lighting power density and extrapolate to annual energy usage based on assumed total workdays, weekend days, and holidays per year.[6] The controls system data was processed into parallel datasets for comparison of hypothetical lighting energy usage from different controls scenarios.

CONTROLS SCENARIOS

1. Automated on/off zone schedules

   The first option considered was how the lighting load would operate if simply switched on and off based on automated schedules. Daily schedules based on the lighting usage patterns apparent in the controls data were chosen. Automated schedules that turn lights on in the morning and off at night are common in open office spaces with predictable occupancy patterns. For this scenario, a dataset was produced in which each zone's lighting load was set to full power during scheduled business hours. The lights in this dataset also were set to full power for any after-hours occurrences when lights were on in the controls system data (presumably for workers staying late, cleaning crews, and security details).

2. Zone occupancy sensors

   This scenario provides tighter automatic on and off control than automated schedules since the lights are only on when sensors are tripped by occupants. Zones are turned off individually during business hours if the space is vacant and the zone occupancy sensor times out. The lighting controls data for this option was transformed by setting the lights in each zone to full power whenever the controls dataset reported greater-than-zero lighting intensity.

3. Zone occupancy sensors and institutional tuning

   This scenario represents a system with occupancy sensors as well as institutional tuning to reduce the maximum lighting power. The tuned power level chosen for each zone was the maximum power level resulting from the tuned settings in the actual advanced control system. The controls data was

[6] The one month of lighting power data processed from the controls system was November 24 – December 23, 2013, for the Appraisers group, and November 1 – 30, 2013, for the Moss groups. This included 19 to 21 workdays, 8 to 9 weekend days, and 1 to 2 holidays. Daily power averages are converted to annual energy figures by multiplying by 251 annual work days, 104 annual weekends, and 10 annual holidays.

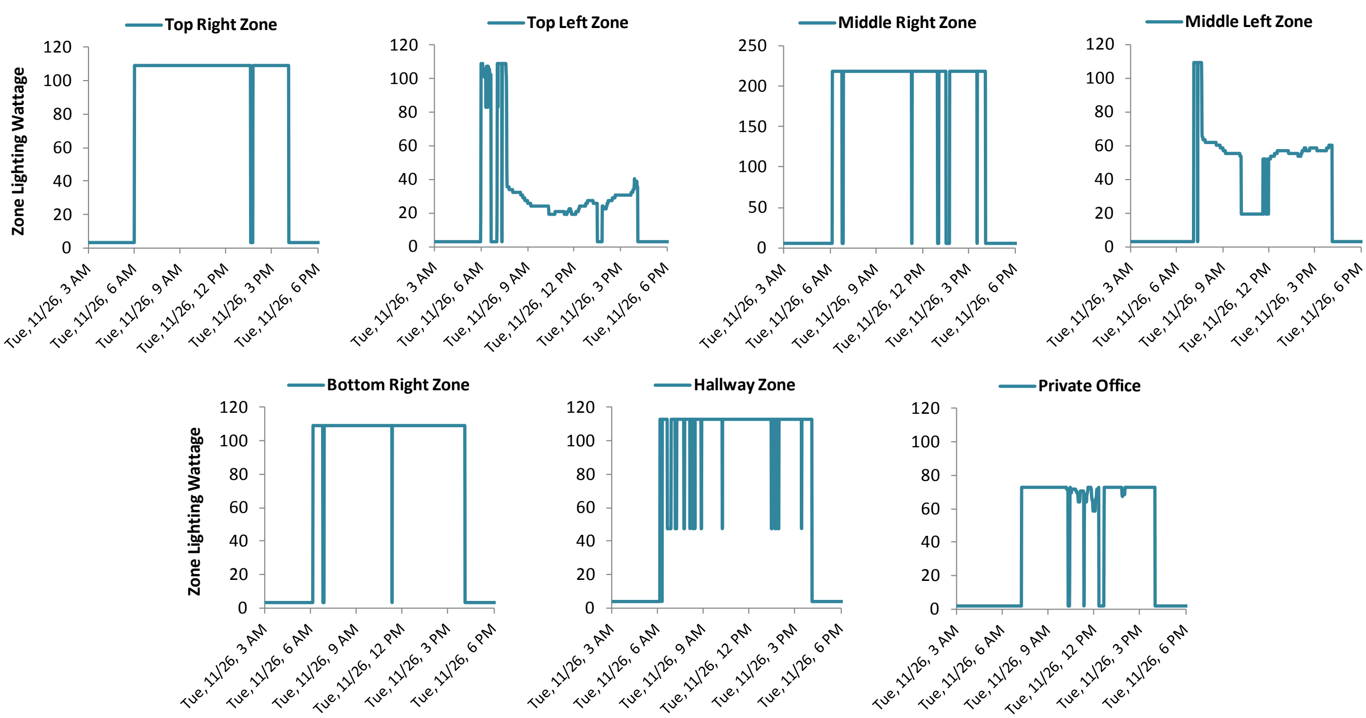
transformed by setting the lighting load in each zone to the maximum tuned power level whenever the controls dataset reported greater-than-zero intensity for that zone.

LOCATIONS

For controls system data analysis, three groups of fixtures were chosen within the two buildings where the advanced wireless controls were installed. One group was an open office area in the Appraisers; two groups were in the Moss building, one being interior open offices and the other private perimeter offices. Remember that dimmable fluorescent fixtures were used in the Moss building, while dimmable LED fixtures were installed in the Appraisers building.

Controls data for each zone in the three groups was processed to one-minute interval lighting power data equivalent to the data measured at the lighting circuits for these areas. An example of one day's lighting power trend for each zone in the Appraisers third floor group is illustrated below. Look at the zone load shapes and notice the zones that show obvious daylight dimming curves in early through late afternoon hours (top left and middle left zone). Note also the hallway zone, where occasional occupancy sensor timeout during work hours resulted in the lights dimming to a low level, but not turning completely off until after-hours.[7]

Figure 21: Lighting load shapes snapshot for zones in Appraisers group



[7] Observe that there is a very small continuous load throughout the night. This is the small amount of power that the fixture controllers constantly draw to communicate with devices in the mesh network and to pass controls commands to the fixture ballast or driver. This continuous load, or "phantom power," incurs a small energy penalty for the use of distributed controls, such as the advanced control system evaluated here.

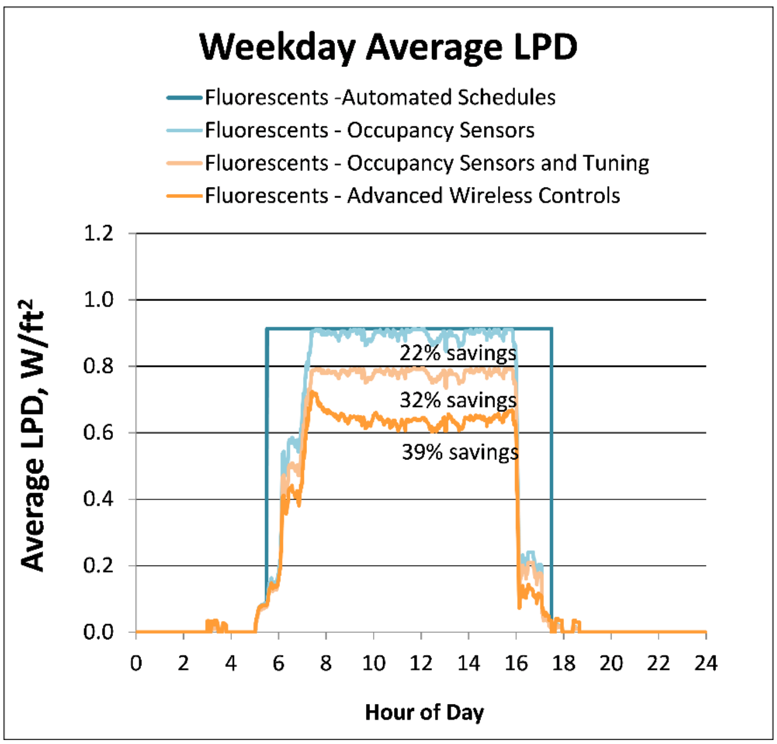
RESULTS

A APPRAISERS THIRD FLOOR PERIMETER AND INTERIOR OPEN OFFICES

For analysis of the Appraisers group of fixtures, the effects of the LED wattage reduction were excluded so the impacts of the advanced wireless controls strategies could be evaluated independently. Looking at the savings levels expected from the controls features on the fluorescent baseline, lighting energy savings of 39% accrue from the various controls strategies implemented together.

Occupancy sensors provide 22% savings above automated scheduling, with an additional 10% coming from institutional tuning. Daylight harvesting, which was only implemented on about one third of the fixtures in the space studied, accounts for another 7% savings. Note that one of the zones where daylighting controls were installed was found to not be dimming even when daylight was available, indicating some issues with implementation.

Figure 22: Appraisers daily LPD without LED retrofit savings



It should be noted that savings due to the controls are a function of how the strategies are deployed and commissioned and are highly adjustable. For example, the 10% savings from institutional tuning is simply a result of the level programmed into the system. If more aggressive tuning is possible (contingent upon lighting levels and tenant preferences), that savings fraction could easily double or even triple.

Table 20: Appraisers annual EUI and savings (excluding LED wattage reduction)

Fixture and Controls Scenario	Annual EUI ($kWh/ft^2/year$)	Incremental Annual Energy Savings	Total Annual Energy Savings
Fluorescents and Automated Schedules	2.89	0%	0%
Fluorescents and Occupancy Sensors	2.26	22%	22%
Fluorescents and Institutional Tuning	1.97	10%	32%
Fluorescents, Advanced Controls (occupancy sensors, tuning, dimming, daylighting along perimeter)	1.75	7%	39%

B MOSS FOURTH FLOOR INTERIOR OPEN OFFICES

The next group considered is the Moss fourth floor interior open office area with no daylighting controls. The controls system in this case was installed on the incumbent fluorescent fixtures, with dimmable ballasts installed, as well. Similar to the Appraisers' group, automated scheduling would be a relatively common baseline lighting controls option for the Moss fourth floor open offices, though, in fact, this space was controlled by occupancy sensors prior to the retrofit. A scheduling controls baseline for the Moss fourth floor group is outlined for consideration, along with an occupancy sensor baseline for comparison.

Figure 23: Moss fourth floor interior offices daily LPD

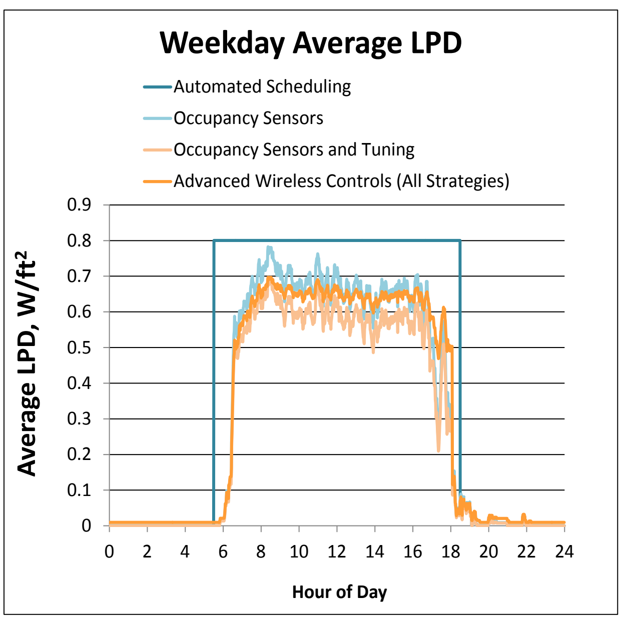
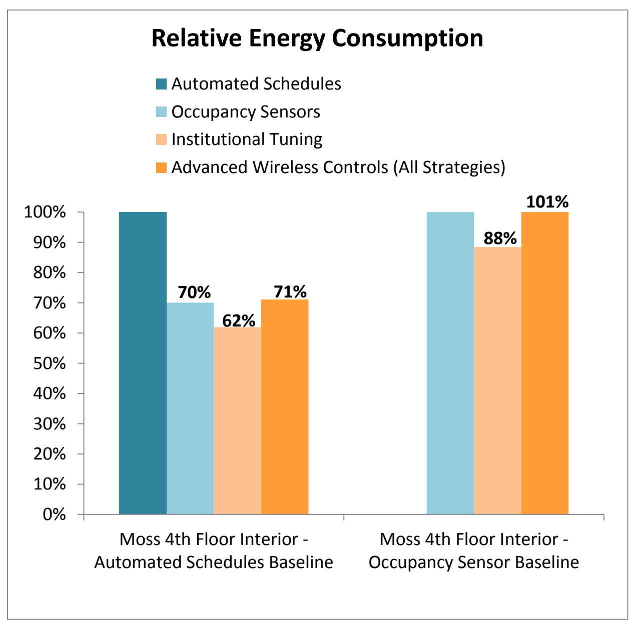


Figure 24: Moss fourth floor comparison of relative annual energy usage with each controls scenario



The advanced wireless controls provided almost 30% savings relative to an automated scheduling baseline. However, annual energy usage with the advanced controls is not substantially different than what might be provided by occupancy sensors alone. Savings are, in fact, negative by one percent in this analysis. There is an important distinction between the baseline and retrofit occupancy controls strategies that helps explain this result. This location already had occupancy sensor controls before the advanced controls installation. Importantly, those controls were connected to non-dimmable fluorescent ballasts and simply turned the fixtures off when the occupancy sensors timed out. In contrast, the advanced controls are commissioned to dim the zones to a minimum level during working hours when occupancy sensors time out, rather than turning them completely off. This strategy incurs an obvious energy penalty relative to on/off occupancy controls. However, it is an intentional design decision intended to address “checkerboard” patterns of un-illuminated areas within view of tenants working in other areas, which can happen in adjacent open office zones with on/off occupancy controls.

