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Evaluation of Advanced Lighting Control Systems in a Working Office Environment

Disclaimer

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PNNL-27619 Report

The GSA's Proving Ground (GPG) program and the DOE High Impact Technology (HIT) Catalyst program enable federal and commercial building owners and operators to make sound investment decisions about next-generation building technologies based on their real-world performance.

Abbreviations

CCT	correlated color temperature
DOE	U.S. Department of Energy
EUI	energy use intensity
fc	footcandle
GHG	greenhouse gas
GSA	General Services Administration
HOU	hours-of-use
kWh	kilowatt-hour(s)
LED	light-emitting diode
LPD	light power density
O&M	Operations and Maintenance
PNNL	Pacific Northwest National Laboratory
SIR	savings-to-investment ratio
SPB	simple payback

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I. Executive Summary

This report presents an evaluation of a set of advanced lighting control systems and their potential application to U.S. General Services Administration (GSA) facilities.

A. DEMONSTRATION DESIGN

This evaluation project measured and analyzed five different light-emitting diode (LED) lighting systems with advanced controls. The evaluations were conducted within a large office-type GSA building in Fort Worth, Texas, which was originally lighted with 4-foot, T8 fluorescent lighting fixtures with electronic ballasts. Five separate zones were identified within the building as individual test beds for each lighting system.[1]

Energy was measured separately on an individual lighting circuit level for each of the zones. Measurements were taken for a minimum of 2 weeks during each project period and included the following:

- pre-retrofit baseline conditions (existing fluorescent lighting)
- initial LED lighting installation (no controls)
- light-level-tuned conditions
- occupancy sensing enabled
- daylighting enabled.

Building occupants were surveyed before and after the project to provide information about how they perceived the new lighting and how well it served their needs. Light-level data also were measured in selected open spaces in each evaluation zone pre- and post-project to provide insight into changes in light levels that help drive energy savings and contribute to occupancy satisfaction.

This project was not intended to compare specifically one product with another. The project was designed to evaluate the capabilities of these advanced technologies and highlight their positive and negative attributes.

B. EVALUATION RESULTS

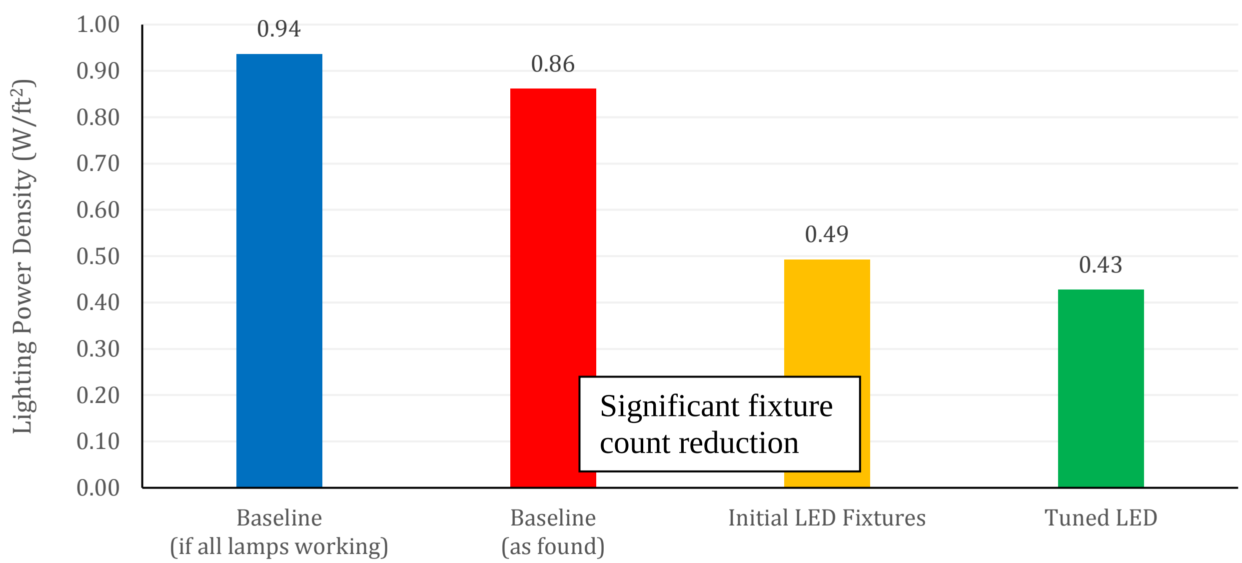
Energy Savings. Energy savings for lighting systems come from reduced maximum lighting power density [LPD] (watts /ft^2) and control of the lighting (on/off/dimming). The measured data for this project show a significant reduction in LPD, which varies between zones but is significant in all of them. These reductions are primarily attributable to a significant reduction in light levels, which were based primarily on a large reduction in the number of fixtures installed to replace the previous lighting fixtures (approximately 30%, from 1,212 down to 847).

[1] Zone 7 included office (mezzanine) and non-office (hallway) spaces. Because the non-office space type has different use characteristics than the office space, it was removed from the results presented in the main section of the report. Data for the hallway portion of Zone 7 is presented in Appendix A.

Figure S1 shows the total site LPD as it existed before the project and as the new LED lighting system was installed and tuned to final light levels. The “baseline” bars represent the maximum lighting power of the pre-retrofit fluorescent lighting system if all lights were working and as found (some lights were burned out or removed) and without any active controls. The after LED fixture and after tuning bars represent the reduction in maximum lighting power with new LED fixtures and light levels adjusted to occupant needs. The LPD reduction across all zones going from fluorescent to LED lighting is 53% (0.86 W/ft^2 to 0.41 W/ft^2) of the original lighting power.

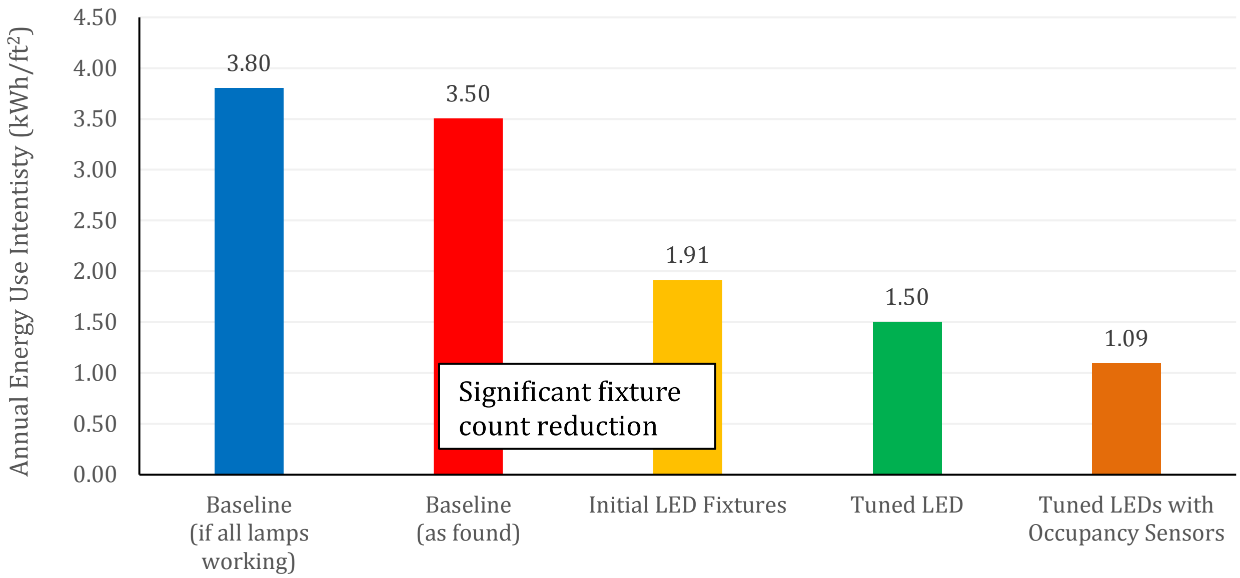
This energy reduction is caused by more than one effect and was accompanied by a significant (32%) average reduction in light levels supported by a large reduction in fixtures as part of the retrofit, which could reasonably account for the first 32% of the 52% overall savings.

Figure S1. Ft. Worth All Zone Weighted Average Lighting Power Density



The addition of control effects provides a complete picture of actual energy savings. The addition of advanced controls provided additional savings but with less variation between zones. The total estimated annual energy use per square foot for all zones combined is shown in Figure S2.

Figure S2. Ft. Worth All Zones Total Estimated Annual Energy Use Intensity



For all office zones combined, the total annual energy use intensity (EUI) savings of 2.41 kWh/ft^2 (3.50–1.09) represents a 69% overall reduction in lighting energy use. Note that the final EUI of 1.09 kWh/ft^2 is well below the reported GSA average of 3.25 and the national office average of 2.7.[2] These significant savings are attributable to several factors:

- 45% of the savings resulted from a combination of improved lighting efficiency (LED) and significant light-level reductions (up to 76%) supported in part by a reduction in total light fixtures.
- Another 12% of the savings resulted from using the light-level tuning capability of these advanced systems. (This tuning is typically an initial setting of light levels to meet occupant needs and is a feature of advanced lighting systems that can be applied later to accommodate changes in occupancy or task needs. This is different from active occupant-activated dimming during the workday that may be an option with some systems).
- The remaining 12% of savings resulted from the networked occupancy sensor and limited daylighting control.

Table S1 provides the EUI values of each of the zones with different lighting systems and controls employed in the space. Table S1 also shows the EUI savings per zone as well as the total of the entire space monitored.

[2] Energy Information Agency Commercial Building Energy Consumption Survey 2012. https://www.eia.gov/consumption/commercial/data/2012/c&e/cfm/e6.php

Table S1. Ft. Worth Energy Use Intensity by Zone

	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7 (Mezzanine)	Total
Fluorescent Baseline	3.49	2.32	3.97	3.00	5.33	3.50
LED Only	2.86	0.98	1.99	1.95	1.66	1.91
Savings	[0.63]	[1.34]	[1.98]	[1.05]	[3.67]	[1.59]
LED+Tuning EUI	2.34	0.84	1.03	1.71	1.55	1.50
LED+Tuning Savings compared to fluorescent baseline	[1.15]	[1.84]	[2.94]	[1.29]	[3.78]	[2.00]
LED+Tuning+Occ. Sensors EUI	1.79	0.54	0.83	1.03	1.25	1.09
LED+Tuning+Occ. Sensor Savings compared to fluorescent baseline	[1.70]	[1.78]	[3.14]	[1.97]	[4.08]	[2.41]

Total lighting energy savings in this evaluation project are significantly driven by reduced light levels. Light-level tuning savings that are part of reduced light levels are typically driven by occupant preferences or task needs, which can significantly vary from office to office. Occupancy sensor savings vary by occupant activity, sensor arrangement, and sensor settings and these also can vary significantly.

The total 69% facility savings found in this evaluation varied from zone to zone with a low of 49% to a high of 79% for office areas, as shown in Table S2. Some of the difference in savings between zones can be related to differences in each lighting/control system and its application. However, significant differences are also attributable to the initial characteristics of the site and final application of controls and light levels. An important observation of these results is the variability in savings, which may not always be easily identified in each application.

Table S2. Ft. Worth Estimated Annual Percentage Savings by Zone

	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7 (Mezzanine)	Total	Typical
Fixture Count Change	[16%]	[47%]	[47%]	[8%]		[30%]	---
New LED fixture install only	18%	58%	50%	35%	69%	45%	---
Tuning Savings	[15%]	[6%]	[24%]	[8%]	[2%]	[12%]	[36%]
LED fixture + tuning	33%	64%	74%	43%	71%	57%	---
Occupancy Controls Savings	[16%]	[13%]	[5%]	[23%]	[6%]	[12%]	[24%]
Total Savings from Lighting Controls	[31%]	[19%]	[29%]	[31%]	[8%]	[24%]	---
LED fixture + tuning + occupancy controls (total)	49%	77%	79%	66%	77%	69%	---

The savings from lighting controls in this project are consistent with energy savings from lighting controls on other projects. A meta-analysis of energy savings from lighting controls includes typical values of 24% occupancy sensors; 28% daylight harvesting; 31% personal tuning; 36% institutional tuning; and 38% multiple control strategies.[3] The tuning value for this site and the meta-analysis differs because of other reductions in equipment (and subsequent illuminance values) occurred before the tuning controls were employed.

Illuminance Values Changes. Section 6.2.2, Lighting Quantity, of GSA PBS-P100 states for Tier 1 that the lighting quality meets the Illuminating Engineering Society (IES) 10th Edition Handbook. Chapter 32, Lighting for Offices, of the IES Lighting Handbook 10th Edition has an illuminance table with a range of values based on occupant age and task. The IES recommends 300 lux [28 fc] for visual display terminal (IES uses the VDT abbreviation referring to computer screens). GSA actively looks to provide appropriate light levels for office tasks. Horizontal illuminance values after the retrofit in all areas also ended up being below typical lighted commercial office environments. Table S3 provides the baseline and tuned LED horizontal illuminance values which ranges between 7 and 35 fc post retrofit. These illuminance values may be practical for applications at this and similar sites, but may not be applicable for all typical office environments and this will affect the potential energy savings compared to those found in this project.

Table S3. Ft. Worth Change in Illuminance

	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7 (Mezzanine)
Baseline (fc)	35.7	30.1	37.7	45.6	Not measured
Tuned LED (fc)	35.4	7.3	24.7	27.0	Not measured
Light Level Change	1%	76%	35%	41%	Not measured

Occupant Satisfaction. The results of surveys of occupants before and after the project show that acceptance of the new LED lighting systems varied some but appeared to be generally lower than for the original system. Given the small sample sizes, it is not clear that the actual differences are numerically instructive. It also is known that human response to change tends to be cautious at first and, therefore, it is not clear whether future responses will be more positive. Regardless, the acceptance percentages after the retrofit are still generally above a reasonable 70% acceptance threshold set by GSA.

Cost Effectiveness as Installed at the Site. The calculated cost effectiveness of this particular project is not encouraging: simple payback periods (SPB) ranged from 26 to 48 years. Note that these cost effectiveness results are specific to this particular site. They should not be used to determine the potential cost effectiveness or applicability of advanced LED-based lighting controls to other sites or projects. The results at this site are related to characteristics that may be found at some, but not all, typical GSA applications. These include:

- A very low electricity rate of $0.07/kWh compared to a typical National average rate of $0.11/kWh.

[3] Williams et al, *Lighting Controls in Commercial Buildings.* Leukos. January 2012. Savings vary on baseline conditions, building configuration, occupant profiles, and even specific rooms within a given building.