Looking at the institutional tuning enabled by the advanced wireless controls and dimming ballast, this strategy provided 12% savings compared to occupancy sensors alone. Again, those savings are offset by the occupancy-based dimming feature during work hours. From an energy savings standpoint alone, it might have been better simply to install lower ballast factor ballasts on the existing fluorescent fixtures to, in effect, implement tuning without installing advanced controls. However, such a strategy is essentially a static solution in that it is implemented once by ballast replacement. It is not easily undone or adjusted later and is not nearly as flexible as the advanced controls’ ability to set custom levels in various spaces or space types.

Table 21: Moss fourth floor group annual EUI and savings – automated scheduling baseline

Fixture and Controls Scenario	Annual EUI ($kWh/ft^2/year$)	Incremental Annual Energy Savings	Total Annual Energy Savings
Automated Schedules	2.78	0%	0%
Occupancy Sensors	1.95	30%	30%
Occupancy Sensors and Institutional Tuning	1.72	8%	38%
Advanced Controls (Occupancy sensors, tuning, dimming)	1.98	-9%	29%

Table 22: Moss fourth floor group annual EUI and savings – occupancy sensor baseline

Fixture and Controls Scenario	Annual EUI ($kWh/ft^2/year$)	Incremental Annual Energy Savings	Total Annual Energy Savings
Occupancy Sensors	1.95	0%	0%
Occupancy Sensors and Institutional Tuning	1.72	12%	12%
Advanced Controls (Occupancy sensors, tuning, dimming)	1.98	-13%	-1%

C MOSS SIXTH FLOOR PERIMETER PRIVATE OFFICES

For the group of private offices along the south perimeter of the sixth floor, there were wall switches and occupancy sensors controlling the lights before the installation of the advanced wireless controls. The automated scheduling option is excluded in this case since it is uncommon for private office lighting to be automatically turned on by scheduling controls. Manual wall switches in private offices are the more common option and, if tenants are consistent in using their wall switches to turn lights off when they leave the office, there is little difference between wall switches and occupancy sensor controls.

Compare the Moss fourth floor interior office results to those of the sixth floor offices, where there is plenty of light available from the perimeter windows. Predictably, energy savings on the sixth floor are much greater. Even with occupancy sensors in the baseline condition, the advanced wireless controls achieve significant energy savings of 38%. Institutional tuning provided 6% annual energy savings, but the savings really accrue with daylight harvesting and any additional manual dimming tenants implement.

Figure 25: Moss sixth floor perimeter offices daily LPD

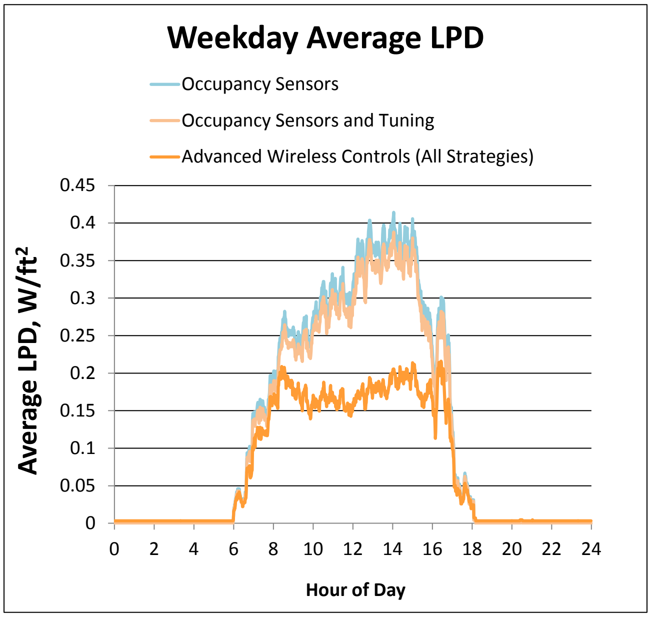
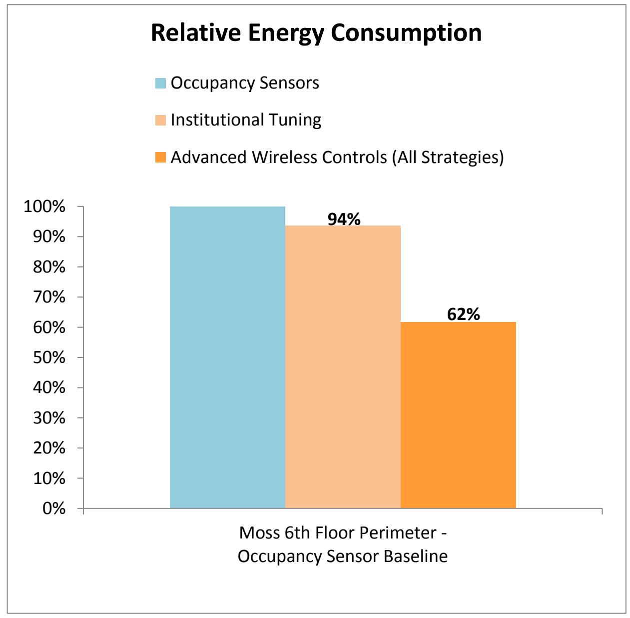


Figure 26: Moss sixth floor comparison of relative annual energy usage with each controls scenario



Importantly, for this group, unlike in the fourth floor case, there is no need for the advanced wireless controls to dim fixtures when occupancy sensors time out during work hours. Since the lights are in private offices, on/off switching based on occupancy is appropriate and does not impact tenants in other spaces. There is, therefore, no energy penalty from the advanced system's occupancy controls to offset savings in the manner seen in the fourth floor open office areas.

Table 23: Moss sixth floor group annual EUI and savings – occupancy sensor baseline

Fixture and Controls Scenario	Annual EUI ($kWh/ft^2/year$)	Incremental Annual Energy Savings	Total Annual Energy Savings
Occupancy Sensors	0.76	0%	0%
Occupancy Sensors and Institutional Tuning	0.71	6%	6%
Advanced Controls (Occupancy sensors, tuning, dimming, daylighting)	0.47	32%	38%

CONTROLS SAVINGS DISCUSSION

The controls data analysis for the three groups of fixtures evaluated here shows that implementing the wireless control system can save significant lighting energy, but savings are not guaranteed. They are heavily dependent on the baseline controls condition. Total savings are almost 40% in Moss sixth floor private offices with abundant daylighting. Similar controls savings are found in mixed perimeter and interior offices at Appraisers compared to automated lighting schedules (excluding fixture retrofit). However, even with institutional tuning, the advanced controls slightly increase energy usage in the Moss fourth floor interior open offices that already had occupancy sensor controls.

A LIGHTING SCHEDULES AND OCCUPANCY SENSORS

Overall, the results indicate that advanced wireless controls can save substantial energy in situations where simple on/off switching by automated schedules is the norm. If the lighting system already employs occupancy sensors, there will need to be significant daylight harvesting and institutional tuning opportunities for advanced controls to have a large impact, and, especially, to offset any additional energy used if occupancy sensors are set to dim, rather than turn off, fixtures during work hours. Of course, energy savings are only part of the picture here; dimming unoccupied open office area fixtures during work hours rather than turning them off may cost some energy, but improve tenant satisfaction. All design considerations should be weighed appropriately.

B FIXTURE RETROFITS

In cases where fixture retrofits and advanced wireless controls are being considered, the relative costs and benefits of the options alone and in combination should be considered. It was found at Appraisers that the LED retrofit resulted in over 50% wattage reduction. Controls energy savings were found to be 39%, and the very highest energy savings were achieved when both options were installed. Also, the savings from a fixture retrofit are locked in once the new fixtures are specified, whereas savings from controls are highly adjustable and will be different in each case depending on how they are implemented. Controls savings could have been higher with different programming and commissioning choices.

C DAYLIGHT HARVESTING

For the daylighting savings analysis here, the month of controls data evaluated is from a time period in the year with lower daylight availability. The months of November and December include some of the shorter days in the year in the northern hemisphere, with the sun also at a lower elevation than at other seasons, limiting daylight availability. Our annual energy savings analysis extrapolates from this winter data and, therefore, understates the energy savings possible from daylighting controls. Good daylight dimming and energy savings opportunity was, nevertheless, found in the sixth floor south facing perimeter area.

D INSTITUTIONAL TUNING

In general, institutional tuning opportunities will be highest in locations where the baseline condition is considered overlit. Light levels delivered by lighting systems are sometimes higher by design than necessary for given spaces. This is done to compensate for expected light source depreciation over time or for the simple fact that there are only a limited number of options for traditional fixtures outputs, based on available ballast factors and number of lamps per fixture. If, for example, a two-lamp fixture would provide just enough light or slightly less light relative to facility requirements, a three-lamp fixture might be specified to facilitate compliance with a standard or to guarantee adequate light levels down the road, as the lamps' output is expected to depreciate over time. This design approach may lead to almost 50% more energy usage. A common result is office spaces with three-lamp T8 troffers where tenants find their desk space overlit and remove lamps from fixtures overhead or place baffles over fixtures to reduce light output. With continuously dimmable light sources and advanced wireless controls, on the other hand, this can all be avoided. Lighting power and output can be finely tuned to provide desired light levels without wasting energy or annoying tenants.

Institutional tuning provided energy savings in the groups analyzed, but may not have realized full potential due to discrepancies between the controls "intensity" settings and fixture power response. It was found that the "intensity" values recorded in the zone state reports do not correspond accurately to fixture intensity. Instead, the fixture power and output was higher than indicated by the intensity settings in the controls system. For example, we found in the Appraisers case that the system would report 65% "intensity" when the fixtures were actually operating at around 87% power. At Moss, the fluorescent ballasts would operate at around 93% power when the controls system registered 65% intensity. Users would tend to assume they are saving more energy and lowering light levels more than they really are. This issue underscores the need for controls vendors and system implementers to know precisely how dimmable fixtures respond to dimming control signals to implement tuning effectively.

C. PHOTOMETRIC PERFORMANCE

APPRAISERS

Pre-retrofit photometric measurements were taken at 29 workstations and 4 private offices during the pre-retrofit visit on December 20, 2012. Post-retrofit photometric measurements were taken at 30 workstations and 3 private offices on February 13, 2014. During both the pre-retrofit and post-retrofit visits, only 16 out of the 33 workstations and 3 out of 4 private offices were occupied. There were no task lights observed at this site. The following results are based on the installed LED fixtures from one manufacturer and are not applicable to all LED fixtures.

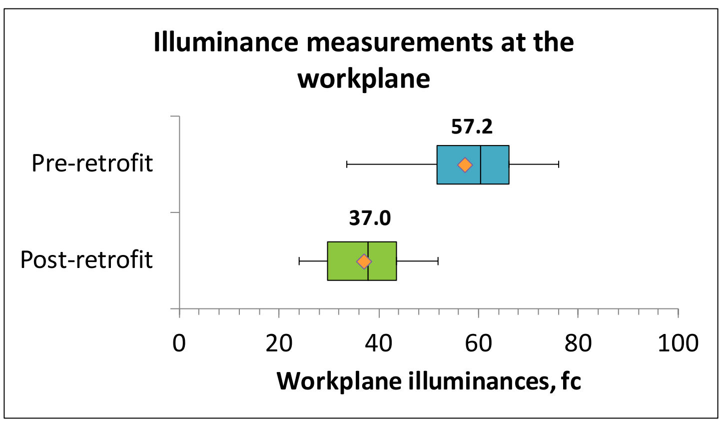
Pre- and post-retrofit illuminance values are presented below (Table 24 and Figure 27). The pre-retrofit fluorescent system provided light levels at the primary work surface ranging from 33.5 to 76.0 fc, with an average illuminance of 57.2 fc. The post-retrofit LED system provided light levels at the primary work surface ranging from 24.1 to 51.6 fc, with an average illuminance of 37.0 fc. The retrofit lowered the measured lighting levels at the work planes, though the high pre-retrofit levels suggest that the office space may have been over-lit. The LED fixtures bring light levels down closer to, but still above, the 30 fc GSA standard for the type of work performed by this site's occupants.