- Typical fixture installation cost of approximately $168/fixture.[4] Actual costs at this evaluation site are likely higher than typical because of the need for much relocation of fixtures to accommodate lighting needs.
- Occupancy sensor controls already existing in most spaces in all zones prior to the project, which reduced the amount of savings found after installing the new advanced system.
- Extremely limited daylight capability (only a few windows in one zone). This site evaluation provides data in support of installations without daylight availability. Other evaluations will provide better information for sites with significant daylight capability.

Potential for Project Cost Effectiveness by Varying Site Conditions. The results of this study provide useful data on the potential savings available from advanced LED-based lighting systems. These data can be used to help determine the cost effectiveness of this technology at any office-type site based on selected site-specific characteristics. As a result of this project evaluation a method has been developed that allows sites to determine possible project cost effectiveness. The results of this evaluation also help confirm a set of useful recommendations for prioritizing the application of this technology across GSA facilities. In general, sites or projects with the following attributes are prime candidates for lighting projects and should be considered first:

- Higher than needed existing light levels
- No existing automatic controls
- High electricity rates (energy and demand charges)
- Utility rebates available to help offset first costs.

The attributes of advanced control systems can provide additional energy savings over more typical stand-alone lighting controls, but these may not be cost effective unless the appropriate opportunities exist.

Table S4 presents a summary of the performance objectives identified for this project and the results from this project. In summary, the technology has advantages and effective application opportunities, but it is clear that its application at a specific site may be limited and each potential project needs to be evaluated to determine the cost effectiveness and applicability.

Table S4. Performance Objectives – Advanced Lighting Controls Systems Evaluation

Quantitative Objectives	Metrics & Data Requirement	Success Criteria	M&V Results
Reduce energy usage	Real-time energy metering pre- and post-installation plus comparison with lighting requirements	Energy savings compared to standard expected GSA facility lighting	**Criteria Met.** Savings of an average 63% were achieved with the installation of this control technology
Reduce costs	Cost comparison of current technology and	Favorable energy savings based on SPB and savings-to-	**Criteria Not Met**. Although savings are significant, SPB

[4] Costs used in this analysis are based on estimates developed for GSA by an architect and engineering firm for typical GSA projects. Actual costs at this site were higher but are known to include additional project work costs so they are not considered typical.

Quantitative Objectives	Metrics & Data Requirement	Success Criteria	M&V Results
	advanced lighting control replacement	investment ratio (SIR) over standard lighting controls	and SIR based on estimated typical costs are very high
Easy installation	Installer survey	No issues identified that would raise safety or excessive labor concerns	**Criteria Mostly Met.** Installers found installation time/effort mostly similar to or easier than traditional lighting. Some issues with fit and extra time for separate components
Reduce maintenance	Installer survey plus operator survey plus equipment specifications	Lower calculated maintenance needs compared to the fluorescent system	**Criteria Potentially Met.** Operations indicate systems functioning well and LED technology historically requires less lamp maintenance.
Occupant satisfaction/comfort	Occupant Survey	70% of occupants expressing no issues with the system that would cause dissatisfaction in terms of light levels or function of the system in performance of tasks	**Criteria Just Met.** 77% of occupants found the new lighting acceptable for office tasks and 70% indicated the light was comfortable.

II. Introduction

A. WHAT WE STUDIED

This evaluation project measured the energy savings potential and evaluated the performance, occupant satisfaction, and ease of installation and operation of LED lighting systems with advanced controls. These evaluations were conducted within a large office-type U.S. GSA building in Fort Worth, Texas. Note that these systems were evaluated in order to understand the savings potential for these types of advanced systems. The goal of the project was not to compare the systems or any differences in their individual effectiveness.

Five different advanced control systems that incorporated LED technology were installed in separate zones within the building. Before and after the project, the energy use of each zone was metered to provide accurate energy use profiles and estimates of potential annual savings.

The building occupants were surveyed both before and after the project to provide information about how they perceived the new lighting and how well it served their needs. Those responsible for installing and operating the new systems also were surveyed to evaluate the relative ease of installation and operation of the new systems compared to standard lighting. The five systems evaluated are described in Table 1.

Table 1. Advanced Lighting Control/LED Systems for Evaluation

Lighting System Product	Zone	Fixture Formats	Control Product	Control System
Patriot LED (Axis LED Group) w/Lutron Vive Control	3	2’x4’ and 2’x2’ replacement fixtures and panel retrofits	Lutron Vive ad-on system	Lutron PowPak wireless ad-on control module with remote sensors. Commissioning at each module
Energy Planning & Associates Envirobrite LED w/ Enlighted control	4	2’x4’ and 2’x2’ replacement fixtures and linear lamp retrofits in recessed panels	Enlighted embedded system	Enlighted wireless control and sensors (fixture embedded). Web access
RAB Lighting w/Lutron Vive Control	5	2’x2’ replacement fixtures and panel retrofits	Lutron Vive ad-on system	Lutron PowPak wireless ad-on control module with remote sensors. Commissioning at each module
Philips Lighting LED	6	2’x4’, linear, and surface replacement fixtures and retrofit kit panels	Philips SpaceWise	Integral SpaceWise wireless. Remote control commissioning
FLOW Lighting LED	7	2’x4’ and 1’x4’ replacement fixtures and surface panel retrofits	FLOW SmartNET	Integral SmartNET wireless

B. WHY WE STUDIED IT

The current trend in the use of more efficacious LED lighting in new installation and retrofit projects creates additional opportunities for more energy effective and occupant-friendly lighting control. This is primarily because LED technology as a digital lighting source offers easier dimming control than other technologies, which greatly improves control options. One area of building lighting that always has been difficult to control effectively for energy savings is the area typically labeled as open office. This can include larger open areas with office cubicles as well as similar shared space with multiple occupants and tasks. These spaces historically have been controlled as a single large area with on/off light switches controlling sections of the area. This makes it very difficult or impossible to achieve energy savings by turning lights off or down in smaller specific areas when they are unoccupied.

Currently available, new advanced lighting control systems that combine basic control technology with advanced wireless protocols can take advantage of LED controllability. The systems can harvest energy savings in these open work environments and other similar areas by providing more discrete area and light-level control. These systems offer a variety of advanced control-related features, including light-level tuning as part of initial commissioning to meet the needs of typical tasks or occupant preference, individual networked fixture control and integrated occupancy sensor and daylighting control, as well as system diagnostics and scheduling. These additional options can provide further energy savings depending on the building/space type and can improve occupant satisfaction and comfort.

III. Evaluation Plan

A. EVALUATION DESIGN

The evaluation protocol for this project was designed to measure and evaluate the performance of five different advanced lighting control systems in a working office environment. The data and information collected and analyzed as part of these performance evaluations were then used to develop an assessment of the viability of advanced lighting control strategies in applications at typical GSA office-type facilities. This project was not intended to compare specifically one product with another. The project was designed to evaluate the capabilities of these advanced technologies and highlight positive and possibly negative attributes. The evaluation also was specifically designed to provide useful data and information about multiple aspects of performance, including energy savings potential, occupant satisfaction, installer experience, and system operation.

Energy Savings. This includes overall energy savings as a complete new LED advanced control system and separate savings for identifiable system components. These separate savings allow users to evaluate the savings from and costs of system features for a more effective choice of options for specific facility applications. Separate energy savings information can be important because every potential site application is different and not all aspects of an advanced lighting system will be applicable or will produce the same savings as in other site applications. This evaluation was designed to capture separately the energy savings potential for the following:

- Lighting technology change (fluorescent to LED) separate from control energy savings,
- Light-level tuning (initial light-level setting that is different from active occupant dimming) to meet occupant or programmatic needs,
- Occupancy sensor control, and
- Daylight sensor control.

Energy measurement was provided by The Cadmus Group operating as a subcontractor to Pacific Northwest National Laboratory (PNNL).

Occupant Satisfaction. This includes collected opinions about and ratings of the new LED plus control systems on their own merits compared with previous standard fluorescent-based lighting systems with limited controls.

Installation Considerations. An assessment was completed of the ease with which the various systems could be installed and commissioned for operation.

System Operation. This entails an evaluation of how well the system functions to provide effective space lighting and how practical the system is to operate by facilities staff.

B. TEST BED SITE

The site for this evaluation, chosen by GSA, was the 110,000-square-foot office building #23 at 501 West Felix Street in Fort Worth, Texas. The building includes typical GSA office-type environments that perform the following tasks: administration, engineering, and design. The LED/control evaluation project encompassed approximately 75,760 ft^2 of the building. The remaining portions of the building either were already scheduled for a retrofit project or were not included for security reasons.

Prior to the evaluation project, the building was primarily lighted with 4-foot, T8 fluorescent lighting fixtures with electronic ballasts and a mixture of 2-lamp, 3-lamp, and 4-lamp fixtures. This lighting covered approximately 95% of the building. Lighting control involved wall switches and hard-wired, circuit-based occupancy sensors controlling nearly all luminaires.

The five new control technologies for the evaluation were assigned to different test “zones” within the building based on discussions with GSA staff and the system manufacturers. The zone assignments for four of the five technologies were in contiguous spaces in primary areas of the building. The fifth zone (#7) covered a combination of the mezzanine office area, plus the corridors running throughout the rest of the building test area. Figure 1 and Figure 2show the location of each zone and associated control system. Note that two other zones (1 and 2) initially were identified, but were subsequently not used for either programmatic or security reasons, or both.

Figure 1. Lighting Zones 3–7 Main Floor Offices

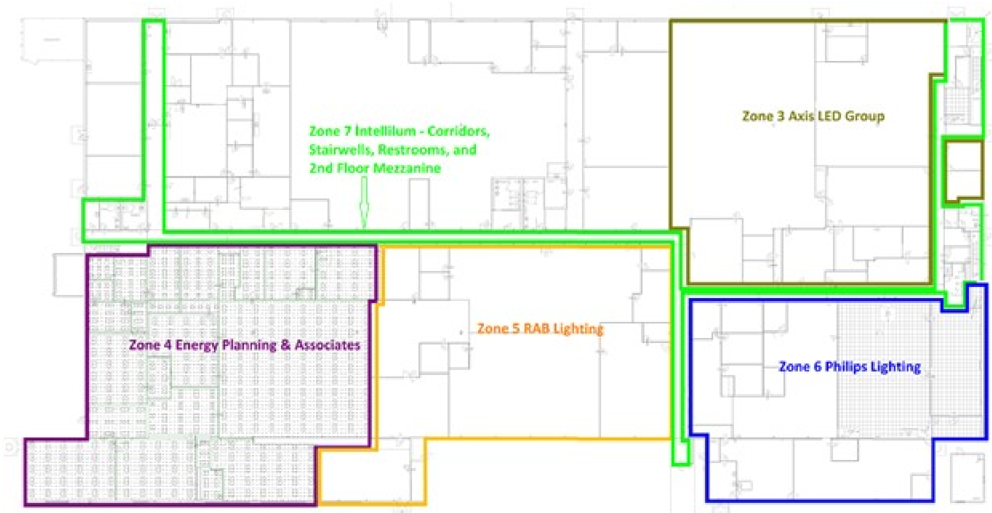
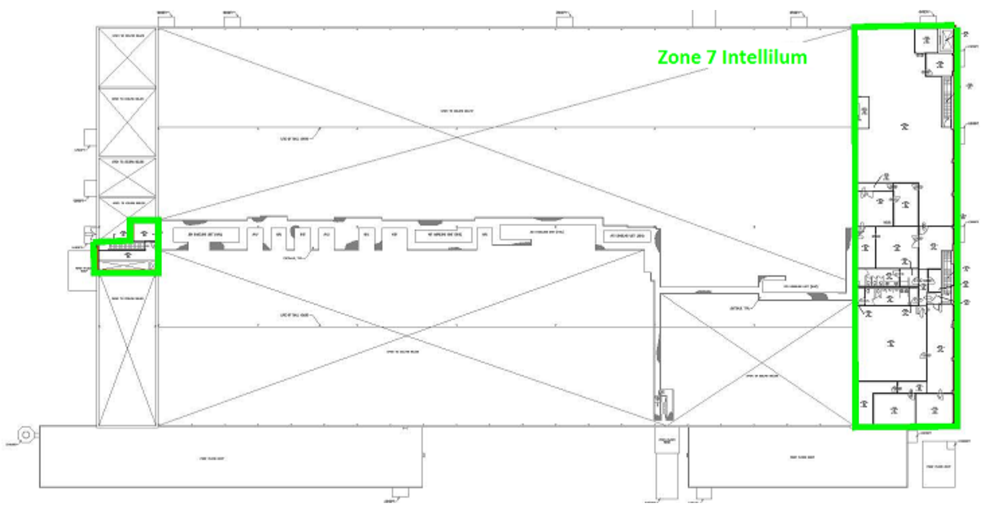


Figure 2. Lighting Zone 7 Mezzanine Office



C. METHODOLOGY

QUANTITATIVE STUDY DESIGN

First, specific lighting circuits representing the various test zones and space types (where possible) were identified to support the metering work. Meters and loggers were installed in May 2016 to capture the baseline energy use of these individual circuits prior to the installation of the new lighting systems. A minimum of 2 weeks of baseline energy data were collected during a time period that was considered to represent typical operating conditions for the various zones.

The metering equipment remained in place after this initial 2-week period and throughout the duration of the evaluation project. As each new LED advanced control lighting systems was installed in its test zone (between November 2016 and February 2017), PNNL and Cadmus worked with the system installation contractor and system manufacturer to set up and operate the system initially in a manner that would allow the metering equipment to capture three post-project data collection periods:

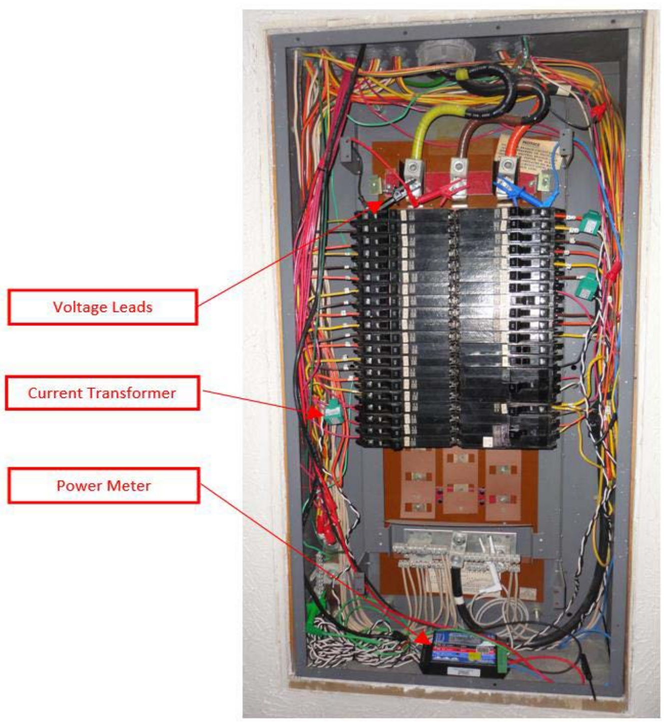
1. Lighting technology change (fluorescent to LED) separate from control energy savings,
2. Light-level tuning (initial light-level setting that is different from active occupant dimming) to meet occupant or programmatic needs, and
3. Occupancy sensor control (i.e., minimal daylighting savings were collected as part of this period for zones with daylighting capability – zone 7 mezzanine office).