Table 24: Appraisers photometric results

	Pre-retrofit illuminance, fc	Post-retrofit illuminance, fc
Minimum	33.5	24.1
Quartile 1	51.7	29.5
Quartile 2	60.4	37.7
Quartile 3	66.1	43.5
Maximum	76.0	51.6
Mean	**57.2**	**37.0**

Figure 27 displays the range of illuminance measurements for pre- and post-retrofit lighting systems. Orange diamonds and adjacent values give the mean, rectangles represent the range between the 1st, 2nd, and 3rd quartiles, and bars cover the entire range of data. Pre-retrofit results are in blue while post-retrofit results are in green.

Figure 27: Appraisers measured illuminance



MOSS

Pre-retrofit photometric measurements were taken on January 30, 2013 and post-retrofit photometric measurements were taken on October 23, 2013. Workstation layout did not change during the retrofit.

- **M4NW:** Pre-retrofit photometric measurements were taken at 39 workstations and 8 private offices during the pre-retrofit visit. During the pre-retrofit visits, 8 out of 57 workstations were unoccupied. All 11 private offices were occupied. Task illuminance readings also were taken for 12 workstations during the pre-retrofit visit. Post-retrofit photometric measurements were taken at 56 workstations and 11 private offices.

- **M4S:** Pre-retrofit photometric measurements were taken at 21 workstations and 2 private offices during the pre-retrofit visit. During the pre-retrofit visits, 8 out of 22 workstations and 2 out of 3 private offices were unoccupied. Post-retrofit photometric measurements were taken at 22 workstations and 3 private offices.

- **M6S:** Pre-retrofit photometric measurements were taken at 10 workstations and 11 private offices during the pre-retrofit visit. During the pre-retrofit visits, only one of the private offices was unoccupied. Post-retrofit photometric measurements were taken at 10 workstations and 11 private offices.

Pre- and post-retrofit illuminance values are presented below (Table 25 and Figure 28). Overall, the average light levels were fairly similar. However, the wireless controls allowed occupants more flexibility to vary their light levels according to their preferences.

- **M4NW:** The pre-retrofit fluorescent system at M4NW provided light levels at the primary work surface ranging from 4.92 to 76.2 fc, with an average illuminance of 32.6 fc. The post-retrofit LED-based system provided light levels at the primary work surface ranging from 2.88 to 65.2 fc, with an average illuminance of 34.9 fc. The wireless controls retrofit noticeably tightened the range in light output at the workstation; the average pre- and post-retrofit illuminance are comparable.

- **M4S:** The pre-retrofit fluorescent system provided light levels at the primary work surface ranging from 16.8 to 47.7 fc with an average illuminance of 32.0 fc. The post-retrofit advanced wireless controls system provided light levels at the primary work surface ranging from 9.66 to 42.5 fc with an average illuminance of 29.0 fc, also quite similar to the pre-retrofit average.

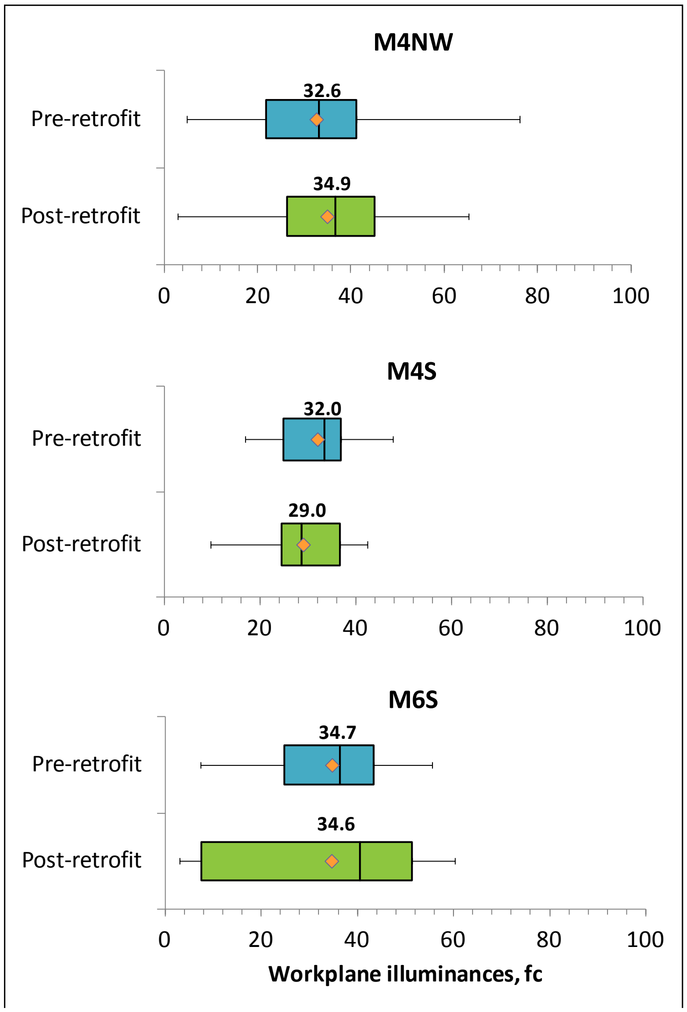
- **M6S:** Pre-retrofit fluorescent system provided light levels at the primary work surface ranging from 7.34 to 55.6 fc, with an average illuminance of 34.7 fc. The post-retrofit advanced wireless controls system provided light levels at the primary work surface ranging from 3.07 to 60.2 fc, with an average illuminance of 34.6 fc.

Table 25: Moss photometric results

Location	M4NW		M4S		M6S	
	Pre-retrofit illuminance, fc	Post-retrofit illuminance, fc	Pre-retrofit illuminance, fc	Post-retrofit illuminance, fc	Pre-retrofit illuminance, fc	Post-retrofit illuminance, fc
Minimum	4.92	2.88	16.8	9.66	7.34	3.07
Quartile 1	21.7	26.4	25.0	24.4	24.8	7.62
Quartile 2	33.1	36.7	33.4	28.7	36.4	40.5
Quartile 3	41.2	45.1	37.0	36.6	43.3	51.3
Maximum	76.2	65.2	47.7	42.5	55.6	60.2
Mean	**32.6**	**34.9**	**32.0**	**29.0**	**34.7**	**34.6**

Figure 28 displays the range of illuminance measurements for pre- and post-retrofit lighting systems. Orange diamonds and adjacent values give the mean, rectangles represent the range between the 1st, 2nd, and 3rd quartiles, and bars cover the entire range of data. Pre-retrofit results are in blue, while post-retrofit results are in green.

Figure 28: Moss illuminance measurements



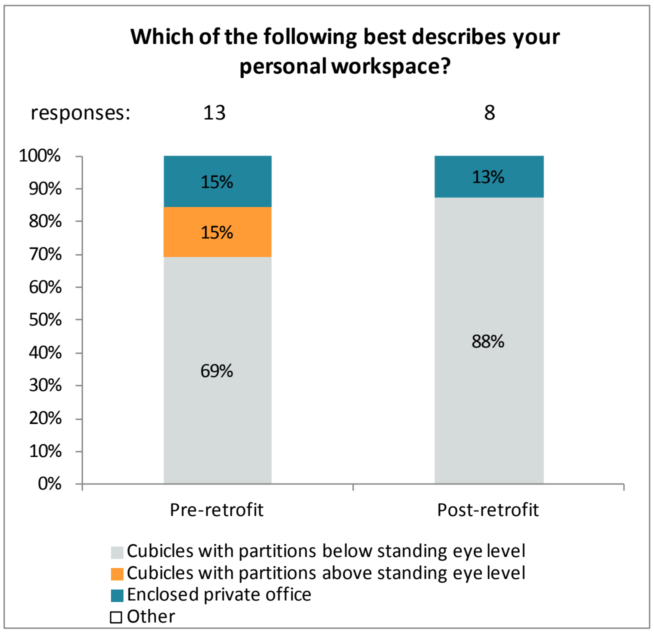
D. OCCUPANT SATISFACTION

For a lighting controls system to be implemented well, users must understand and accept it. Occupant satisfaction was assessed here through the administration of occupant surveys both pre- and post-retrofit to determine how occupants felt about their existing lighting and lighting controls and how they responded to the retrofit system. Selected results are presented and discussed below.

APPRAISERS

Paper copies of the pre-retrofit survey were distributed to 13 occupants, all of whom responded between December 10, 2012, and December 20, 2012, for a response rate of 100%. Paper copies of the post-retrofit survey were distributed to all occupants again in January 2014. Nine responses were received for a response rate of 69%. To first get a sense for the types of office spaces occupied by respondents to the survey, Figure 29 provides the pre- and post- number of responses from occupants in cubicles and private offices. Pre- and post-retrofit surveys were completed mostly by occupants in open offices, whether with high or low cubicle walls, with only one to two respondents from private offices.

Figure 29: Appraisers respondent location details



At Appraisers, occupants responded considerably more favorably regarding the lighting service and performance from the new LED lighting system. Overall, comfort level with the light levels doubled from pre- to post-retrofit condition, with more occupants post-retrofit also feeling like work surfaces were evenly lit and that the lighting system created a good image for their organization.

Figure 30 Appraisers survey results: overall lighting quality

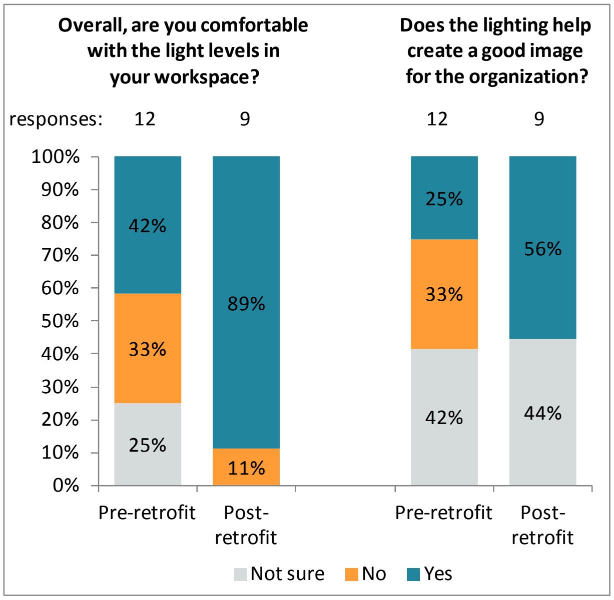
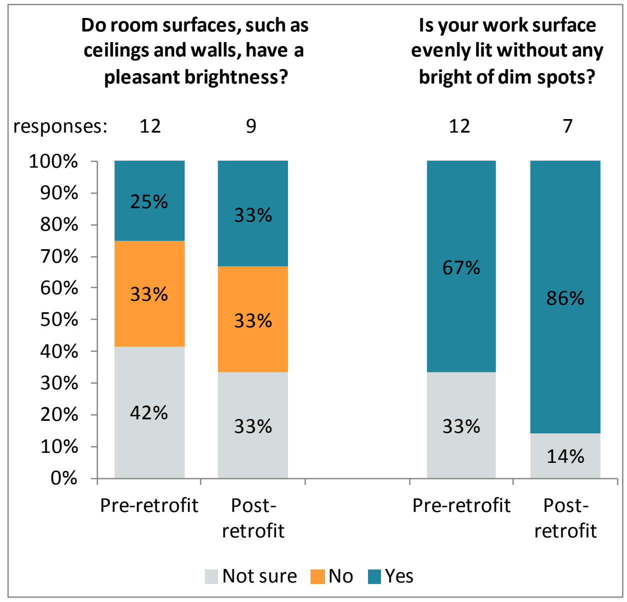


Figure 31 Appraisers survey results: work environment appearance



With respect to the lighting controls, more occupants expressed satisfaction with the retrofit system, as well. All respondents indicated that they understood that the retrofit system includes adjustable light levels.