Ongoing remote collection of the various data streams was performed, from meter installation through meter removal, to ensure the data stream's validity. In May 2017, the meters were removed and the quantity and types of fixtures in each zone and on each metered circuit were verified.

Each panel or group of panels instrumented for data collection included current transformers, voltage leads, a power meter, and a data logger with cellular transmitting capability (Figure 3). Metering and data logging equipment included the following:

- Wattnode model WNB-3D-480-P3 power meters with 20-ampere current transformers, manufactured by Continental Control Systems.
- Cellular-enabled RX3000 data loggers, manufactured by Onset Computer Corporation.

Figure 3. Typical Fort Worth Power Meter Installation



After the meter installations, one-time measurements of the power of each metered circuit were performed using an AEMC 3945-B power analyzer to confirm that the readings remained consistent with the wattage and quantity of luminaires on the circuit and that the installed power meter/logger combinations reported the correct value. Figure 3 shows the installed metering components.

A total of 28 circuits within the five building zones were metered to characterize separately each advanced system and, where possible, various space types within each of the five zones. For each circuit and zone, the type, wattage, and quantity of all fixtures metered and non-metered within each zone were identified. This aided in understanding the savings contributions from changing the lighting technology alone (without controls) based on either as-found or fully re-lamped conditions. Table A1 in Appendix A summarizes the panels/circuits metered for this evaluation, along with their as-found baseline lighting equipment.

QUALITATIVE STUDY DESIGN

Qualitative topics evaluated included occupant acceptance, installer experience, and system operation.

Occupant Acceptance. The occupants' acceptance or rejection of lighting and its control in their work space can be an important part of occupants' satisfaction with their general work environment. This evaluation project used a short occupant survey distributed before and after the evaluation project to help understand occupant acceptance.

A survey developed to gather occupant opinions about lighting and its control characteristics was provided to building staff to administer to occupants in each evaluation zone. The surveys did not include any personal identification questions, so the anonymity of responses assured the most candid input possible. The surveys were initially distributed prior to the project to get a baseline level of acceptance of the existing fluorescent lighting system.

A second survey, which used the same survey instrument and questions, was distributed 2 weeks or more after the evaluation project with the new systems was completed. This allowed occupants to have some settling time to get used to the new lighting and avoid instant reactions that may not be representative of their overall system acceptance or rejection.

Staff turnover within the various departments in the building was relatively low; therefore, the responses received can be expected to be from generally the same pool of occupants both before and after the evaluation project. A copy of the survey instrument used in this evaluation can be found in Appendix A.

Installer Experience. Shortly after the installation work was completed, project staff administered a separate survey to the individuals performing the physical replacement of the lighting and connections. Questions on this survey were specifically aimed at identifying any issues related to installing the technology that might make it different, easier, or more troublesome compared to installing more typical fluorescent or standard LED technology. A copy of the installer survey used in this evaluation can be found in Appendix A.

System Operation. The GSA staff responsible for operating facility systems, including the lighting, also received a survey with specific questions. These questions were designed to evaluate how easy or involved the operation of the new system with its advanced control features was compared to the previous, simpler system. The survey also inquired about the operator's opinion regarding the effectiveness of the new system for meeting facility needs.

DATA ANALYSIS

Data analysis included the processing of raw data collected for each separate zone both before and after the evaluation project for comparison purposes. This included metered lighting energy use, measured typical illuminance values, surveys of occupant satisfaction, lighting equipment installer experience, and building operator experience.

The raw metered lighting energy data were collected, processed, and analyzed in combination with cost information to develop results indicating energy savings potential and cost effectiveness. Pre- and post-project light-level data were analyzed to understand the effect of the project on the quantity and quality of lighting in the facility. Pre- and post-project building occupant survey responses were collected and analyzed to evaluate how the lighting project impacted occupant satisfaction and comfort with the new lighting. Separate survey input from the lighting system installers and building operators also was collected to provide information about the ease of installation of these advanced systems and their effects on building operation.

Energy Data. Actual energy use for pre- and post-project conditions was measured, and the associated data were processed along with one-time load measurements and fixture count data to produce relevant energy use metrics.

While onsite, baseline and retrofit fixture types and quantities were inventoried to estimate the maximum power for each lighting circuit. This site inventory revealed a considerable number of burned-out lamps. Based on the number of burned-out lamps identified on a circuit, the measured baseline power for each circuit also was adjusted to provide a reference for savings that would have occurred had all fixtures been fully operable during the baseline period. These data also were used to provide energy use information for circuits that were not able to be measured. Not all lighting circuits in the zones measured were usable for evaluation purposes. Some included light fixtures across more than one study zone and others included non-lighting equipment. To include this energy use, the lighting fixture count and fixture wattage data collected both pre- and post-project were applied to extrapolate this energy use based on collected energy use in similar space-type circuits.

For each circuit, annual hours-of-use (HOU) were estimated by multiplying 8,760 hours (1 year) by the use ratio determined by dividing the average baseline power (averaged over the measurement period) by the maximum circuit power for the same period. This equates to the effective HOU that can be applied to energy use baselines to calculate savings from occupancy controls. Weekend and weekday usage were calculated separately and combined to determine the total annual HOU.

To calculate energy savings from lighting technology replacement alone (fluorescent to LED with no control savings), the HOU estimate was multiplied by the baseline and retrofit power demand, resulting in a consistent value for annual energy consumption in the baseline and post-project conditions for each circuit.

To assess savings from light-level tuning control (sometimes called “high-end trim”), the calculation included what the annual energy usage would have been with the maximum power measured during the final configuration for each circuit compared to the baseline HOU and then compared to fixture replacement annual energy usage. The difference represents savings from dimming the lighting to preferred occupant light levels.

To assess occupancy sensor control savings, the calculation included the raw data needed to distinguish between pre-project occupancy-based controls savings from savings provided by the new occupancy sensor controls. The HOU with occupancy controls enabled for each space were estimated using the same method used to calculate the baseline HOU and extrapolated to a full year using the ratio of the metered period to a full year. This calculation assumes that actual occupancy during the metered period is representative of a full year. Staffing, task, or other operational changes could increase or decrease the actual savings from occupancy controls.

The building presented very little opportunity to achieve energy savings from daylight harvesting, because most of the retrofitted spaces did not have windows. Therefore, this evaluation could not effectively consider energy savings from daylight harvesting, and any such savings are encapsulated with the occupancy sensor savings.

Illuminance Data. Illuminance was measured in lux using handheld meters in selected open spaces in each evaluation zone.[5] Data were collected on floor grids, typically 2' by 2', where practical. Measurements were taken both pre- and post-project (including final commissioning) in the same locations, when possible. In a few cases, new grids had to be used to match the relocation of the new LED lighting. The pre-and post-project data for each grid were analyzed based on how representative the measurements were of typical lighting. In some cases, individual grid point measurements were not used in either pre- or post-project measurements because of blockage after the project. The data were processed to develop average illuminance values for each area for comparison pre-and post-project. These representative measurements were not expected to capture specifically each entire zone, but are considered representative of the typical change in illuminance values across each zone.

Occupant Satisfaction Data. Survey responses from occupants both before and after the project were summarized by determining the average responses to each question. These average responses were compared to identify any characteristics of the existing versus new lighting systems that were significantly better or worse.

The number of occupants responding to the survey within each zone was relatively small, ranging from 3 to 22. Total responses for the combined test areas were 58 pre-project and 44 post-project, for an effective comparison sample of only 44. The total estimated number of occupants in the combined evaluation zones was approximately 230 based on a total building occupancy of 350 and just over 65% of the building covered by the evaluation zones.

In general, statistical significance related to quantifying human responses to their environment (i.e., satisfaction by age or gender or percentage "level" of satisfaction) is considered unavailable until sample sizes of over 50 responses are achieved.[6] However, that does not mean that input from sample sizes smaller than this is not valid for some purposes. The general trend of collected responses across all respondents, as well as specific issues raised within individual responses, are valuable in assessing the

[5] Illuminance was measured in lux (lumens/m^2). The values were converted to footcandles [fc] (lumens/ft^2) by dividing lux values by 10.76.

[6] Online sites that provide statistical information about human survey instruments, such as Survey Monkey, offer calculators showing that for a population of approximately 230 occupants at reasonable levels of confidence (90%) and margin of error (10%), the sample size (occupants responding to surveys) needs to be at least 53. (https://www.surveymonkey.com/mp/sample-size-calculator/?ut_source=help_center)

general acceptance of the lighting as well as highlighting any potential individual issues with the technology.

Installer Experience Data. A survey with specific questions about the experience of the installers with the new lighting systems was developed and distributed by building staff to the installation crews. Results were analyzed primarily as a comparison of this installation with a more typical fluorescent lighting installation. All notations were presented, as well as a general assessment of the ease of installation based on the responses.

Operator Experience Data. A survey also was developed specifically for building operators responsible for operating or managing the control system. Results were analyzed primarily as a record of any notations regarding the ease of operating the system and how effective it was at providing lighting conditions to meet occupant needs.

IV. Demonstration Results

The viability of a new technology or advanced form of existing technologies depends on more than one factor, including cost effectiveness and occupant satisfaction. This evaluation project was designed to provide information about the potential cost effectiveness of and occupant satisfaction with advanced LED-based lighting control systems. Specific site or project characteristics always will play an important part in determining effective applications. The quantitative and qualitative results presented here will help in determining application effectiveness.

A. QUANTITATIVE RESULTS

Energy savings for lighting systems come from reduced LPD (W/ft^2) and control of the lighting (on/off/dimming). LED lighting systems with advanced integrated controls can do both, and the data collection for this project was developed to identify these specific savings separately.

The measured data for this project show a significant reduction in measured lighting power that varies between zones. Reductions in lighting power can be attributed to the fewer light fixtures in the post-retrofit, increased efficacy of the new lighting type to help meet lighting needs, as well as reductions in light levels from fewer fixtures or dimmed levels. At this evaluation site, the total number of fixtures was reduced from 1,212 to 847 for an approximate 30% reduction. Although the power and light output for previous fluorescent and new LED fixtures were not the same, this large reduction is clearly the driver for reduced light levels contributing to significant energy savings. The variation in this reduction between zones at this site is attributed primarily to the differing initial light levels. Existing levels before the project were not uniform across all evaluation zones. This can be typical and expected for older facilities with multiple tenants and multiple past retrofit projects. Light levels also were significantly reduced in several areas as part of the project to meet differing occupant needs.

Lighting reduction and corresponding LPD reduction are not directly one-to-one relationships. However, in the case of this project, the significant reductions resulted in yearly energy reductions.

The data also show control savings attributable to the new advanced control systems. These savings are more consistent between zones than the power reduction savings but some variability is still attributable to multiple factors, including the following:

- Varying occupant behavior. The automatic controls of the new lighting systems will control the lighting according to the differences in occupant activity between zones, resulting in different amounts of savings from automatic controls.
- Potentially varying system sensor control settings. Each system can have varying control time-out settings, both pre- and post-project that will affect energy savings.
- Sensor location and type. Different products can have different capabilities, but the capabilities are typically related to sensitivity and control settings and are not considered a primary driver of differences in this evaluation.

REDUCED LPD SAVINGS

Part of the energy savings at this evaluation site are derived from changes in LPD to meet occupant and task needs. This reduction in LPD is derived from a combination of a reduced number of fixtures associated with the installation of new LED fixtures and light-level tuning. Light-level tuning is typically part of the initial installation and commissioning and is used to set the basic light level for the space, which also sets the maximum lighting power use that is responsible for significant savings over the previous system.

In Figure 4 and Figure 5, the savings values represent the LPDs at the various different stages/functions of the new advanced lighting system, as follows:

- "Baseline (if all lamps working)" = old fluorescent (FL) system if all lamps were working and without any active controls.
- "Baseline (as found)" = old FL system as found with some lamps not working and no active controls.
- "Initial LED Fixtures" = new LED system as initially installed (typically with lower light delivery than the old system) but with no light-level tuning and without any controls activated.
- "Tuned LED" = new LED system with light levels adjusted (light-level tuning) to meet occupant needs. This varied from no adjustment to varying adjustment in a zone to meet individual occupant requests.

Figure 4 shows the total site LPD as it existed before the project and after the new LED lighting system was installed and tuned to final light levels.

- The LPD (W/ft^2) reduction from the as-found condition to the Initial LED Fixtures condition across all zones is 43% (reduction from 0.86 to 0.49 W/ft^2), which can translate to the same percentage energy (kWh) savings. However, this value represents the installed power and does not actually indicate use. Notice that operational changes occurred and the actual energy savings are only 41% as shown in Figure 7.

Replacing fluorescent technology with LED does typically improve efficacy and, therefore, can reduce the amount of energy used.

Figure 4. Ft. Worth All Zones Lighting Power Density

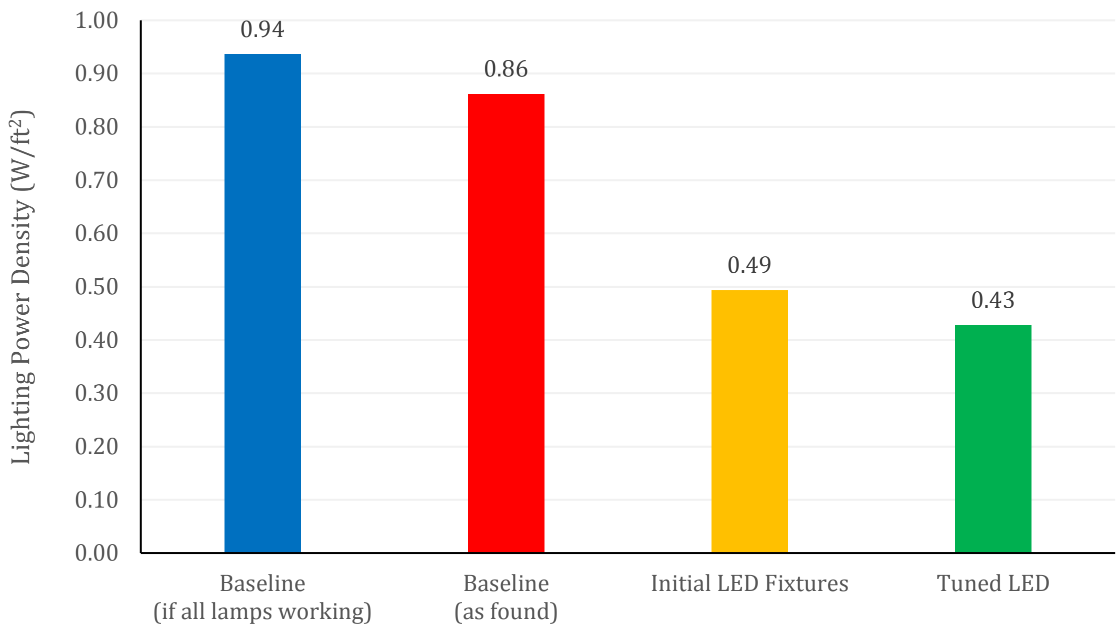
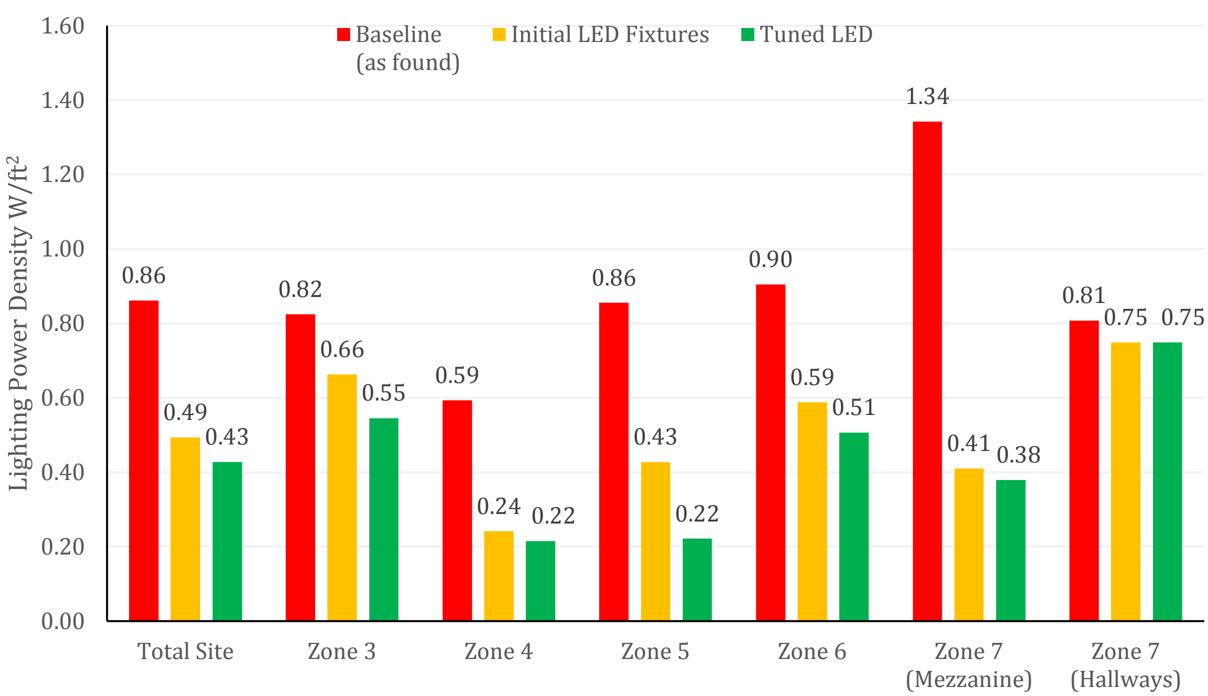


Figure 5 represents the LPD values by zone related to the as-found pre-project baseline. This figure serves to show the variety of existing LPDs before the project, as well as the variety after the project, which is the driving force for the savings at this site.

Figure 5. Ft. Worth Lighting Power Density - Total Site and Per Zone



Figures presenting the estimated annual kilowatt-hour savings by zone can be found in Appendix A.

TOTAL SAVINGS INCLUDING CONTROL

The total estimated annual EUI (kWh/ft^2) for all zones combined is shown in Figure 6. This represents both equipment and control savings achieved by going from the previous fluorescent system with occupancy sensors to the new LED systems with advanced integrated controls. Similar to Figure 4, Figure 6 represents the EUI at the various different stages/functions of the new advanced lighting system with the added level that includes the activation of occupancy sensors. The relative percentage savings attributed to each function of the new advanced lighting control system are shown in Figure 7. The total annual savings of 2.41 kWh/ft^2-yr (3.50–1.09) represents a total 69% overall reduction in lighting energy use.

- 45% of the savings resulted from a combination of improved lighting efficiency (LED) and significant light-level reductions caused by reduced quantities of fixtures and light-level tuning**.**
- Another 12% of the savings resulted from using the light-level tuning capability of these advanced systems to, in some cases, further reduce the light levels to meet specific area and occupant needs.
- The remaining 12% of the savings resulted from the networked occupancy sensor and limited daylighting control.

Total lighting energy savings in this evaluation project are significantly driven by reduced light levels, primarily from significant reductions in the number of new fixtures installed to replace the older system. Light-level tuning savings are typically driven by occupant preferences or task needs. Occupancy savings vary by sensor arrangement and settings.

It also should be noted that the light-level tuning and controls savings percentages (12% and 12%, respectively) are a percentage of total project savings, which include significant savings from initial lighting power reductions and therefore may be considered relatively small. In similar office setting projects where light-level tuning and control capabilities are considered separately from lighting power reductions, the relative savings are found to be as 36% and 24%, respectively.[7]

The total energy savings vary between zones based on natural differences in each area's characteristics and occupant work behavior. In this case, total savings vary from a low of 49% up to 79%. Figure 8 through Figure 12 present the EUI for each zone. Each figure also provides specific zone retrofit details including fixture counts, pre-existing controls, and savings percentages. Note that in Zones 3 through 6, the pre-retrofit fluorescent fixtures were primarily 2-lamp fixtures. Zone 7 (Mezzanine) had predominantly 4-lamp fixtures. The LED fixtures in all zones were predominantly panel type and therefore no "lamp" quantities are applicable.

[7] Williams et al, *Lighting Controls in Commercial Buildings.* Leukos. January 2012. Savings vary on baseline conditions, building configuration, occupant profiles, and even specific rooms within a given building.