Figure 32 Appraisers survey results: lighting controls satisfaction

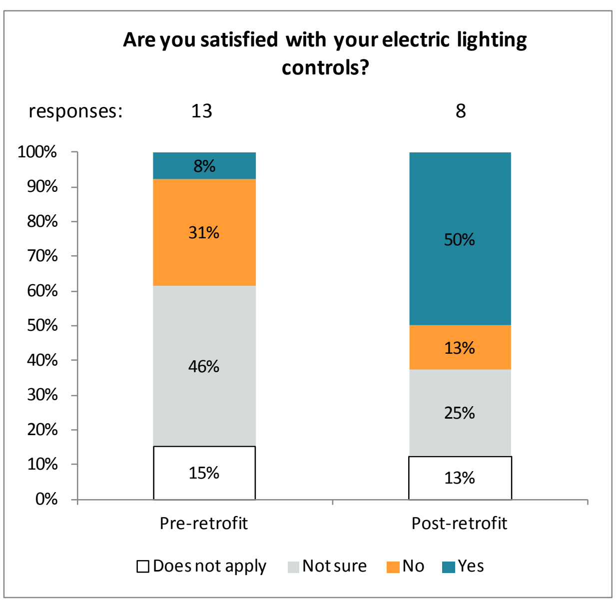
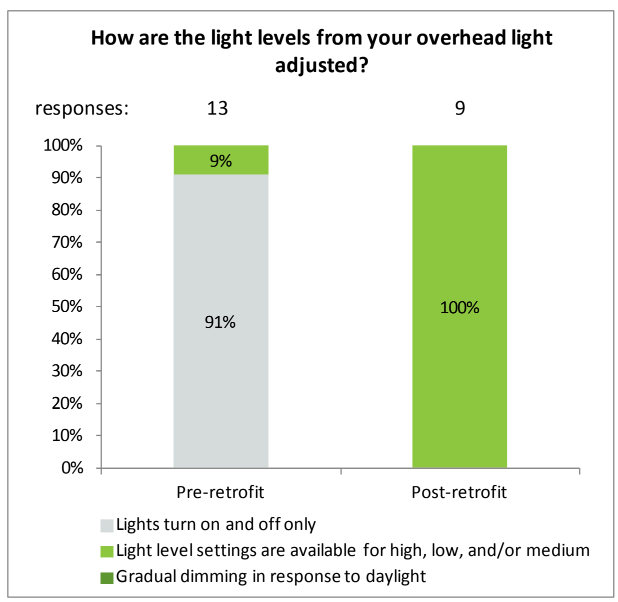


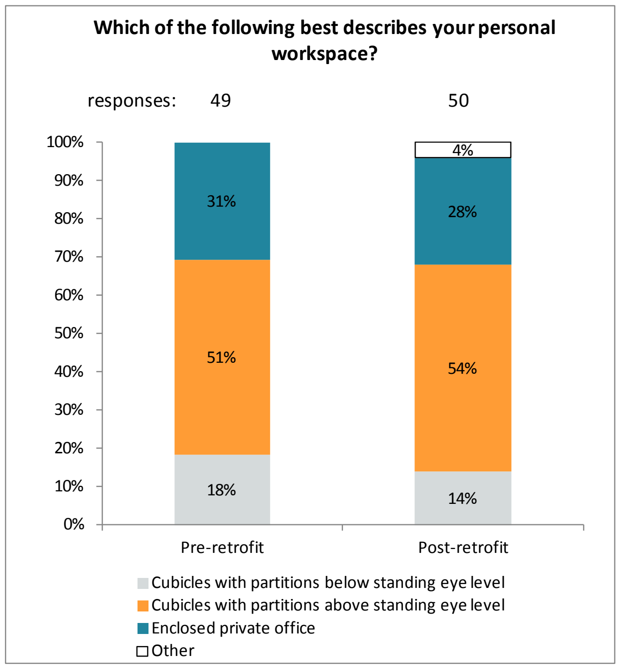
Figure 33 Appraisers survey results: how lighting controls work



MOSS

Overall, there were 51 respondents to the pre-retrofit surveys at the 3 Moss locations and 50 respondents to the post-retrofit surveys. As the same questions were asked of occupants in all three locations before and after the retrofit, which was the same technology throughout, the survey responses are combined here. To first get a sense for the types of office spaces occupied by respondents to the survey, Figure 34 provides the pre- and post- number of responses from cubicles and private offices. Clearly, a very similar sample was captured at each survey phase.

Figure 34: Moss respondent location details



In the case of the Moss lighting controls retrofit, Figure 35 and Figure 36 show that responses generally become slightly less favorable regarding the lighting service and lighting performance after the controls retrofit. There are decreases in favorable responses with regard to workspace comfort level, illumination of surfaces in the workspace, and perception of the lighting system's reflection on the organization's image. However, there is a slight increase in favorability regarding uniformity of work surface illumination.

Figure 35 Moss survey results: overall lighting quality

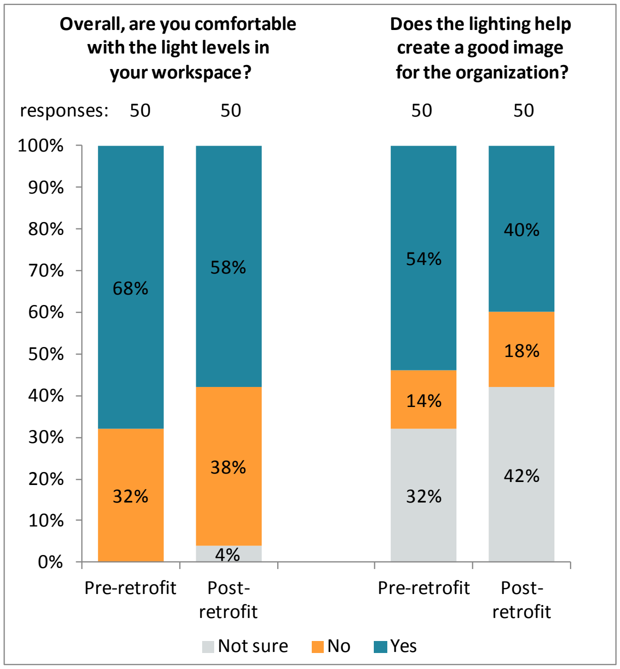
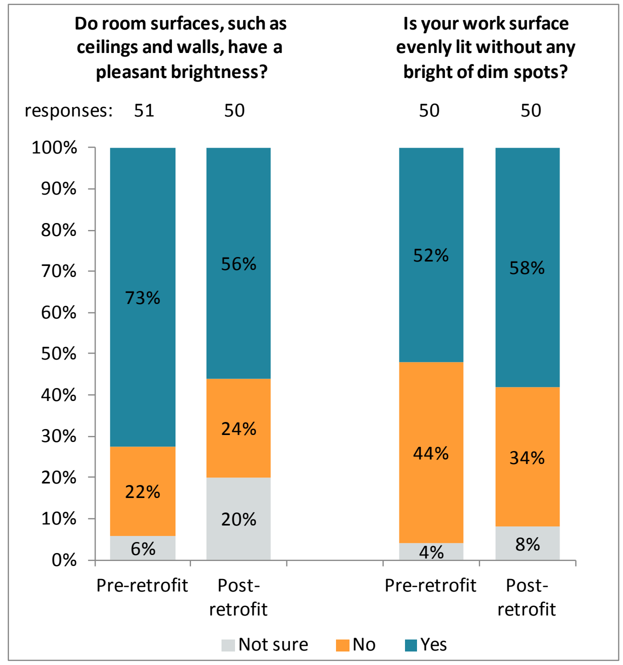


Figure 36 Moss survey results: work environment appearance



Satisfaction with the lighting controls also is just slightly lower in the post-retrofit case, as shown in Figure 37. Many occupants do appear to understand that the new controls provide daylight dimming response and adjustable light levels (see Figure 38), but there is dissatisfaction from a few on the way the occupancy and dimming controls work.

Figure 37 Moss survey results: lighting controls satisfaction

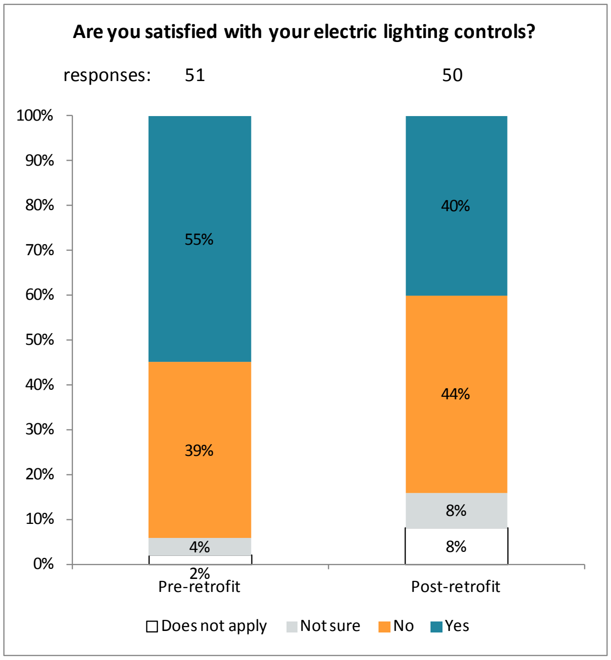
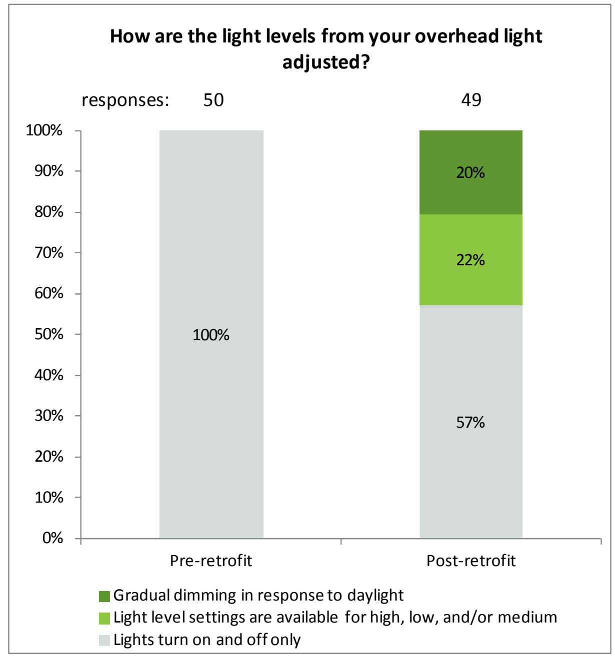


Figure 38 Moss survey results: how lighting controls work



Overall, it appears that there was around a 5% increase in dissatisfaction with the lighting controls after the retrofit (20 out of 51 respondents dissatisfied with controls pre-retrofit, and 22 out of 50 respondents dissatisfied post- retrofit). Although the statistical significance of this apparent increase in dissatisfaction with the new lighting controls was not evaluated, it is clear from the free occupant responses that some occupants were dissatisfied. The majority of occupant complaints were directly or indirectly attributable to poor operation of the occupant sensors. False offs, where the sensor incorrectly turns off the lights even though the space is not vacant, is a well-documented weakness of many of yesterday's "dumb" occupant sensors.

During the installation of the new lighting controls, it was decided to re-use some of the legacy occupant sensors that were already in place to reduce project installation costs. In retrospect, it would have been preferable to remove the old occupancy sensors and install more modern occupant sensors in strategic locations better reflecting current occupant locations, zone size, and workgroup preferences. Occupants' concerns could be addressed by system design and commissioning improvements, from better occupancy sensor placement and coverage to more wireless switches for personal control and better programming.

Lessons:

- Clear communication of design intent is essential for a successful installation, including verifying how fixtures should be zoned and occupancy sensors placed such that they corresponded to actual occupant patterns.
- Prior to installation, an agreement on commissioning process and details needs to be reached between the vendor, contractor, and property manager.
- Identify and communicate any dissatisfaction with technical issues clearly and early so they can be appropriately addressed. Avoid blaming old equipment failures and issues on new technology:
- New fluorescent lamps should be "seasoned" (operated at full power for 100 hours or more) before being used in a dimming system to prevent early failures.
- Using legacy occupancy sensors with a new advanced controls system may force old, suboptimal zoning schemes onto new workstation and controls layouts.

E. COST-EFFECTIVENESS

OVERVIEW

This cost-effectiveness analysis examines whether the value of the future energy savings from the installation of wireless advanced lighting controls justifies the expense of the investment. Cost-effectiveness results are not calculated for the experimental installations implemented for this study because the installation costs do not reflect expected costs of "real-world" projects at typical project scales and with typical project scoping, bidding, and installation processes. For reference, the labor and material costs for the projects were determined via communication with GSA and the technology vendors. The actual cost of the advanced wireless controls retrofit with LED fixtures at Appraisers totaled $7.97/ft^2$, including labor and equipment (controls and fixtures). For the advanced wireless controls retrofit at Moss (with dimmable ballasts and new fluorescent lamps), labor and material costs totaled $2.74/ft^2$.

To calculate cost-effectiveness for projects as they would be implemented in more typical real-world projects, normalized costs and savings scenarios were formulated to represent anticipated costs with competitive bidding and economies of scale for larger project sizes (greater than 200,000 ft^2). The zonal approach to advanced wireless controls implementation was used for the normalized costs and savings scenarios, as this is the more common method for deploying the technology evaluated here. Under this strategy, multiple fixtures, averaging around five, would be wired to a single wireless adapter, rather than installing one adapter for each fixture. This saves material costs and, since fixtures are typically grouped into control zones through the system software, a highly granular one-to-one relationship between adapters and fixtures is not normally necessary.

Energy savings for normalized costs and savings are based on the difference between GSA and national average building lighting energy usage intensities and the weighted average of the measured post-retrofit lighting energy usage intensities at the study locations. Only energy savings due to the advanced wireless controls operations are included and not those related to changes in fixture technology or wattage reduction. Energy cost savings are valued according to the national average electricity rate ($0.10/kWh), and cost-effectiveness results for a range of electric utility costs also are provided.

Retrofits of wireless advanced lighting controls on existing lighting systems (typically fluorescent) are considered and new construction or major renovation installations of wireless advanced lighting controls with a new lighting system (LED or fluorescent) also were evaluated. The cost of the advanced controls system for these cases would only be the incremental cost (the cost difference) compared to other options, such as typically specified code compliant systems (*e.g.,* traditional lighting controls like wall switches and zone schedulers). In other words, the incremental cost analysis assumes that a lighting system upgrade is already going to happen and has been budgeted and analyzes only the cost-effectiveness of including or not including advanced wireless controls with the lighting system upgrade. The cost of the advanced lighting controls system options in new construction and major renovation scenarios is, therefore, much lower, and the energy savings from the controls pay for the advanced system costs more quickly.[8]

DETERMINING BASELINE LIGHTING ENERGY USAGE FOR TYPICAL GSA BUILDINGS

Energy savings from the wireless advanced lighting controls system depend on the difference between annual energy usage from the building's baseline lighting system and that of the wireless advanced lighting controls system. For the demonstration sites evaluated here, the baseline lighting energy usage was quite low, so lower absolute energy savings were achieved even though the systems performed well from a percent energy reduction perspective. In both locations, the lights were already operating quite efficiently, likely due to many of the fixtures already being controlled by occupancy sensors. As such, the energy savings available for the advanced wireless lighting systems were limited.

For the cost-effectiveness projections in GSA buildings, a typical, baseline lighting energy usage intensity (EUI) was derived. A baseline lighting EUI for GSA buildings was calculated from a sample of 12 GSA buildings located in California, Nevada, Illinois, Indiana, and Missouri, using an average EUI weighted according to the floor area at each site. The typical GSA building pre-retrofit EUI was found to be 3.25kWh/ft^2 at an installed lighting power density of approximately 1W/ft^2. This average EUI is substantially higher than the lighting EUI at the two demonstration sites, the implication being that energy savings and associated energy cost savings from the retrofit technologies will be higher in typical GSA buildings.

While the sample of data from GSA buildings used to estimate the typical baseline is small, a simple calculation of lighting EUI using some basic assumptions suggests that the value calculated from the sample is reasonable. At an installed LPD of 1 W/ft^2 (.001 kW/ft^2) and 250 days of operation per year, at 12 hours operation per day, a lighting EUI of 3 kWh/ft^2/yr results; very close to the weighted average above. The LPD

[8] In the incremental cost and savings approach for new construction or major renovation, the baseline lighting energy usage against which energy savings are valued is held equal to the GSA and national building average lighting energy usage values. This is a simplification since new lighting systems may include lower power demands than the baseline systems already installed in "typical" buildings. In reality, energy savings will be achieved by lower-wattage lighting systems, as well as energy-efficient wireless advanced lighting controls. The approach here is to consider the controls energy savings first and solely, since lighting controls operations and savings are the focus of this study. Wattage reductions and resultant energy savings from new lighting systems (fluorescent or LED) are outside of the scope of this analysis.

of 1 W/ft^2 reflects the average LPD of the sample buildings, several of which are in California. It is worth bearing in mind that the CEC's Title 24 is among the most stringent building codes in the nation, so those buildings' LPDs, and resultant EUIs, are, therefore, likely to be at the low end of the nationwide range. The number of full load daily operating hours also reflects the low penetration of occupancy sensor controls and other advanced lighting control features into the commercial building market. Lights in the vast majority of commercial buildings are controlled by automatic scheduling only and, therefore, operate at full power during occupied hours (*i.e.* 6:00 AM to 6:00 PM).

Note that moving from the GSA-average baseline EUI of 3.25 kWh/ft^2/yr to the weighted average post-retrofit EUI measured at the study locations (around 1.5 kWh/ft^2/yr) yields around 54% lighting energy savings, as opposed to around 33% lighting energy savings found at the study locations where baseline lighting EUI was significantly lower. Estimating lighting energy as around 26% of total building electric energy usage equates to the wireless advanced lighting controls saving around 14% total building electricity in this analysis.

WIRELESS ADVANCED LIGHTING CONTROLS PROJECT COST ESTIMATE DETAILS

For the advanced wireless controls equipment cost estimates, the technology vendor provided costs per unit as of the fall of 2014. Costs will continue to decline as the fixture adapter component of the wireless system is integrated into the dimmable ballast or the LED driver rather than installed as a separate unit (as done in the demonstration sites for this study). This is in keeping with the evolution of the wireless advanced lighting controls technology and partnerships already in place between the controls vendor and lighting equipment suppliers.

Lighting equipment costs and labor costs per square foot for installation of the advanced controls are based on project data from an actual installation in 2012 of the demonstration technology in a three building portfolio project totaling over 200,000 ft^2. Electrician labor costs are estimated at \$75/hr. To summarize, fluorescent retrofit project cost estimates for this analysis include:

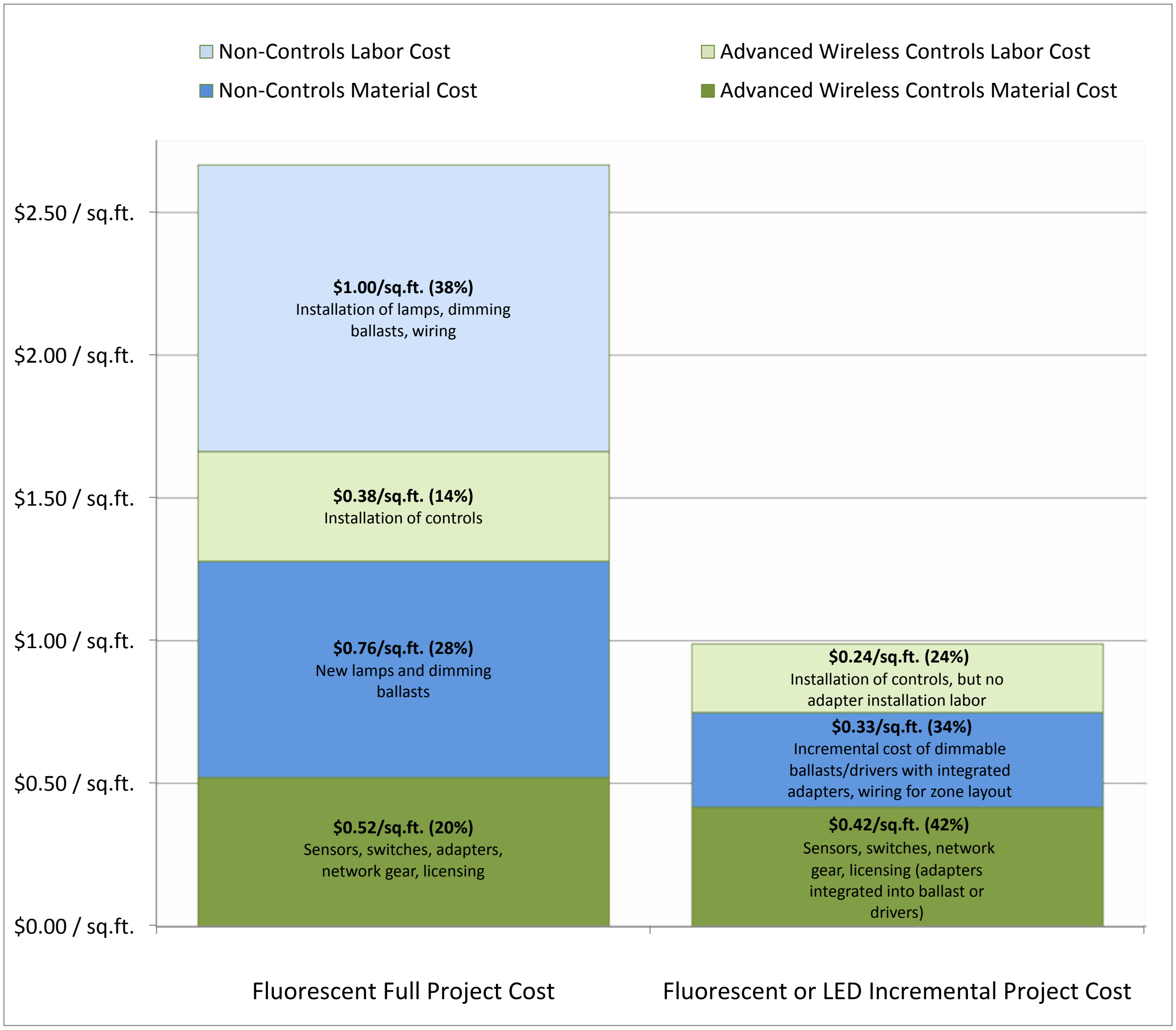
- All advanced wireless controls equipment (*e.g.* sensors, switches, fixture adapters and zone controllers)
- Licensing fees for controls software
- Commissioning labor to setup, program, and configure the controls system and software
- Lighting equipment replaced for the retrofit, including new fluorescent lamps and dimmable ballasts and wiring
- Labor to install all equipment, including contractor "mobilization" costs that include project setup and takedown, permitting, and equipment transportation to and from site. Labor costs do not include contingencies or construction management and inspection costs allocated by the agency for the project.

For new construction or major renovation projects, only the incremental material and labor costs of including advanced wireless controls into a lighting project scope (LED or fluorescent) are considered. For these projects, incremental equipment costs include the costs of all advanced wireless controls equipment and licensing, as well as the incremental cost of dimmable ballasts or LED drivers over regular non-dimming ballasts or drivers. The labor costs are only for the labor needed to install the advanced wireless controls components. For these projects, it also is assumed that the fixture controller is already integrated into the dimmable fluorescent ballast or LED driver, rather than installed as a separate unit, further reducing material and labor costs. This is an increasingly common option for the technology evaluated here (the fixture adapter is installed in the fixture factory or integrated directly into the ballast or driver). Incremental costs for new construction or major renovation projects include:

- All advanced wireless controls equipment (*e.g.* sensors, switches, and system controllers)
- The incremental cost of dimmable lighting equipment (ballasts or LED drivers) over standard non-dimmable lighting equipment that would otherwise be installed
- Licensing fees for controls software
- Labor to install only the advanced wireless controls components
- Commissioning labor to setup, program, and configure the controls system and software.

Figure 39 illustrates the estimated current labor and material costs per square foot for retrofit and new construction installations of wireless advanced lighting controls. The labor and material costs due to the controls system components are presented separately from the labor and material costs due to the non-controls lighting components (e.g. fixtures and ballasts).

Figure 39: Current wireless advanced lighting controls installation cost breakdown



RESULTS

Figure 40 illustrates the sensitivity of simple payback to installed project costs for projects with savings relative to the GSA average lighting energy baseline and to the national average lighting energy baseline. Two payback contour lines, for utility rates of $0.08/kWh and $0.12/kWh, are graphed for the GSA and national baselines. The area between the contours encompasses utility rates between $0.08 - $0.12/kWh. Indicated on the graph are cost estimates for fluorescent retrofit projects and new construction or major renovation projects (only the incremental cost of including advanced wireless controls) for fluorescent or LED lighting projects.

It is clear that baseline lighting EUI, which is determined by the types of lighting systems and controls installed at a location and how those systems operate (*i.e.* annual operating hours) is critical in determining project cost-effectiveness. Where baseline lighting energy usage is higher energy savings are higher and the value of those savings is reflected in lower paybacks. Paybacks are around two to six years faster over the entire range of project costs for projects in buildings with U.S. average baseline lighting energy usage, compared to projects in building with the lower lighting energy baseline of the GSA average. For fluorescent retrofits today, projects with GSA average baseline lighting energy usage reach paybacks of 13 - 19 years for the range of utility rates illustrated, while those with national average baseline lighting energy usage reach payback in 8 - 13 years.