Figure 6. Ft. Worth All Zones Total Estimated Annual Energy Use Intensity

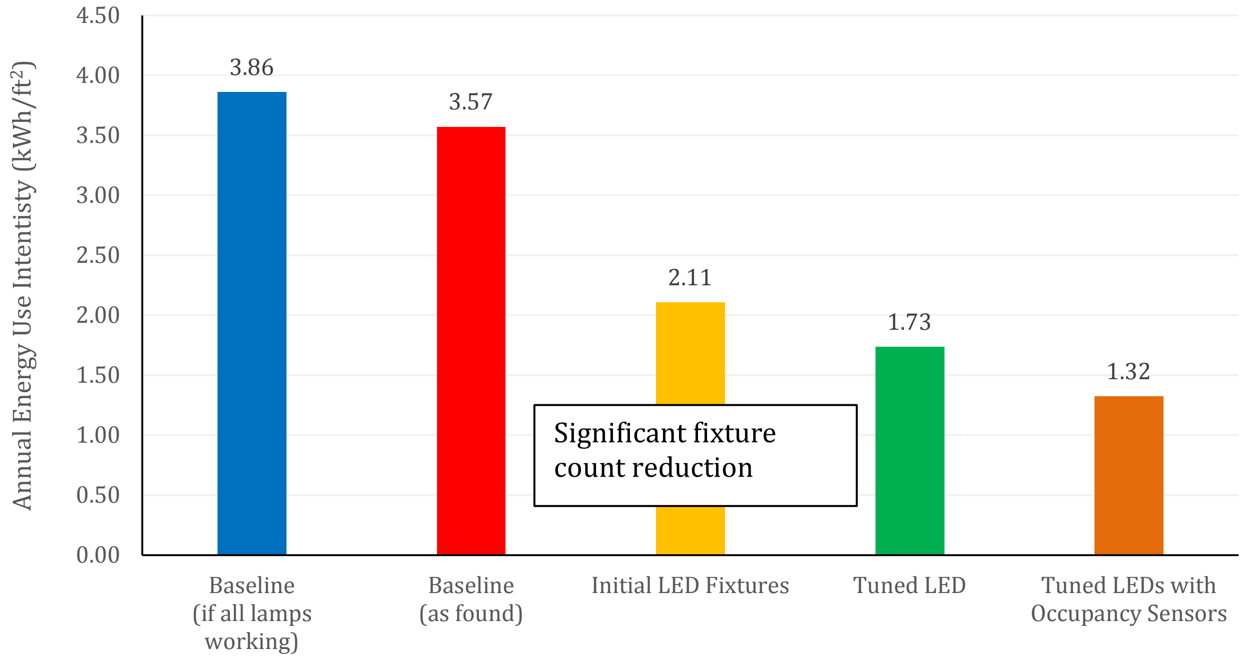


Figure 7. Ft. Worth Total Estimated Annual Percent Savings

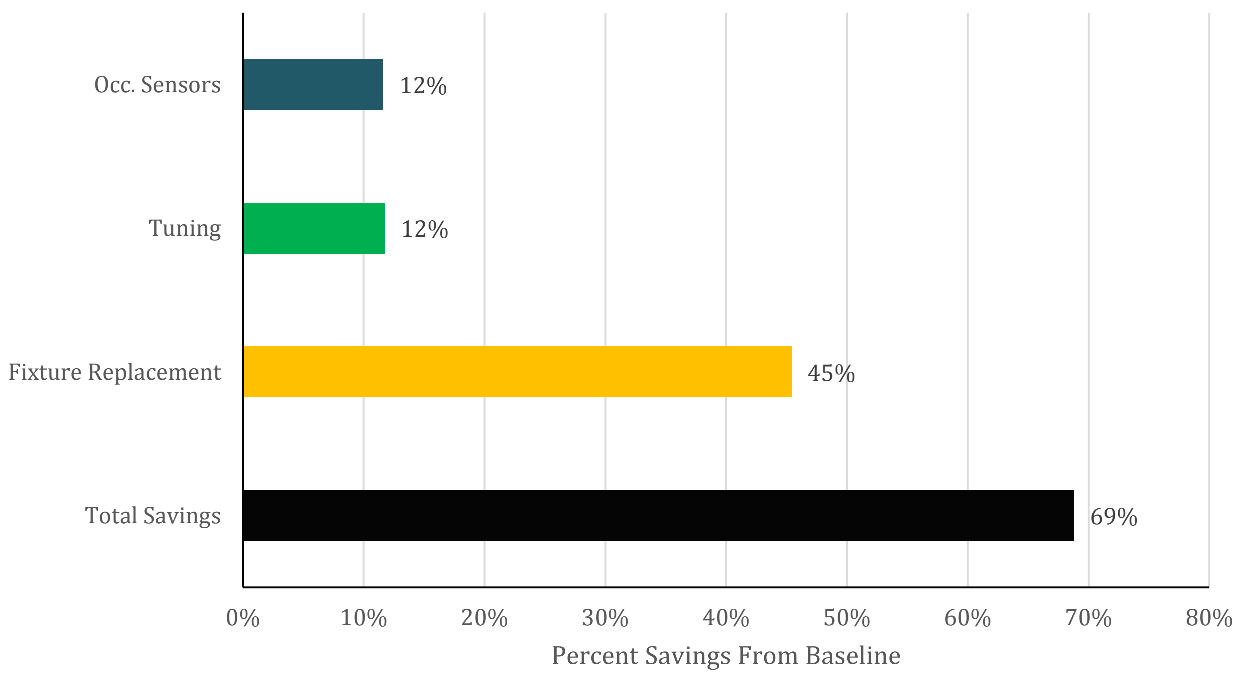


Figure 8. Ft. Worth Zone 3 Estimated Annual Energy Use Intensity

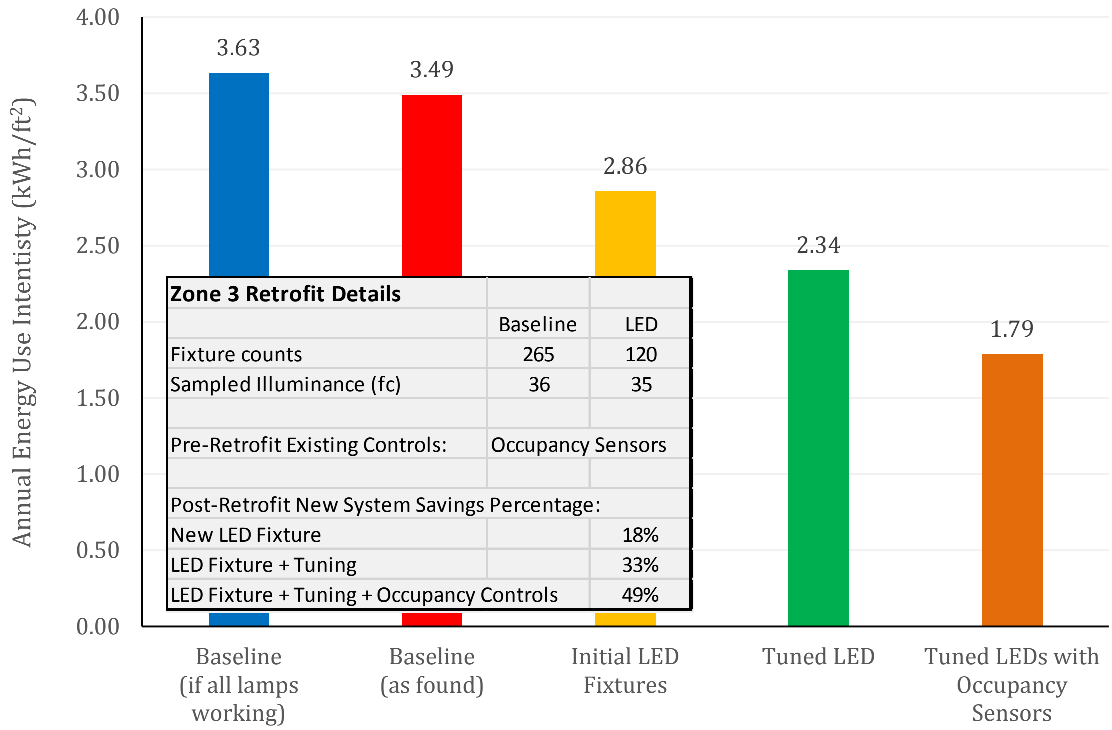


Figure 9. Ft. Worth Zone 4 Estimated Annual Energy Use Intensity

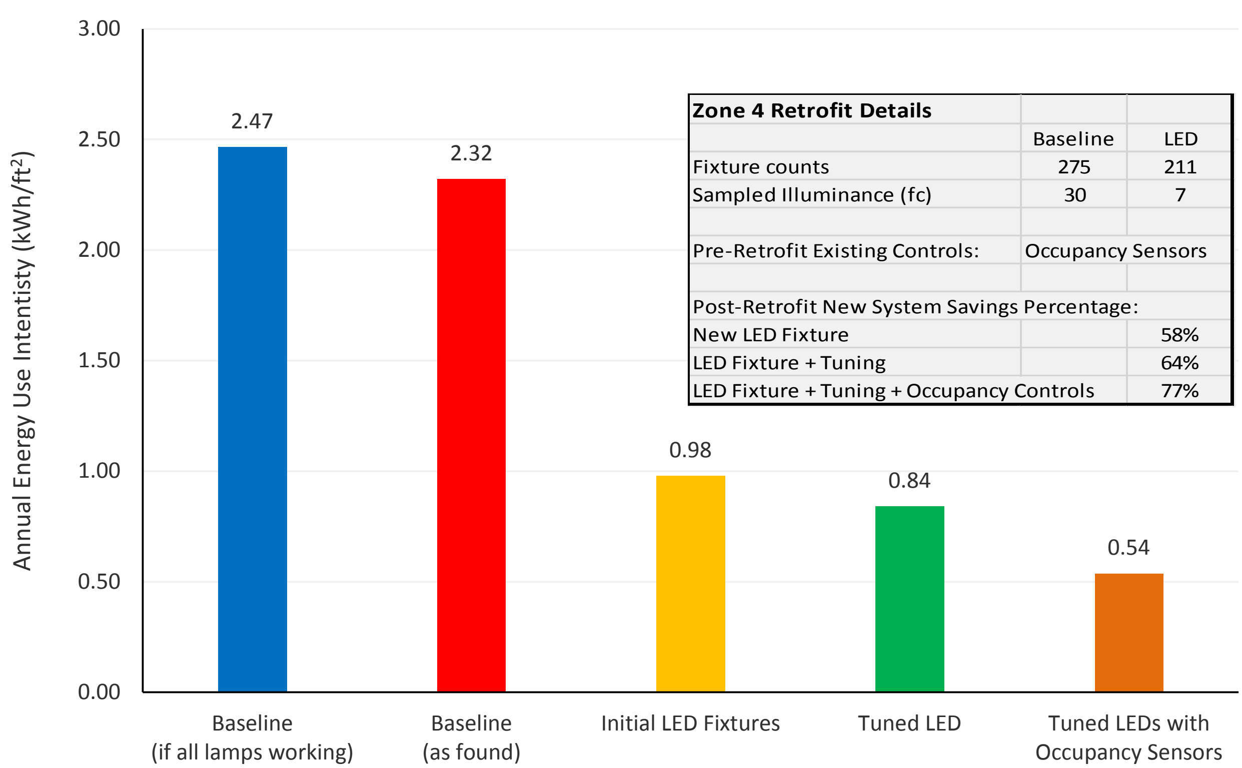
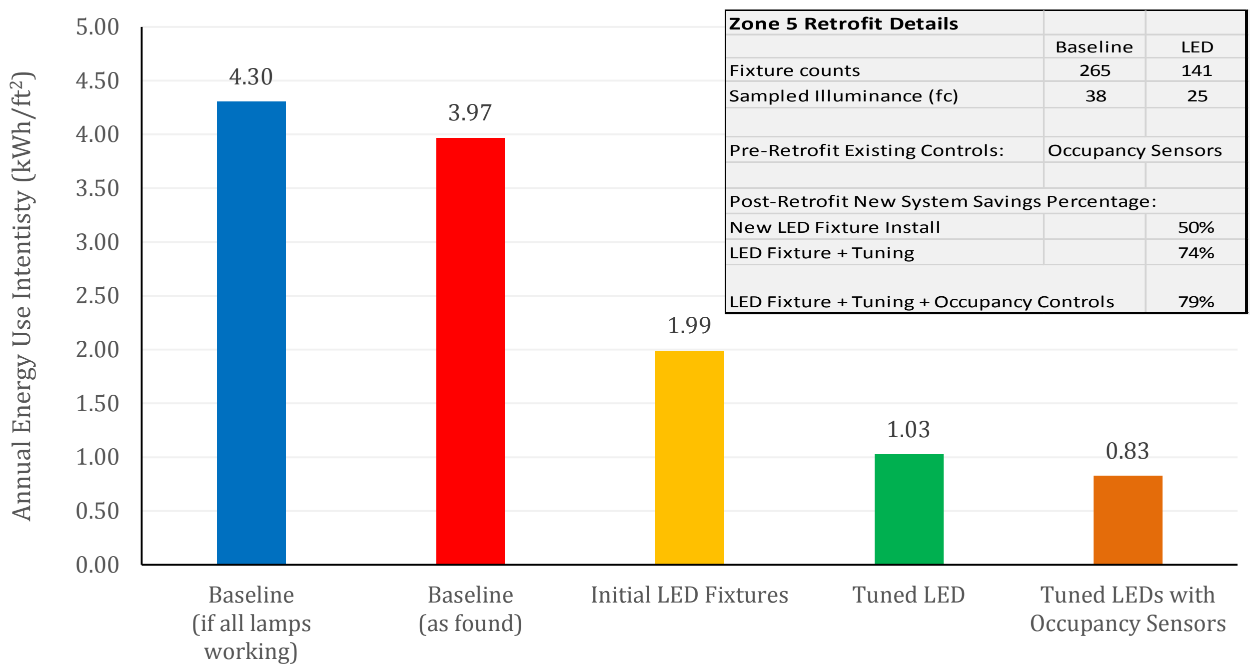
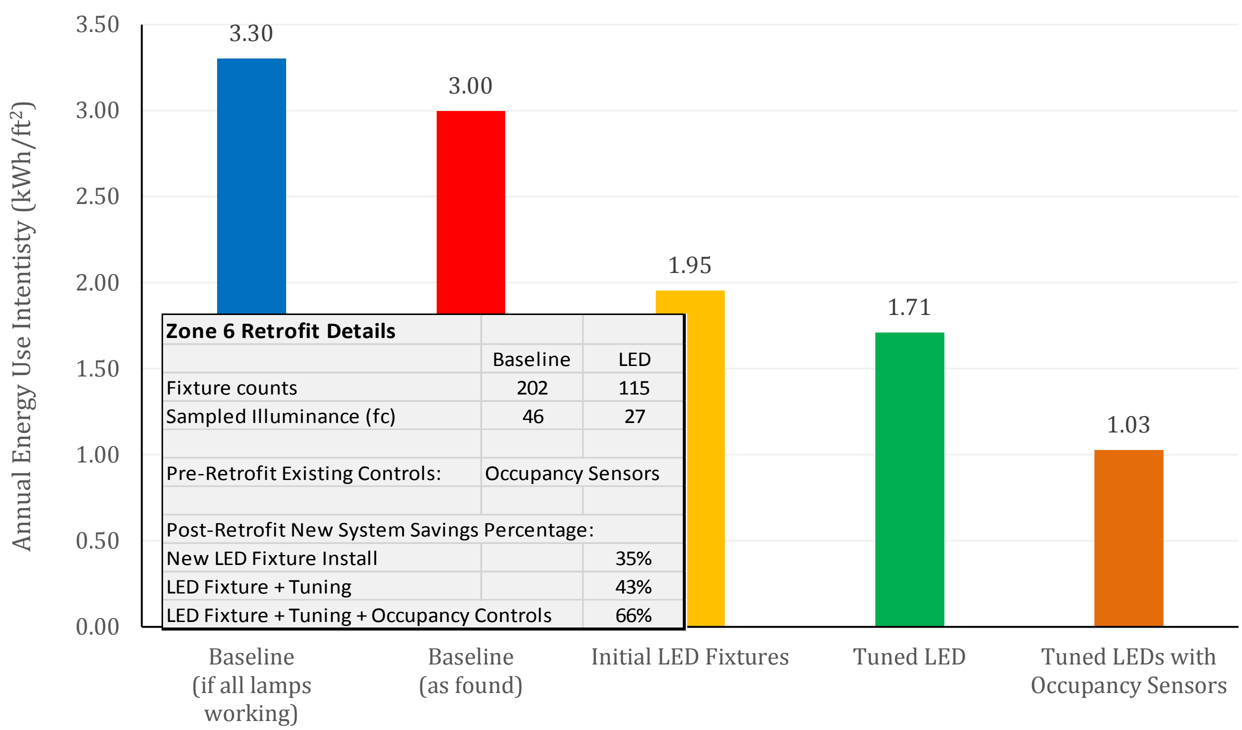


Figure 10. Worth Zone 5 Estimated Annual Energy Use Intensity



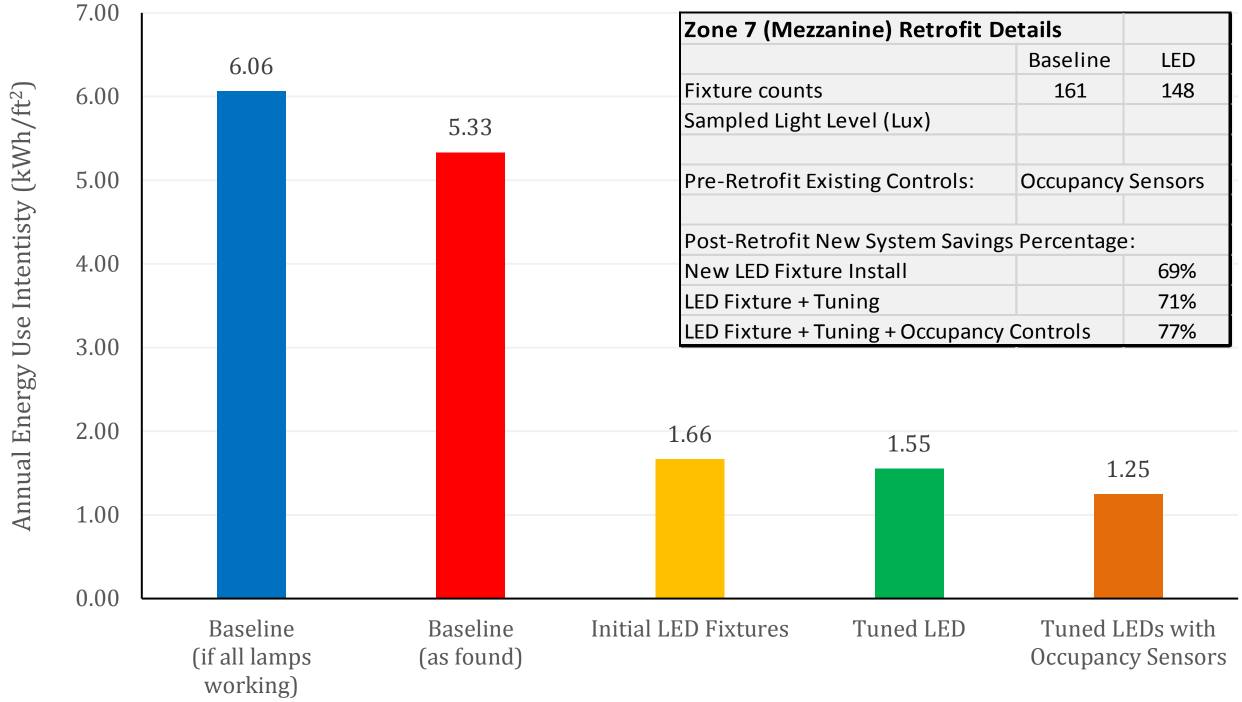
Zone 5 Retrofit Details		
	Baseline	LED
Fixture counts	265	141
Sampled Illuminance (fc)	38	25
Pre-Retrofit Existing Controls:	Occupancy Sensors	
Post-Retrofit New System Savings Percentage:		
New LED Fixture Install		50%
LED Fixture + Tuning		74%
LED Fixture + Tuning + Occupancy Controls		79%

Figure 11. Ft. Worth Zone 6 Estimated Annual Energy Use Intensity



Zone 6 Retrofit Details		
	Baseline	LED
Fixture counts	202	115
Sampled Illuminance (fc)	46	27
Pre-Retrofit Existing Controls:	Occupancy Sensors	
Post-Retrofit New System Savings Percentage:		
New LED Fixture Install		35%
LED Fixture + Tuning		43%
LED Fixture + Tuning + Occupancy Controls		66%

Figure 12. Ft. Worth Zone 7 (Mezzanine office) Estimated Annual Energy Use



B. QUALITATIVE RESULTS

The usability of a lighting system and how it meets the needs of occupants is an important part of project success, and is critical for GSA project acceptance and decisions to move forward at other GSA locations. This project used occupant surveys both before and after the project to evaluate occupant satisfaction. Surveys also were administered to the installation crews and the building operators to assess how installation and operation of advanced control systems compared to standard lighting systems.

Occupant Satisfaction. Department staff administered surveys to occupants in all five of the evaluation zones. Replies before and after the project were limited in number as shown for each zone and total in Table 2.

Table 2. Occupant Response Counts

Zone	Pre-Project	Post-Project
3	22	16
4	7	6
5	19	7
6	3	4
7	7	8
Other	6	7
Total	**64**	**48**

From a statistical significance perspective, all of the individual zone response rates are too low to be used to provide any zone-specific evaluations or comparison between zones. The large reduction in responses after the project (25% less) also has a detrimental effect on the significance of the differences between pre- and post-project responses. However, where large differences in average responses are found, they can be instructive in identifying potential trends in occupant acceptance. The analysis of survey responses for this evaluation focuses on the totals of responses for all zones.

The occupants were asked a variety of questions related to the lighted environment and their satisfaction with it related to their work tasks. See Appendix A for a copy of the survey. Table 3 shows a comparison of the significant pre- and post-project responses. A primary question related to occupant satisfaction is general “comfort” of the lighting in their space. The responses showed a decrease after the project of 11%, indicating potentially less comfort with the lighting conditions. The results varied from zone to zone, but it is not clear from the limited sample sizes that any differences are either significant or related specifically to products installed. The responses to the questions about light levels for typical office functions show an average reduction of 5%, again indicating a potential reduction in “just right” lighting conditions. As seen from the data collected, there was a significant reduction in light levels in most zones, which could contribute to these results. However, at the same time, the relatively limited response count and significant reduction in responses after the project make it unclear that this is a significant trend.

The responses also indicate an approximate 10% increase in occupant awareness of glare with the new lighting systems. Again, this may not be a significant trend based on limited sample sizes, but there is generally an acceptance in the industry that brighter point-sourced LED light sources can contribute additional glare.

The responses also indicate that the occupants view the new advanced LED lighting systems as being significantly less “warm” in color appearance by a difference of 27%. The manufacturers of the new LED lighting did attempt to match the color appearance of the original fluorescent lighting. However, the metric for color appearance, correlated color temperature (CCT) is a limited calculation of the spectrum of light produced by the light source. CCT standards have two sets of tolerances, thus one source could be less than the specified value (e.g., 3500 K) and another source slightly above, but both would be characterized as the same CCT value. Further, CCT standards also allow for other deviations related to this calculation. Thus different light sources can have the same CCT, but might seem appear “cooler” or less “warm.”

Responses related to the fit of controls to the occupant needs show only a slight decrease (4%) after the project. A similar small (3%) increase was found in instances of the controls not activating to match user needs. Given the limited response counts available, these may not indicate significant trends. It is also very likely that the survey results were affected by the fact that changes in a person’s working environment (including lighting) can adversely affect their opinion until sufficient time has passed for them to become acclimated. Therefore, it is very likely that occupant satisfaction with the controls will improve over time.

Table 3. Occupant Survey Responses

General Lighting Experience	Pre-Project	Post-Project
Lighting **is comfortable**	81%	70%
Light level **is "just right"** for office functions (paper, computer screen, keyboard)	82%	77%
Glare is experienced "**sometimes," "rarely," or "never"**	93%	83%
Glare is experienced "**often"**	7%	17%
Lighting appears **"warm"**	38%	11%
Lighting Control Experience	**Pre-Project**	**Post-Project**
The lighting controls **do fit my needs**	76%	72%
Lights turn off or dims too much at the wrong time **– "sometimes," "rarely," or "never"**	75%	78%
Lights turn off/dim at wrong time **"often"**	6%	7%

Installer Experience. Surveys were provided to the installation crews to collect input about their experience of installing advanced LED lighting system compared to more standard fluorescent or LED systems. The number of responses was limited to only three installers, but does represent direct input about the experience. The installers found the new advanced lighting controls systems to be relatively similar to install compared with more standard LED fluorescent products. However, a few differences were noted that did cause a little additional extra time or effort:

- Fixtures with power connections at the end of the fixture were a tight fit between support wires. Retrofit kits were more complicated to install than standard fixtures. The wiring diagram for the emergency battery connection was missing, and this required additional time. (Zone 6)
- Fixtures were a tight fit in the grid, and required mallet to install. (Zone 4)
- The use of 2'x2' fixtures in the existing 2'x4' grid required extra work. More time was needed (10–15 min) to install the separate add-on controls. (Zone 5)
- More time was needed (10–15 min) to install the separate add-on controls (sensors); some needed additional holes drilled in the boxes for control wires. (Zone 3)

Some of these issues may not exist in other applications where ceiling grids may be different (tight fit, 2'x2' vs 2'x4'). Others may be characteristics that could be adjusted with manufacturing modification. It is clear, however, that any changes in fixture layout (i.e., different size, fixture movement) will likely cause additional time and cost. In some cases, this may be necessary to light the space correctly and improve lighting quality. Separate controls that are added in the field also will likely increase installation time and cost. Again, there likely will be some cases (i.e., existing LED fixtures in good condition) where this option is considered the most cost effective and least disruptive.

In some areas, installers found that occupants had erected additional (higher) walls to their cubicle enclosures and chose not to have burned-out lamps replaced in order to combat light levels that were uncomfortably bright. As part of the new LED lighting system installation, commissioning was completed to adjust light levels to meet occupant needs and wants. Installers noted that several occupants expressed gratitude for having the option with this new system to adjust light levels.

The lighting distribution and appearance of the light fixture differed between the existing fluorescent systems and the new LED systems. The LED fixtures emitted a higher angle of brightness compared to the fluorescent fixtures. As indicated in Figure 5, there was significant task tuning of the LED fixtures. Task tuning is the dimming of the installed equipment to meet design illuminance or occupant preferences. It should be noted that the LED fixtures were not tuned immediately after installation. As a result, occupants in the space worked under the new equipment (but not tuned) light levels for a period of time. To counteract the brightness and ultimately glare from the non-tuned new LED fixtures, in Zone 3 many of the occupants created physical shields/canopies to block the glare while at their work stations. Other occupants in the space anecdotally suggested that the new non-tuned lighting might be the root cause of discomfort, including a spat of reported headaches, because the headaches subsided once the lighting was properly tuned.

Sites can take steps to help ensure occupant satisfaction with lighting retrofits through a number of best practices. First, sites should conduct a mockup of proposed new lighting equipment and evaluate it for any glare issues. Second, sites need to right size the design through proper equipment selection and layout. If significant tuning is required due to glare or other user satisfaction issues, the design may not have been properly sized. Finally, tuning features should be included with lighting controls, because tuning allows flexibility with lighting levels to meet occupant needs and saves energy.

See Appendix A for a complete list of the installer comments specific to this site installation, but that may not apply to other projects.

Operator Experience. Survey responses were received from four building staff members who were active in building operation, including lighting systems. In general, the operators found the systems to be operating as designed. No significant differences were noted between the systems in terms of performance. However, a few notes were provided, as follows:

- The control system applied in Zones 3 and 5 required some component replacement and a firmware update prior to commissioning. The manufacturer notes this issue has since been permanently corrected.
- A few fixtures in Zone 6 exhibited some flicker at the lowest dim level (no occupants). LED and other technologies have historically had some issues with flicker, visible to some but not all, at very low dimming ranges. It is not clear if other zones experienced the same situation and no occupant responses noted any flicker in any zone.

The operator experience generally has been positive for the limited amount of time under the new lighting. Operators believe any issues that may arise in the future likely will be associated with needs or desires of occupants to change light levels or control settings to meet specific needs.

C. COST EFFECTIVENESS

This section is not intended to be a comprehensive market assessment, but rather a rough indicator of the potential cost effectiveness of the types of control systems evaluated in this project. This specific project involved lighting equipment (fixtures and controls), as well as installation and commissioning labor, at a GSA facility with low electricity rates. Because all potential applications will be different, the results of this evaluation also should be presented for use in multiple locations with differing labor and electricity rates. Therefore, this section provides information about the cost effectiveness of the advanced lighting control technologies at this specific site, as well as metrics to determine the cost effectiveness at other sites.

PROJECT COST EFFECTIVENESS AS INSTALLED AT THE SITE

The following results represent the calculated cost effectiveness of advanced LED-based controls using the test evaluation site-specific information and measured savings:

- Product manufacturers gifted the lighting fixtures and controls, but also provided estimates of equipment costs for their fixtures and controls that represent typical costs for this type of project. Pricing can vary by location as well as fixture quantity. This cost effective analysis developed an additional fixture price. The Estimate price in this analysis was developed using a standard construction estimating guide which has a price of LED troffers less than 4800 lumens of $138 per fixture.
- Control equipment prices were provided as part of the gifted equipment. An analysis of the gifted controls indicates that the additional controls for this project were 76% of the fixture costs. This percentage was applied to the Estimate price for the alternate scenarios in this cost effective analysis.
- Labor costs can vary depending on location and building architecture. In this case, the actual labor for this evaluation project included additional embedded work to facilitate this test evaluation. It also included doing some non-typical work to rework from 2’x4’ openings for existing fluorescent fixtures to smaller 2’x2’ openings/fixtures, which can have significant cost. Because of these potentially significant differences from typical projects, the actual total evaluation project cost was not used for this evaluation. Instead, estimated labor costs for similar typical installations of replacement fixtures developed for recent projects in the region were provided by GSA and are used here. The analysis in this section for cost effectiveness assumes 2 person-hours of labor and a blended $84.29 crew rate per fixture[8]. A secondary analysis was also conducted using additional data points. Using a standard construction estimating guide, a secondary labor rate was developed. This labor rate includes 1.5 person-hours at a rate of $55 per labor hour.
- Fixtures and controls are assumed to have a 20-year life for purposes of calculating savings-to-investment ratios (SIRs), and the blended electricity rate was provided by the utility at $0.07 per kWh.
- Operations and Maintenance (O&M) savings can be significant with LED technology because of its extended life compared to fluorescent technology. Some studies indicate as much as 25% is

[8] Costs used in this analysis are based on estimates developed for GSA by an architect and engineering firm for typical GSA projects. Actual costs at this site were higher but are known to include additional project work costs so not considered typical.

possible.[9] O&M savings will vary depending on factors including the age and life expectancy of existing installed technology and the cost of future replacement LED products. This evaluation project focuses on measured data and therefore does not include O&M savings.

Table 4 presents the calculated cost-effectiveness in terms of SPB and SIR for this evaluation project separately for each test zone and as a total for the entire project.[10] These results show that, although there is variation, no one zone reaches reasonable cost effectiveness (a SPB of 5 or even 10 years). The results are not encouraging, but are related to some site characteristics that may not be representative of typical GSA applications. These include the following:

- A very low electricity rate ($0.07/kWh) that makes most pure energy projects difficult to cost-justify.
- Occupancy sensor controls existed in most areas prior to the project, which greatly diminish any additional occupancy-based control savings from the new control systems.
- Extremely limited daylight capability (only a few windows in the Zone 7 mezzanine office), all but eliminating any potential savings from daylight control.

Note that these cost-effectiveness results are specific to this particular site. They should not be used to determine the potential cost effectiveness or applicability of advanced LED-based lighting controls at other sites or projects. See the cost-effectiveness approach for sites with varying site conditions, below.

Table 4. Cost Effectiveness by Zone – LED Fixtures with Advanced Control

	Annual Savings				Installed Cost			Simple Payback Period		SIR (20-year life)	
	LED Annual EUI Savings	Control Annual EUI Savings	LED + Control Annual Savings $0.07 / kWh ($/ft^2)	LED + Control Annual Savings $0.11 / kWh ($/ft^2)	Area per Fixture (ft^2/fixture)	Actual LED + Controls Installed Cost ($/$ft^2$)	Est. LED + Controls Installed Cost ($/$ft^2$)	SPB Actual $0.07 / kWh	SPB Est. $0.11 / kWh	SIR Actual $0.07 / kWh	SIR Est. $0.11 / kWh
Zone 3	0.63	1.07	$0.12	$0.19	73	$5.68	$4.48	48	38	0.42	0.53
Zone 4	1.34	0.44	$0.12	$0.20	106	$4.33	$3.08	35	25	0.58	0.81
Zone 5	1.98	1.16	$0.22	$0.35	94	$5.69	$3.48	26	16	0.77	1.26
Zone 6	1.04	0.93	$0.14	$0.22	60	$5.33	$5.45	39	40	0.52	0.51
Zone 7 (Mezz.)	3.67	0.42	$0.29	$0.45	63	$6.26	$3.05	33	16	0.60	1.23
Total Site	1.59	0.82	$0.17	$0.27	---	$5.46	$3.91	36	27	0.58	0.87

Actual Labor Rate: 1.75 hours for integrated fixtures; 2 hours for add-on control @ $84.29 / hour Actual Fixture Costs: $151-$409 (Supplied by Manufacturers) Actual Controls Costs: $107-$208 (Supplied by Manufacturers)	Estimate / Web Labor Rate: 1.5 person-hours @ $55 / hour Estimate LED Fixture: $138 Estimate Add-on Controls: 76% of fixture cost (derived from actual costs)

[9] Retrofit Demonstration of LED Fixtures with Integrated Sensors and Controls, Francis Rubinstein (LBNL), July 2015, p.77

[10] Per U.S. Energy Information Administration, the 2017 commercial average was $0.1068 / kWh which is similar to GSA's national average. This table uses $0.11 /kWh as an alternative analysis to reflect the national average electricity rate.

V. Summary Findings and Conclusions

A. OVERALL TECHNOLOGY ASSESSMENT AT THE DEMONSTRATION FACILITY

The application of LED-based advanced control lighting in this evaluation is shown to save energy at an average rate of 63%. This savings comes from several effects of the project:

1. Increased lighting efficacy (fluorescent to LED).
2. Light-level reductions. Reductions in illuminance as a result of installing fewer replacement fixtures along with light-level tuning as part of the new lighting systems were found to be a significant part of the savings in most zones. These savings can be extremely variable depending on the site. Most often, they are conscious adjustments to provide appropriate lighting as part of a project and are a reality of lighting projects.
3. Control savings, including occupancy sensing and light-level tuning, that reduce the initial installed light levels to occupant preferences and task needs

These savings and associated cost effectiveness may not be representative of applications at commercial office facilities but are likely typical for GSA facilities that have generally lower existing light levels.

The survey results show reasonable occupant satisfaction with the new lighting, noting some common issues, such as some increased glare but also appreciation of the adjustability of light levels. System installers found the process to be similar to the installation of standard fluorescent or LED fixtures, but noted some additional time was required for separate controls and relocation of fixtures.

Costs compared to savings at this site proved to be comparatively high, with resulting simple payback periods being, on average, 35 years across the project. This is primarily related to a low energy rate at the site, limited control savings due to existing occupancy control, and limited daylighting capability. The results of this study can be instructive in representing potential savings for similar sites with limited daylight. Other studies will be able to provide more appropriate data for buildings that have different characteristics.

B. LESSONS LEARNED AND BEST PRACTICES

The results of the analysis and survey responses were generally positive, but provide some suggested cautions for projects involving advanced LED-based control systems (as well as other lighting projects):

- When spaces are over-lighted, significant energy savings can be harvested by reducing light levels to reasonable levels. This will not always be the case and needs to be carefully considered when evaluating a project's cost effectiveness.
- Light-level tuning to reduce (or increase) light levels to meet occupant needs can produce significant energy savings. Light-level tuning is a common capability of advanced lighting systems and is available as a fixture adjustment option in some systems without advanced controls.