Figure 40: Wireless advanced lighting controls simple payback results

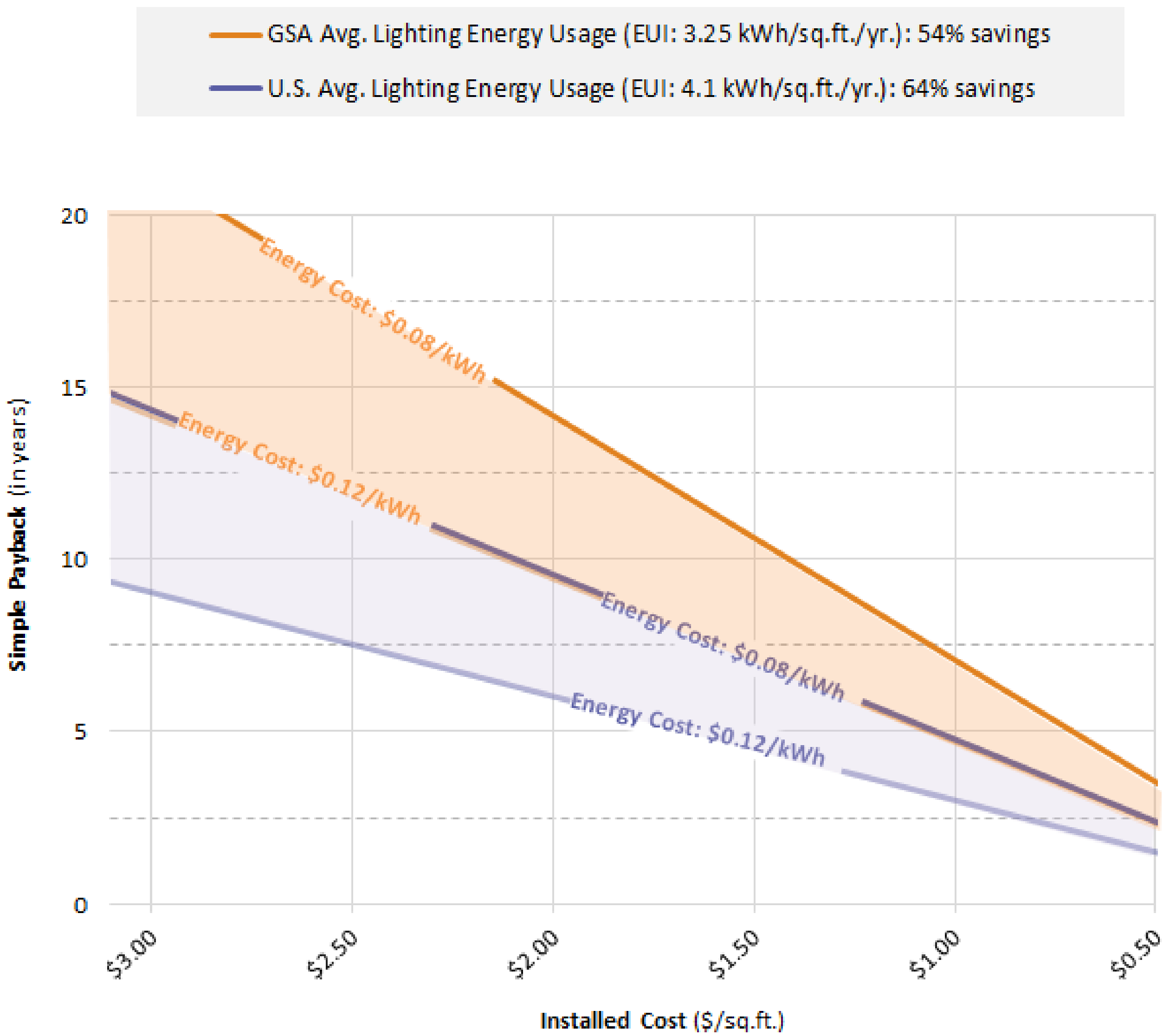
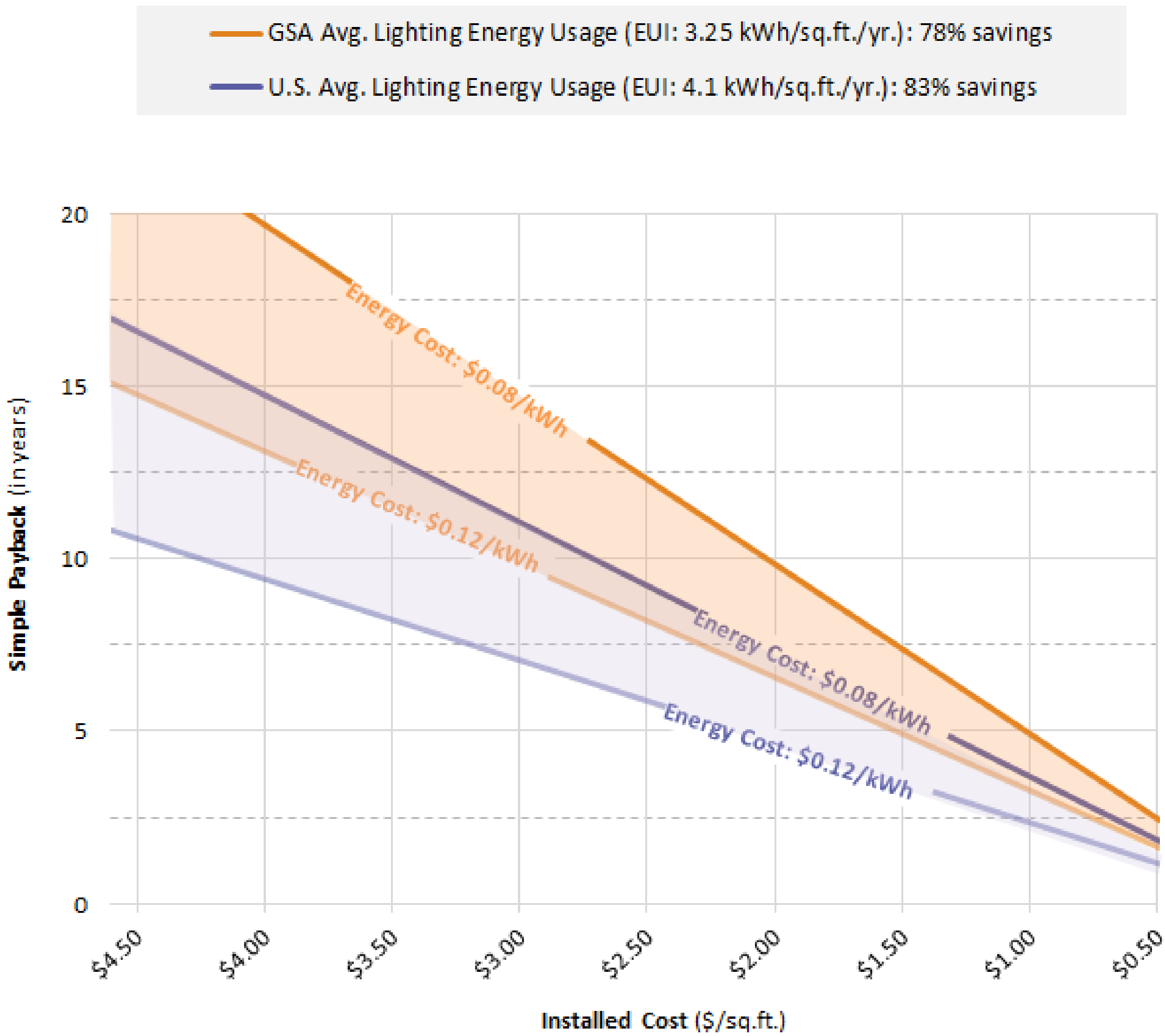


Figure 40 shows that the utility rate, which translates project energy savings into economic value, has a significant effect on payback. Paybacks are better (lower) at the higher utility rate of $0.12/kWh than for the $0.08/kWh rate. Results of the cost-effectiveness modeling indicate that for fluorescent retrofit projects in office spaces with a lighting EUI equal to the GSA average (3.25 kWh/ft^2) and a utility rate of $0.10/kWh or more, simple paybacks of 15 years are realistic now. Where utility rates are \$0.12/kWh or greater, fluorescent retrofits in average GSA buildings should achieve paybacks under 13 years.

The sensitivity analysis of project payback to installed costs and utility rates shows that for new construction and major renovation lighting system projects (LED or fluorescent), for which only the incremental costs of including the wireless advanced lighting controls in the project scope are considered, the payback outlook is significantly better. At a current estimated incremental cost of around \$1/ft^2, paybacks range from 3 to 6 years, making wireless advanced lighting controls a compelling case for these types of projects.

Energy savings increase between 19% and 24% when savings from LED lighting and wireless advanced lighting controls are combined. Installed costs, on the other hand, will be higher when replacing existing lighting with LEDs. Bottom line, LEDs will cost more money initially but save more in the long term. Figure 5 below illustrates the sensitivity of simple payback for wireless advanced lighting controls combined with LED. For locations with GSA-average lighting energy usage, installed costs would need to reach a target of \$3.00/ft^2 at an electric rate of \$0.12/kWh to hit retrofit paybacks in the 10-year range.

Figure 41: Sensitivity of wireless advanced controls with LED simple payback to installed cost, EUI, and utility rate



VI. Conclusions and Recommendations

A. OVERALL TECHNOLOGY ASSESSMENT

ENERGY SAVINGS

BOTTOM LINE

- Energy savings potential for wireless advanced lighting controls is clear, but savings are heavily dependent on the baseline controls condition.
- Advanced controls will be most effective in situations where simple on/off switching by automated schedules and wall switches are the norm and lighting energy usage is higher.
- Institutional tuning opportunities will be highest in locations where the baseline condition is considered overlit.
- Controls vendors and system implementers need to know precisely how dimmable fixtures respond to dimming control signals to implement controls effectively.

The energy savings potential for wireless advanced lighting controls is clear. Even with low, pre-retrofit lighting EUI at the Moss and Appraisers locations (2.2 – 2.3 kWh/ft^2/year), the wireless lighting controls were able to save over 32% annual lighting energy (retrofit EUIs of 1.5 – 1.6 kWh/ft^2/year). Combined with LED fixtures at Appraisers, the energy savings jumped to an impressive 69%. Looking at the energy savings potential at buildings with more typical baseline lighting energy usage than found at the project sites, the case is even more persuasive. A typical baseline of around 3.25 kWh/ft^2/year was found for a larger sample of GSA buildings. The energy savings going from the GSA average lighting EUI baseline to the measured advanced controls retrofit EUI was around 54%. Energy savings, if based on the national average baseline lighting EUI, are even more impressive, at 64%. That increase in energy savings speaks to the influence of existing lighting controls on wireless advanced lighting controls project outlooks in commercial buildings. Whereas occupancy sensors were installed in most of the rooms in the demonstration locations, typical buildings are controlled by wall switches and sometime automated scheduling, resulting in higher annual operating hours and higher energy savings potential.

Lighting circuit and controls system data analysis showed that implementing the advanced wireless control system can save significant lighting energy, but savings are not guaranteed. They are heavily dependent on the baseline controls condition and tenant use patterns. Total savings were high in the Moss sixth floor private offices with abundant daylighting. Similar controls savings were found in mixed perimeter and interior offices at Appraisers. However, in some locations that already had occupancy sensor controls, the advanced controls can actually increase energy usage, as was originally found in M4NW. Results indicated that advanced wireless controls are most effective in situations where simple on/off switching by automated schedules is the norm. If the lighting system already employs occupancy sensors, there will need to be significant daylight harvesting and institutional tuning opportunities for advanced controls to have a large impact.

In general, institutional tuning opportunities will be highest in locations where the baseline condition is considered overlit. With continuously dimmable light sources and advanced wireless controls, lighting power and output can be finely tuned to provide desired light levels without wasting energy or annoying tenants. Institutional tuning may not have realized full potential, however, in the study sites due to discrepancies between the controls "intensity" settings and actual fixture power response. It was found that the fixture power and output was higher than indicated by the intensity settings in the controls system. This issue underscores the need for controls vendors and system implementers to know precisely how dimmable fixtures respond to dimming control signals to implement tuning effectively.

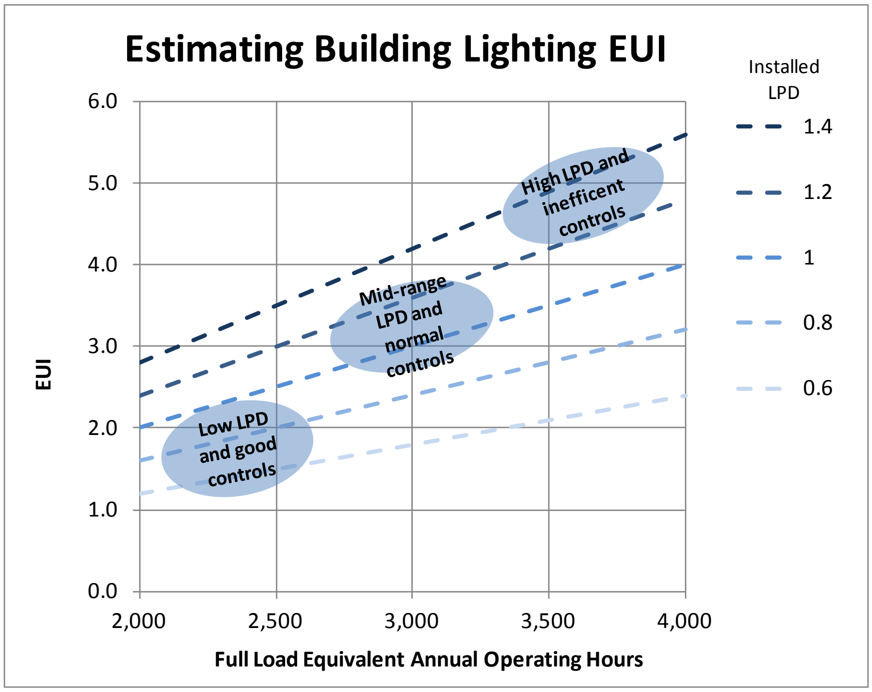
SIMPLIFIED MODEL FOR ESTIMATING LIGHTING ENERGY USAGE INTENSITY

Given that baseline lighting energy usage is such a critical factor in determining whether an advanced lighting controls project makes economic sense, knowledge about baseline lighting systems in existing buildings in the GSA portfolio is imperative. Often, building owners and managers simply do not know important factors about their buildings' lighting systems, such as installed LPD and annual EUI, that would facilitate decision-making about advanced controls investments. Without good working knowledge of lighting controls and usage patterns in a building, an advanced controls investment may not prove to be cost effective in the long run in one case, or an advanced controls project may not be pursued in another case where the savings would justify the cost.