- Reworking fixture spacing (i.e., existing 2'X4' troffers replaced with 2'X2' troffers requiring rework of ceiling grid tiles), and fixture relocation (potentially requiring reworking electrical connections) can both significantly increase costs, but are sometimes necessary to achieve lighting quality.
- Add-on lighting controls installed in the field or separate sensors installed outside of fixtures can increase project costs.

C. COST RECOVERY

Cost recovery is dependent on many variables. The following sections analyze recovery of different scenarios.

POTENTIAL FOR PROJECT COST EFFECTIVENESS BY VARYING SITE CONDITIONS

The results of this study provide useful data on the potential savings available from advanced LED-based lighting systems. These data can be used to help determine the cost effectiveness of this technology at any specific office-type site based on selected site-specific characteristics. The output of the method is a maximum project cost (equipment + labor) that could be afforded to meet the SPB requirements for the project. This method makes a set of basic assumptions based on data from this evaluation and other common office application characteristics:

- Workdays = 260 (standard 5-day work week, 52 weeks a year – typical for an office environment)
- Occupancy sensor savings = 24% of newly installed system (this value is based on an average of data collected at Fort Worth)
- Daylighting sensor savings =14% of newly installed system (based on data from two other similar studies where daylight savings was measured[11])
- Anticipated post-project light power density (LPD) = 0.48 (value to meet PBS P-100 criteria)
- Desired simple payback period = 5 years

Site-specific project characteristics can then be applied to make the analysis specific to a particular site. These user inputs include:

- blended electricity rate ($/kWh)
- existing LPD (W/ft^2) of the existing lighting system (prior to a project)
- existing utility/program rebates.

Note that potential O&M savings are not included in this simple cost-effectiveness evaluation method. If O&M savings are expected to be significant or desired for consideration, a more detailed lifecycle type analysis is recommended.

This method is usable for all possible variables (if different from those in Table 4) and can be represented by the following formula:

$$M_{Cost} = (\frac{SPBK * ([(LPD_1 - LPD_2) * 2600] + (SAV * LPD_2 * 2600)) * Rate}{1000}) + R_{Bate}$$

[11] https://www.designlights.org/lighting-controls/case-studies/

where:

M_{Cost} = The maximum project cost supported by site-specific advanced lighting project characteristics

SPBK = desired simple payback period

LPD_1 = existing pre-project LPD (W/ft^2)

LPD_2 = desired post-project LPD (W/ft^2)[12]

SAV = estimated savings percentage from new control application. Apply **only** when occupancy sensors or daylighting were not already part of the existing pre-project lighting. (Use 0.20 for occupancy sensors only and 0.34 for occupancy sensing plus significant daylighting potential, based on the results of this and similar advanced lighting control system evaluations – see Quantitative Results section)

Rate = local applicable blended electricity rate in $ /kWh

R_{Bate} = local utility rebate amount in dollars (typically based on dollars per watt saved or dollars per fixture or control)

Note that the “2600” value represents the typical number of annual work hours (52 weeks * 5 days * 10 hours) and “1000” converts the typical utility rate to $/watt.

Table 5 presents a selection of outputs using this method for determining the applicability of these controls at a specific office building site. These results are based on savings from occupancy sensing + daylighting, assume a final light power density of 0.48 (GSA Tier 1 target level), and require a simple payback of 5 years. Note that this table does not include any results that might include utility rebates for installing these systems. Utility rebates were not available for application at this site for this evaluation, but may be available and applicable for other projects and locations.

Table 5. Maximum Project Cost to Meet Desired Project Requirements ($0.07, $0.11, and $0.14 per kWh)

Pre-Project LPD (W/ft^2)	Post-Project LPD (W/ft^2)	Desired Simple Payback Period (yr)	Electricity Rate ($/kWh)	Maximum Project [Equipment (fixtures and controls) + Labor] (Cost per ft^2)
1.00	0.48	5	$0.07	**$0.62**
1.25	0.48	5	$0.07	**$0.85**
1.50	0.48	5	$0.07	**$1.08**
1.75	0.48	5	$0.07	**$1.30**
2.00	0.48	5	$0.07	**$1.53**
2.25	0.48	5	$0.07	**$1.76**

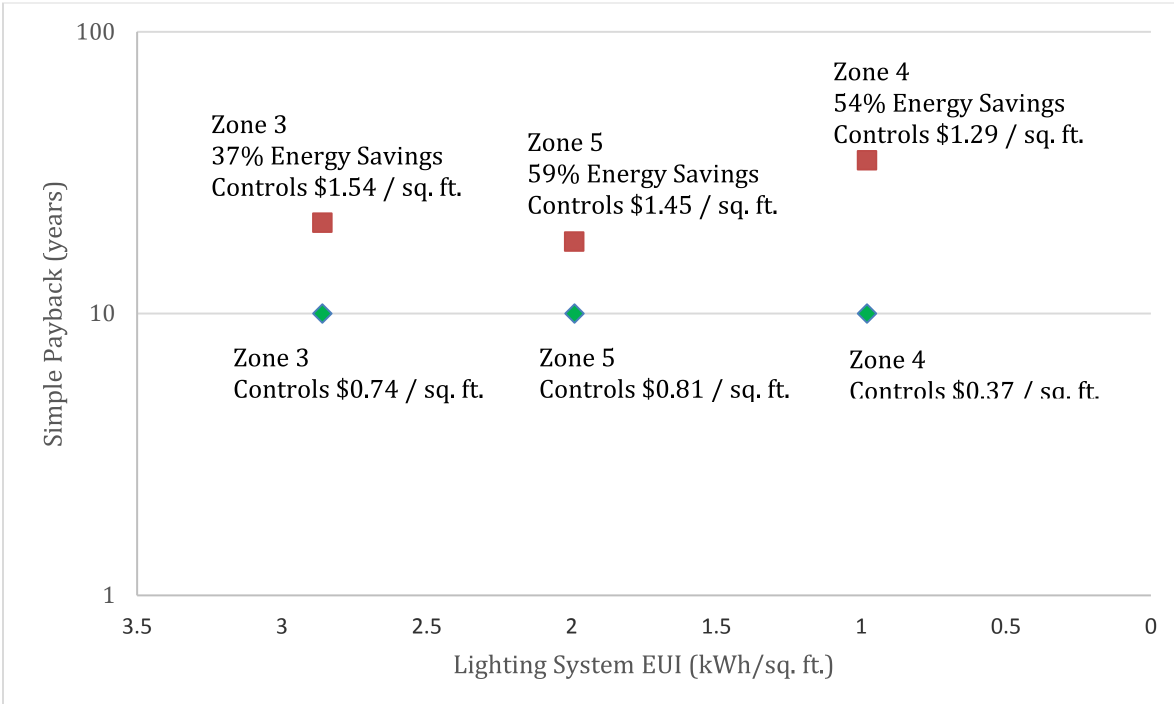
[12] GSA PBS-P100, Facilities Standards for the Building Public Service (2017) Tier 1 High Performance (*): This level exceeds ASHRAE by 40% and lowers the LPD allowances to 0.48 [W/ft2] ambient and 0.12 [W/ft2] task. Additionally, daylight, occupancy, and personal controls are required in all occupied spaces are energy modeling is required as a step toward real-time energy monitoring.

Pre-Project LPD (W/ft^2)	Post-Project LPD (W/ft^2)	Desired Simple Payback Period (yr)	Electricity Rate ($/kWh)	Maximum Project [Equipment (fixtures and controls) + Labor] (Cost per ft^2)
2.50	0.48	5	$0.07	**$1.99**
1.00	0.48	5	$0.11	**$0.98**
1.25	0.48	5	$0.11	**$1.33**
1.50	0.48	5	$0.11	**$1.69**
1.75	0.48	5	$0.11	**$2.05**
2.00	0.48	5	$0.11	**$2.41**
2.25	0.48	5	$0.11	**$2.76**
2.50	0.48	5	$0.11	**$3.12**
1.00	0.48	5	$0.14	**$1.24**
1.25	0.48	5	$0.14	**$1.70**
1.50	0.48	5	$0.14	**$2.15**
1.75	0.48	5	$0.14	**$2.61**
2.00	0.48	5	$0.14	**$3.06**
2.25	0.48	5	$0.14	**$3.52**
2.50	0.48	5	$0.14	**$3.97**

LIGHTING CONTROL COST VARIABLES

There are multiple variables that determine if lighting controls installed into a lighting system would be cost effective. The major variables include the energy use of the baseline lighting system (EUI reported as kWh/sq. ft.), the energy savings from the controls systems, the cost of the lighting controls ($ / sq. ft.), energy rate, and then finally the deemed acceptable cost effectiveness criteria. Figure 13 compares data from GSA Fort Worth zones where lighting control costs were specifically separated from the light fixture costs.

Figure 13. Lighting Control System Cost Recovery and Baseline Lighting System EUI based on $0.07 /kWh rate



Cost effectiveness is a key metric in many energy conservation projects. Simple payback is a quick cost effectiveness metric used to determine if a project should move forward. Figure 13 shows simple payback on the y-axis in a logarithmic scale. A 10-year SPB is typically the limit for many projects. The three GSA Ft. Worth zones shown in Figure 13 have SPBs for only the lighting control systems range from 18 to 35 years. Note Table 4 shows a range of SPB from 26 to 48 years. Table 4 shows the SPB for both LED fixtures and lighting controls replacing fluorescent fixtures. In contrast, the 18 to 35 years related to Figure 13 relates to just installing advanced controls beyond just simply installing LED fixtures.

The green diamonds in Figure 13 depict a 10-year SPB scenario. The dollar per square foot value below the green diamond is what the cost would need to be for that zone, at an electricity rate of $0.07, with the baseline energy use intensity, and the energy savings achieved from the lighting control system.

The energy use of the lighting system where controls are being included also affects the cost effectiveness of the lighting controls. Energy use can be represented as EUI which allows for a direct comparison of projects of different size (as the zones in Fort Worth). Although it might sound contradictory, as the lighting system where the controls are being installed becomes more efficient, the cost effectiveness becomes a challenge. A more efficient lighting system translates to less actual energy being used by the baseline lighting system and thus less total energy savings (and therefore less money saved) to be applied to recover the cost of the lighting controls. The x-axis in Figure 13 shows the EUI of three of the zones at Fort Worth.

In Figure 13, the energy savings and system costs per Fort Worth zone are located near each data point. For all of the data points in Figure 13 were based on the Fort Worth rate of $0.07 / kWh.

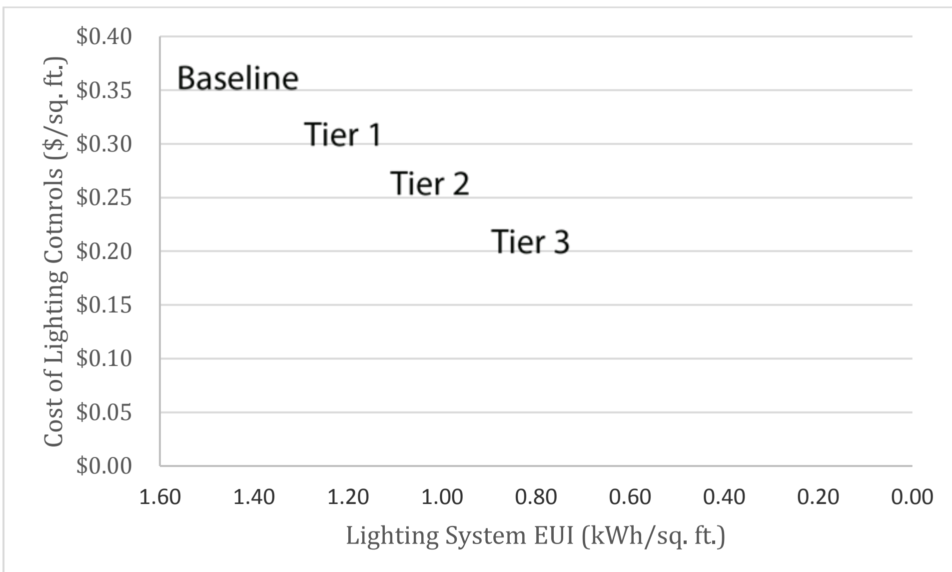
As depicted in Figure 13, lighting system costs need be below $1 per square foot for lighting control systems for 5 or 10 year simple payback periods. The caveat for this statement is that those values are based on $0.07 / kWh as well as only applying economic value to electricity saved from lighting.

GSA P100

Section 6.2.3, Energy Use, of GSA P100 (2018) specifically states that baseline GSA facilities must exceed ASHRAE 90.1 by 30% for LPD values. Similarly, GSA P100 project Tiers 1 – 3 also have reductions related to LPD values. LPD is the amount of power installed in a space and can affect overall energy usage, but is not the sole driver of energy.

Figure 14 illustrates the EUI of the different GSA tiers based on the required reduced LPDs (developed using ANSI/ASHRAE/Standard 90.1 -- reduced LPD x 2,600 annual operating hours) and the requisite cost of controls to achieve a 10-year SPB (assuming a national average electricity rate of $0.11 / kWh).

Figure 14. Cost of Lighting Controls to meet GSA P100 LPD Values and a 10-Year Simple Payback



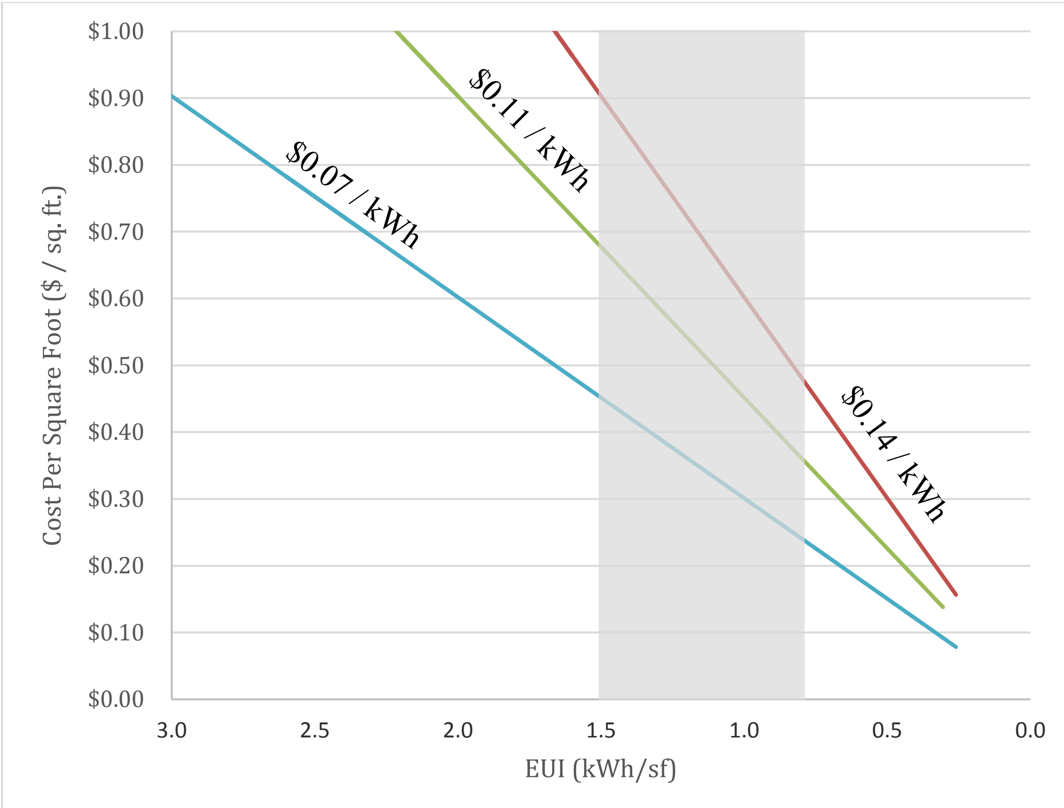
GSA P100 species that daylight and occupancy sensors controls are required in spaces in addition to the reduced LPD values. However, as shown previously, the reduced LPD leads to reduced EUI and the lower the EUI, the harder to recover the cost of controls.