Surveying lighting installations, including total number and distribution of lighting fixtures and the lamps and ballasts in use, as well as the controls in use, will help decision-makers select good sites for retrofits. For a given facility or group of facilities, what are the schedules of operation? Are there already occupancy sensors efficiently controlling the lights? Are spaces overlit, in which case large energy savings may be achieved by using dimming controls to tune lights to a lower wattage, or by installing lower-wattage LED fixtures, or a combined controls and LED fixtures approach?

As guidance on a facility's baseline lighting energy usage, a simplified model for EUI estimation is portrayed in Figure 42. This model requires only some knowledge of installed lighting power density or lighting system annual operating hours, or both, from which lighting EUI can be estimated. Loci have been superimposed on the plot describing the type of controls and lighting that are most likely present for different combinations. These loci are meant to help identify areas of opportunity for advanced lighting controls retrofits. If, for example, installed lighting power is 1W+/ft^2 with high operating hours, lighting EUI is probably over 4 kWh/ft^2/year and significant efficiencies should be gained from installing advanced lighting controls. If lighting power density is very high, but controls are already fairly efficient, with low annual operating hours, a lower-wattage fixture retrofit may be more appropriate. Again, knowledge of existing lighting and controls systems is key to understanding energy savings opportunities.

Figure 42: Estimating lighting energy use from annual operating hours and lighting power density



PHOTOMETRIC PERFORMANCE

BOTTOM LINE

- The addition of advanced wireless controls allowed occupants greater flexibility in varying their light levels according to their preferences.
- Lighting quality was roughly the same pre- and post-retrofit at the Moss location (fluorescent-to-fluorescent retrofit).
- With new LED fixtures at Appraisers, a reduction in installed LPD resulted in a reduction in light levels (still within recommended levels), but lighting quality improved considerably with respect to color rendering.

At the Moss location, wireless advanced lighting controls were installed on existing fluorescent fixtures, which were entirely re-lamped during the retrofit, since new lamps are required when dimming fluorescent controls are used. As both pre- and post-retrofit light sources were fluorescent, lighting quality was roughly the same pre- and post-retrofit. However, the addition of wireless controls allowed occupants greater flexibility in varying their light levels according to their preferences, often producing greater ranges in measured light levels in each site. Pre- and post-retrofit average light levels remained around or above the office workstation light level of 30 fc suggested by IES and GSA's Facility Standard P-100. At the Appraisers location, where advanced controls were installed in conjunction with new LED fixtures, a reduction in installed LPD resulted in a reduction in light levels. However, prior to the retrofit, work surfaces were overlit relative to P-100 required light levels, with an average illuminance of 57.2 fc, which was lowered to an average of 37.0 fc after the LED retrofit. Lighting quality improved considerably with respect to color rendering.

OCCUPANT SATISFACTION

BOTTOM LINE

- At Appraisers, occupants favored the lighting service and performance from the new controls and LED lighting system.
    - Occupants responded considerably more favorably regarding the lighting service and performance from the new LED and wireless advanced lighting controls system. Overall, comfort level with the light levels doubled, with more occupants post-retrofit also feeling like work surfaces were evenly lit and that the lighting system created a good image for their organization. With respect to the lighting controls, more occupants expressed satisfaction with the retrofit system, as well.
- At Moss, occupants responded less favorably post-retrofit regarding the lighting and controls performance, with dissatisfaction regarding the way the occupancy and dimming controls work.
    - Early on in the post-retrofit period, this site experienced significant lamp failures due to the use of unseasoned fluorescent lamps. New fluorescent lamps should be “seasoned” (operated at full power for 100 hours or more) before being used in a dimming system to prevent early failures. Also, legacy occupancy sensors were used in some locations, possibly forcing old zoning schemes onto new work station and controls layouts. Various design and commissioning errors appear to have led to dissatisfaction among tenants at this location. The vendor is currently working with the project location to improve performance and improve occupant satisfaction, which should be the priority of any controls system installation.
    - Missteps in the system design and installation, which have negatively impacted occupants, should be addressed by continued system design and commissioning improvements.
    - An agreement on final commissioning process and details needs to be made between the vendor, contractor, and property manager, and clear communication of design intent is essential for ensuring a successful retrofit, including verifying how fixtures should be zoned and occupancy sensors placed such that they correspond to actual occupant patterns.

COST-EFFECTIVENESS

BOTTOM LINE

- Baseline lighting energy usage is one of the most important attributes for determining if wireless advanced lighting controls make economic sense; high baseline lighting energy use results from very basic controls strategies (no occupancy sensors) and increases the likelihood that advanced controls will pay off.

- A thorough existing lighting system assessment should be completed along with an evaluation of both the technology and costs associated with the retrofit.
- Local utility costs also will affect advanced controls projects' cost-effectiveness.
- In new construction applications or major renovations and replacement of systems at end of useful lives, project cost would only be the incremental cost of selecting advanced wireless controls over typically specified basic controls systems (wall switches and automated lighting schedules only). Cost-effectiveness results for new construction and major renovation scenarios are much better, as the energy cost savings from advanced controls pay for the incremental cost difference more quickly.

Cost-effectiveness will be driven by the ability to reduce project costs and to increase project energy savings. At the demonstration locations, project costs were high and would not necessarily justify the investment even though energy savings were significant. Lowering project costs will require increasing project scales, going for large buildings and competitive bidding to decrease material and labor costs. Costs are projected to decrease further when sensors and controls are embedded directly into the fixture.

Energy savings are expected to be higher for the typical GSA facility than they were at the project demonstration locations. At the average electric utility rate of $0.10/kWh with normalized costs and savings, a fluorescent system retrofit payback of around 15 years was found at present-day pricing for the wireless advanced lighting controls in GSA buildings.

The national average lighting EUI is higher than the GSA average, providing even more energy savings opportunity and better cost-effectiveness for advanced lighting controls. For the normalized costs and savings scenarios, at national average utility cost of $0.10/kWh, the payback dropped to around 10 years for fluorescent system retrofits. Sensitivity analysis for baseline EUI, project costs, and utility cost showed that locations with high EUI and high utility costs will have much better cost-effectiveness results under 10 years in many cases.

B. BARRIERS AND FACILITATORS TO ADOPTION

BOTTOM LINE

- Barriers:
    - Lack of knowledge about baseline lighting systems and operating profiles in existing buildings.
    - Low awareness of lighting as a strategy to achieve significant reductions in electricity consumption.
    - High labor costs as a result of overestimations on install time due to unfamiliarity and perceived difficulty with advanced wireless controls installation.
    - Absence of monetary value applied to benefits of improved lighting control, possibly including improved operational efficiencies (other than energy savings) and worker productivity improvements, as well as an objective methodology to assess these benefits.

- Facilitators:
  - Project economies of scale, more efficient and competitive project bidding, management and execution, and future cost reductions as the products mature and market penetration grows.
  - More stringent code requirements regarding performance of lighting systems (new ASHRAE 90.1 and Title 24 controls requirements).
  - Cooperation between fluorescent and LED equipment vendors and advanced lighting controls vendors, and integration of products for future installations, which should improve performance and project cost.
  - Knowledge about baseline lighting systems and energy usage in existing buildings in the GSA portfolio. Surveying lighting installations, including total number and distribution of lighting fixtures and the lamps and ballasts in use, as well as the controls in use, will help decision-makers select good sites for advanced wireless controls retrofits (see Figure 42).

C. MARKET POTENTIAL WITHIN THE GSA PORTFOLIO

Wireless advanced lighting controls can be installed to achieve significant energy savings and GHG reduction targets throughout the GSA leased and federally owned building stock as well as the private commercial sector, but cost-effectiveness of retrofit projects will depend on the buildings in which they are implemented. Targeted deployment at locations with higher lighting energy usage should be the preferred approach to optimize cost-effectiveness. Results emphasize the need to understand thoroughly the existing lighting system to gauge the potential energy savings. Areas that already have effective lighting controls (such as occupancy sensing in small zones), heavy de-lamping, or otherwise low lighting use may not be able to justify a wireless controls installation with energy savings alone. Projects would be particularly effective in areas with only basic lighting controls and high annual lighting operating hours, as well as higher utility rates. Deployment should be targeted or delayed depending on installation size, application, and utility costs.

GSA manages over 370 million square feet of building space and could roll out advanced lighting controls on a truly impressive scale. Cost reductions and efficiencies at such a scale would surely follow, but undertaking a broad retrofit program would only make sense if the energy savings and other performance benefits justified the cost.

D. RECOMMENDATIONS FOR INSTALLATION, COMMISSIONING, TRAINING, AND CHANGE MANAGEMENT

Results of the cost-effectiveness modeling indicate that, for wireless advanced lighting controls retrofit projects in buildings with lighting energy usage at the GSA average (3.25 kWh/ft^2), at utility rates of $0.12/kWh or more, advanced wireless control systems should pay back in less than 13 years at today's projected prices. At the average utility rate of $0.10/kWh, simple paybacks around 15 years are realistic now and, at projected price decreases in the next 5 years, under 13 year paybacks are realistic then. Significantly lower paybacks will be possible in new construction and major renovation projects, since only the incremental cost of the advanced wireless controls would need to be recovered through energy cost savings; paybacks of five to six years are realistic in those case.

A thorough assessment of the existing lighting system in eligible buildings should be completed to understand whether there is a high potential for advanced controls energy savings. An evaluation of both the technology and costs associated with retrofits should be undertaken when planning for a wirelessly controlled lighting system to guard against unexpected costs and complications and expedite the installation process. In cases where LED fixture retrofits and advanced wireless controls are being considered, the relative costs and benefits of the options alone and in combination should be considered.

It became apparent during the advanced wireless controls installation and commissioning process for the demonstration projects evaluated here that clear communication of design intent is essential for ensuring a successful retrofit. Verifying how fixtures should be zoned such that they correspond with how occupants actually use the space is critical and, as the Moss occupant survey responses showed, incorrect placement or calibration of sensors and other design flaws can lead to tenant dissatisfaction. It seems vital that effective system design and implementation up front be the priority for long-term lighting controls system acceptance and support. In specifying wireless advanced lighting controls, product quality also should be emphasized, including robust product warranties that help ensure system performance for the longer term. Other aspects of system performance and quality assurance, such as reliable communication among networks components and system hosting, also should be stressed during product specification, though details of this nature are beyond the scope of this study.

An agreement on what final commissioning entails needs to be made between the vendor, contractor, and property manager so that the final, commissioned system is effective, energy-efficient, and satisfactory from the tenants' perspective. It is recommended that a protocol for the commissioning of lighting controls system be established and included in contractual documents and agreed to by the commissioning agent. These documents should emphasize the importance of following a clear, well-documented commissioning process. Property managers or others who are familiar with the space should pay particular attention to how fixtures are zoned and how sensors and switches are placed so that they reflect actual usage of the area.

VII. Appendices

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B. GLOSSARY

TERM	DEFINITION
Ambient light	General indirect lighting that illuminates the whole volume of a room softly.
Ballast	A device that regulates the current and voltage supplied to a gaseous discharge lamp or lamps (*e.g.,* a fluorescent lamp).
Ballast Factor (BF)	The ratio of lumen output of lamps operated on a ballast compared to the lumen output of lamps operated on the reference ballast.
Color Rendering Index (CRI)	Quantitative measure of lighting quality, measuring 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 is unitless. The reference source, a blackbody radiator such as an incandescent lamp, is defined as having a CRI of 100. There are 14 pigment color samples that CRIs reference, the first 8 are pastels (R_1-R_8), the next 4 consist of saturated solids (R_9-R_{12}), and the last 2 represent earth tones (R_{13} and R_{14}).
Daylight Harvesting	Lighting control strategy to reduce lighting energy by taking advantage of the available natural light; photosensors detect the level of natural illumination in the area and adjust the electric light output.
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 or kilowatt-hours per square foot per year.
Foot-candle	Unit of illuminance, equal to one lumen per square foot.
Fuel mix	The range of energy sources of a region, including both renewable and non-renewable sources. Also called an *energy mix*.
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).
Greenhouse Gas (GHG)	A gas in the atmosphere that absorbs and emits radiation within the thermal infrared range, resulting in the greenhouse effect in our atmosphere.
IES acceptable light level	Illuminating Engineering Society (IES) sets standards for light levels in different environments. For this study, the acceptable light level for office task lighting is 300 lux, or 30 fc.

Illuminance	The density of incident luminous flux on a surface. In less technical terms, a measure of the amount of incoming light reaching a surface.
Institutional tuning	Lighting control strategy to decrease energy consumption by programming default maximum light levels (below full output) within the lighting management system that reflect area or building policies, or both.
Integrated LED fixtures	Also “LED fixtures”; light fixtures that use dedicated LEDs and drivers integrated into a housing and optical assembly designed for the LED light source
Lamp	An electric light source. Also called a *bulb* or, in the case of linear fluorescent lamps, a *tube.*
LED retrofit kits	Upgrades fluorescent troffers to an LED option by retaining the fluorescent troffer housing, but replacing the fluorescent lamps with a LED light engine along with any relevant thermal management and optics
Life-Cycle Cost (LCC)	A metric that characterizes the costs over the lifetime of the tested technology. LCC results from performing a life-cycle cost analysis (LCCA) that takes into account costs from the initial investment, energy savings, operation and management, and salvage. The costs are converted to net present value (NPV) and are recorded here in $\$/ft^2$ and \$/fixture.
Life-Cycle Cost Analysis (LCCA)	A method to understand the total cost of an investment. This analysis includes costs from all phases in the investment’s life: acquisition, installation, operation and management, use, and disposal. The resulting metric is the life-cycle cost (LCC).
Lighting circuit	Wiring that provides power to light fixtures and ballasts.
Lighting Power Density (LPD)	A metric for characterizing the lighting power in a space at a given time, defined as the lighting power divided by the corresponding floor area. LPD is usually calculated in watts per square foot.
Luminaire	A complete lighting unit, including a light source, physical elements to distribute light, and the necessary electronics to power the light source.
Lux	The International System of Units (SI) unit of illuminance, equal to one lumen per square meter.
Net present value (NPV)	The net present value is the sum of the present values of any present or future cash flows, both incoming and outgoing. *See present value.*

Occupancy sensing	Lighting control strategy to reduce electrical consumption by lowering light levels or turning lights off in an area when occupants leave a control zone.
Photometric characterization	An analysis involving measured illuminance to assess the visible light performance of a lighting system.
Power metering	A measurement strategy involving collecting power consumption data from various circuits.
Present value (PV)	Present value is the current value of a payment or series of payments made at other times. If payments are to be made in the future, a discount rate is used to reflect the time value of money and other factors.
R_a	The general CRI, calculated as an average of the CRIs R_1 – R_8, covering relatively low saturated colors evenly distributed over the complete range of hues.
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 indicates whether the light source will be perceived as warm.
Retrofit	An addition or substitution to the current system. As related to this study, could involve any combination of activities from changing out lamp types to reconfiguring the lighting system.
Savings to investment ratio (SIR)	A metric for characterizing cost-effectiveness by determining the ratio of life-cycle savings from an energy improvement to the initial investment cost. If SIR is greater than 1, the investment is cost-effective over the investment's lifetime. This metric does not have units.
Task lighting	Directed lighting that focuses light output on a specific area within a workspace. Light location and levels depend on the tasks performed in the area.
Workplane Efficacy	Metric for quantifying the lumens available at the surface where visual tasks are performed per unit of power consumed; usually calculated in lumens per watt.

C. SUPPLEMENTAL LIGHTING MEASUREMENTS

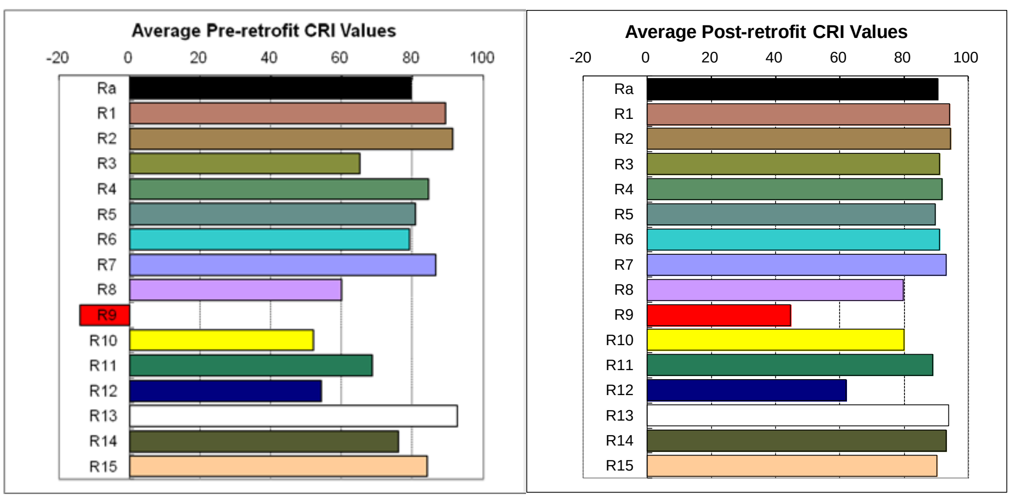
A APPRAISERS COLOR RENDERING

The LED fixtures installed improved the color quality of lighting at Appraisers, indicated by improvements in CRI values (Table 26 and Figure 43). As mentioned previously, the two values that this study focused on were the general CRI, R_a (an average of values $R_1 – R_8$), and R_9, which represents the color rendering quality of strong red tones. Values closer to 100 represent a higher quality of light with color rendering similar to a blackbody radiator, such as an incandescent bulb. The pre-retrofit fluorescent fixtures resulted in an average R_a of 80 and R_9 of -14. The low R_9 indicates that the pre-retrofit fluorescent fixtures did not render strong red tones. The post-retrofit LED fixtures resulted in across the board improvements on all CRI values (Table 26), where the average R_a increased to 91 and average R_9 increased to 45. Results are product-specific and cannot be applied to all LED fixtures.

Table 26: Appraisers average pre-retrofit and post-retrofit CRI

Phase	General CRI, R_a	Red tone CRI, R_9
Pre-retrofit	79.6	-14.0
Post-retrofit	90.6	44.6

Figure 43: Average Appraisers pre- and post-retrofit CRI values

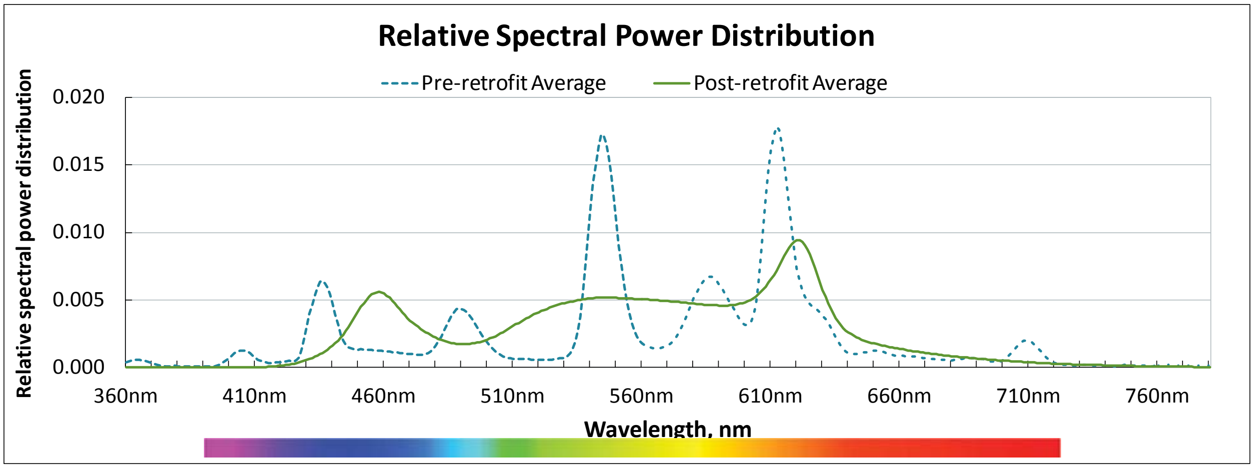


B APPRAISERS SPECTRAL POWER DISTRIBUTION

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 (Figure 44). The pre-retrofit fluorescent fixtures provided a different mixture of light with large spikes of irradiance around 435 nm (blue-violet), 490 nm (cyan-blue), 545 nm (green), 585 nm (yellow), and 610 nm (orange). The pre-retrofit fluorescent fixtures emitted little light at wavelengths greater than 625 nm, correlating with the red tones.

The post-retrofit LED-based fixtures exhibited a more even distribution of irradiance across the visible spectrum, with spikes occurring at approximately 460 nm (blue) and 625 nm (red), and a noticeable trough at 490 nm (cyan-blue). Note that Figure 44 presents results of relative and not absolute spectral power distribution. Although the post-retrofit LED fixtures, in fact, emitted less total light than the pre-retrofit fluorescent fixtures, the area underneath both SPD curves equals 1.

Figure 44: Appraisers pre- and post-retrofit spectral power distribution



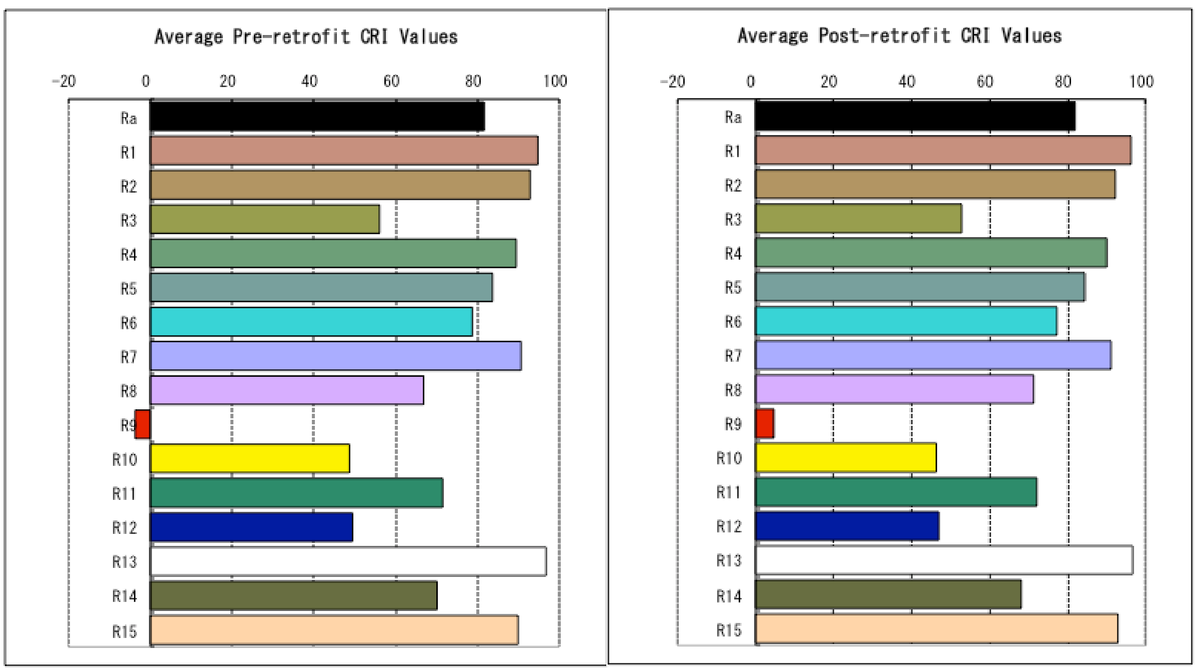
A MOSS COLOR RENDERING INDICES

The re-lamped post-retrofit fixtures at M4NW, M4S, and M6S very slightly improved the color quality of light present at the study location, as indicated by measured CRI values. Overall, color characteristics of the pre- and post-retrofit lighting system are fairly similar, as both systems employed fluorescent lamps. The pre-retrofit fluorescent fixtures resulted in an average R_a in the 80 to 82 range and R_9 in the -9 to 0 range. The low R_9 indicates that the pre-retrofit fluorescent fixtures did not render strong red tones. The post-retrofit fluorescent lamps resulted only in very small improvements in CRI values, with average R_a range increasing to 82 to 85 and average R_9 range increasing to 5 to 16. Average CRI results for M4S pre- and post- are shown in Figure 45, and are very similar to results at the other two Moss locations.

Table 27: Moss average pre-retrofit and post-retrofit CRI

Site	Phase	General CRI, R_a	Red tone CRI, R_9
M4NW	Pre-retrofit	81	0
	Post-retrofit	85	12
M4S	Pre-retrofit	82	-4
	Post-retrofit	82	5
M6S	Pre-retrofit	80	-9
	Post-retrofit	85	16

Figure 45: Moss pre- and post-retrofit CRI values (M4S shown)



B MOSS SPECTRAL POWER DISTRIBUTION

The pre- and post-retrofit relative spectral power distributions indicated that, as expected, the pre- and post-retrofit fluorescent lamps have nearly identical power distribution across the visible light spectrum (Figure 46). Both pre- and post-retrofit fluorescent lamps provided light with large spikes around 435 nm (blue-violet), 490 nm (cyan-blue), 545 nm (green), 585 nm (yellow), and 610 nm (orange). Neither of the pre- or post-retrofit lamps emitted a significant amount of light at wavelengths greater than 625 nm, correlating with red tones. It is worth noting that Figure 46 presents results of relative and not absolute spectral power distribution: the area underneath both SPD graphs equal 1. Spectral power results for M4S are shown in the plot, but are nearly identical for the three Moss sites.

Figure 46: Moss pre- and post-retrofit spectral power distributions (M4S shown)