LIGHTING CONTROL COSTS

GSA operates facilities across the country and electricity rates vary across the U.S. Figure 15 depicts the necessary cost per square foot for lighting controls based on different electricity rates ($0.07 / kWh, $0.11 / kWh, and $0.14 / kWh).

The gray band in Figure 15 shows the range of EUI values for GSA facilities based on GSA P100 requirements. The total cost of lighting controls including materials and labor needs to range between $0.34 to $0.85 / sq. ft. for baseline GSA projects and $0.10 to $0.38 / sq. ft. for Tier 3 projects. The final cost depends on the electricity rate and energy savings (Figure 15 assumes 24% energy savings from the lighting controls).

Figure 15. Lighting Controls Costs for a 10-year Simple Payback (Savings-to-Investment Ratio of 2)



D. DEPLOYMENT RECOMMENDATIONS

Advanced LED lighting control systems can provide more effective energy savings than standard controls in many situations, as well as provide additional lighting quality functions:

- Specific area tuning of light levels to meet occupant and task needs both at initial commissioning and as needed for change in lighting needs. (Note that this capability may also exist as part of fixtures without advanced control systems.)
- Matrixed control to provide more uniform ambient lighting.
- Diagnostic capabilities for simpler maintenance.

These systems also can come with a higher price tag than simple systems with or without basic controls. As lighting power densities get smaller because of more efficient technologies (LED) and tighter building energy code requirements, the availability of wattage to harvest for energy cost savings tends to decrease. This makes it increasingly more difficult to pay for advanced systems.

Some general deployment recommendations can be useful in determining which technologies or control attributes should be considered for selected facility or space types.

In general, sites or projects with the following attributes are prime candidates for lighting projects because they have a higher potential for cost effectiveness and should be considered first when limited project funds are available:

- Higher than needed existing light levels. These are likely to be areas where light levels can be reduced as a part of the project. This reduction can be accomplished with a combination of lower light output fixtures and by further reducing light levels to meet occupant preferences.
- No existing automatic controls. This makes maximum use of the advanced control combinations of the new lighting system.
- High electricity rates (energy and demand charges).
- Utility rebates available to help offset the first cost of the new advanced lighting and control system.

GSA should consider prioritizations including:

- GSA P100 should shift away from focusing on reduced LPDs and instead reference ANSI/ASHRAE/IES Standards 90.1 Appendix G which actually models the energy usage of the space. P100 could then specify reductions compared to Appendix G. This would maintain the spirit of energy savings while not restricting the LPD to the point that the required lighting controls could fail to be cost effective.

It is also important to apply a system that will meet occupant needs and be effective for the specific site. Recommended actions to consider include:

- Identify systems that most economically provide only the control features needed.
- Consider systems that have effective performance histories in proposed applications.
- Specifically ensure that systems feature matched electronics for system components to ensure that controls will work and communicate within the system and with other site systems to avoid control failures or performance issues.

The attributes of advanced control systems can provide additional energy savings over more typical stand-alone lighting controls, but they may not be cost effective unless the appropriate opportunities exist. Advanced control systems are most likely to be uniquely effective and cost effective in larger open office or similar open work areas that house multiple occupants and varied tasks. These space types are commonly not effectively controlled with standard separate control and, therefore, advanced control systems can be very effective. GPG is conducting a follow-on study, to provide better guidance on when controls can be best applied.

All building projects have varying energy savings potentials and energy cost rates and needs. Therefore, it is not practical to state specifically where advanced controls will be cost effective. However, applying the general recommendations above will help identify applications where advanced controls are potentially more effective than standard lighting projects. With this potential identified, the information in the cost-effectiveness section of this report can be applied as a start to determine the cost effectiveness of a specific project.

VI. Appendices

A. RESEARCH DETAILS

Table A1. Power Data Points Collected

Panel ID	Circuit Breaker #	Space Type	Zone	Luminaire Type	Luminaire Quantity	Burnout Lamp Count
LA	17	Open Office	4	4' T8 32W 2-Lamp	35	3
LA	17	Open Office	LA	LED 42W	1	0
LA	26	Private Office	LA	4' T8 32W 2-Lamp	12	0
LA	21	Open Office	LA	4' T 8 32W 2-Lamp	10	2
LB	17	Conference Room	5	4'T 8 32W 2-Lamp	9	1
LB	17	Open Office	5	4'T 8 32W 2-Lamp No Shade	21	3
LB	10	Conference Room	5	4'T 8 32W 2-Lamp No Shade	15	1
LB	18	Corridor	7	4' T8 32W 2-Lamp	6	0
LB	18	Corridor	7	42W LED	1	0
LD	3	Open Office	3	4' T8 32W 2-Lamp	12	0
LD	4	Open Office	3	4' T8 32W 2-Lamp	17	0
LD	5	Open Office	3	4' T8 32W 2-Lamp	12	1
LD	12	Open Office	3	4' T8 32W 2-Lamp	13	0
LD	14	Open Office	3	4' T8 32W 2-Lamp	24	0
LD	22	Open Office	3	4' T8 32W 2-Lamp	22	1
LD	22	Open Office	3	4' LED 60W	2	0
LD	16	Open Office	6	4' T8 32W 2-Lamp	9	2
LD	21	Open Office	6	4' T8 32W 2-Lamp	20	3
LD	17	Private Office C04C	6	60W LED	4	0
LD	17	Open Office	6	2'X2' T8 3-lamp	1	0
LD	17	Open Office	6	4'T8 32W 2-Lamp	16	1
LD	17	Open Office	6	42W LED	2	0
LD	20	Conference Room B12	6	4' T8 32W 3-Lamp	8	0
LD	15	Corridor	7	4' T8 32W 2-Lamp	8	0
LD	15	Corridor	7	2X2 2 lamp T8	1	0
LE	5	Small Cube Farm	3	4' T8 32W 2-Lamp	22	3
LE	7	Private Office	3	4' T8 32W 3-Lamp	1	1
LE	7	Private Office	3	4' T8 32W 2-Lamp	9	2
LE	3	Conference Room	3	4' 3x T8	25	0
LE	3	Conference Room	3	4' LED 60W	1	0
LE	10	Open Office	6	4' T8 32W 3-Lamp	1	1
LE	10	Open Office	6	4' T8 32W 2-Lamp	12	3
LE	11	Open Office	6	4' T8 32W 2-Lamp	8	3
LE	12	Corridor	7	4' T8 32W 2-Lamp	9	3

Panel ID	Circuit Breaker #	Space Type	Zone	Luminaire Type	Luminaire Quantity	Burnout Lamp Count
LF	1	Private Offices and Corridor	7	4' T12 40W 2-Lamp	19	0
LF	3	Open office	7	4' T12 40W 2-Lamp	24	2
LF	10	Hallway	7	4' T8 32W 4-Lamp	5	2
LF	10	Men's room	7	4' T8 32W 4-Lamp	5	0
LF	10	Women's room	7	4' T8 32W 4-Lamp	6	0
LF	12	Storage	7	4' T8 32W 4-Lamp	12	10
LF	13	Corridor	7	4' T8 32W 4-Lamp	1	0

Occupant Survey

Dear building occupant,

GSA is interested in gathering your opinion on your current workplace lighting. In order to do so, we request that you take a quick survey that takes about 5 minutes to complete. Your willingness to provide us with your input is appreciated and will help facilities staff provide a better workplace.
About this survey

- *Responses are anonymous – Responses will be aggregated at the group level so that no individual can be identified in any way.*
- *Participation is voluntary – You are free to choose at any time whether or not to provide responses to the survey or individual questions.*
- *If you have* questions *about your rights as a participant of this research survey, please email the Institutional Review Board at* *Katherine.Ertell@pnnl.gov*

PLEASE return completed surveys in the pre-paid and pre-addressed envelope provided

You and your workspace

Please identify your workspace location – **see the zone map attached**
__ Zone 3
__ Zone 4
__ Zone 5
__ Zone 6
__ Zone 7

Which of these best describes your job?
__ Accounting/financial professional
__ Administrative
__ Engineering/Technical
__ Project or program management
__ Supervisor/team management
__ Other

What is your age group?
__ 30 or under
__ 31-50
__ Over 50

Which best matches your workspace type?
__ Enclosed private office
__ Cubicles with partitions
__ Other - please specify _____________

Which best matches your computer screen type?
__ Laptop
__ Flat panel
__ Other - please specify _____________________

Can you see out a window while sitting in your workspace?
__ Yes
__ No

Do you have task lighting?
__ Under cabinet
__ Desktop
__ None

Your evaluation of your workspace lighting

Overall, is the current lighting in your workspace comfortable?

__ Yes
__ No

How would you rate the lighting in your workspace for each of the following tasks?

	Too Bright	About Right	Too Dim
Paper tasks (reading, writing, filing)	___	___	___
Reading computer screen	___	___	___
Keyboard typing	___	___	___

How often do you experience the following conditions in your workspace during a typical day?

	Often	Sometimes	Rarely/Never
Glare on your work surface	___	___	___
Glare on your computer screen	___	___	___
Glare from the lighting overhead	___	___	___
Glare from far away lighting	___	___	___

Lighting comes in a range of color from “warm” white (more yellow) to “cool” white (more blue).

	Warm	Neutral	Cool	Don’t know
What is it like in your space now?	___	___	___	___
What would you prefer?	___	___	___	___

Do you have any direct control of the lighting in your workspace, e.g., with a wall switch or a remote?

__ Yes
__ No

Is the current lighting controlled in a manner that fits your work needs?

__ Yes
__ No

Have you had any of the following issues with the current lighting control?

	NA	Often	Sometimes	Rarely/Never
Lights turn off when I am in my workspace	___	___	___	___
Lights do not turn on automatically when I am present	___	___	___	___
Lights dim too much when there is daylight present	___	___	___	___
I am distracted by lights going on, off, or dim near me	___	___	___	___

Following questions refer to the applicable common spaces in your building:

Does the lighting present a good public image?
__ Yes
__ No

Do you experience glare from this lighting?
__ Yes
__ No

Does the lighting provide the right amount of light for activities in the area?
__ Too Bright
__ About Right
__ Too Dim

COMMENTS
Please provide any additional comments about your workspace OR common area lighting below:

____

____

____

____

<u>Installer Survey</u>

Location: Fort Worth, Texas
Date: ______________

This survey is intended to capture the experience and insight of individuals responsible for installing the LED retrofit kit and controls technology.

If you worked with products from more than one vendor, please complete a separate survey for each vendor. Thank You!

PLEASE return completed surveys in the pre-paid and pre-addressed envelope provided
____

Please identify which LED Vendor THIS SET of questions refers to. PLEASE SELECT ONLY ONE:

___ Philips (zone 6)
___ RAB (zone 5)
___ Intellilum (zone 7)
___ Energy Planning & Associates – Envirobrite (zone 4)
___ Axis LED (zone 3)

Lighting <u>Fixture/Retrofit</u> installation – Please answer related to just the installation of the fixture or retrofit of the fixture.

1) Were instructions needed to complete the installation?
   a) No (Please Describe) ____
   b) Yes
      If yes, were the instructions complete and effective?
      ___ Yes
      ___ No (Please Describe) ____
      ___ N/A

2) Were there any potential safety issues with this product or the process for installation? Please describe.
   a) No
   b) Yes (Please Describe) ____
   c) N/A

3) If this Vendor product was a complete LED fixture, was there any difference in time or effort involved in installing it compared to a standard fluorescent fixture? If so, please describe.
   a) No
   b) Yes (Please Describe) ____
   c) N/A

4) Did this product have sensors embedded in or on the fixture? If so, did this result in any difference in installation, when compared to a standard fluorescent product without sensors?
   a) No
   b) Yes (Please Describe) ____
   c) N/A

5) Do you see anything about this product or its installation that might result in higher future maintenance costs or time? Please describe.
   a) No
   b) Yes (Please Describe) ____
   c) N/A

6) If this was a complete new fixture installation, can you provide a rough estimate of the typical average time required to install?
   a) One new LED fixture? _________
   b) One standard fluorescent fixture? ___________

7) If this was a fixture retrofit, can you provide a rough estimate of the typical average time required to complete the retrofit of one existing fixture? _________

8) Was there anything else about this product or the process for installing it that would be helpful for future installers to know?

Lighting control system installation – Please answer related to just the control system installation

1) Were instructions needed to complete the installation? If so, were they complete and effective?
   a) No (Please Describe) ____
   b) Yes
      If yes, were the instructions complete and effective?
      ___ Yes
      ___ No (Please Describe) ____
      ___ N/A

2) Were there any potential safety issues with this control system or the process for installation? Please describe.
   a) No
   b) Yes (Please Describe) ____
   c) N/A

3) Do you see anything about this product or its installation that might result in higher future maintenance costs or time? Please describe.

a) No
b) Yes (Please Describe) ____

4) Can you provide a rough estimate of the typical time required to install?
   a) This new complete LED control system? __________
   b) A standard fluorescent control system (i.e. occupancy sensors and/or daylight)? _________

5) Was there anything else about this product or the process for installing it that would be helpful for future installers to know?

Commissioning – if you were involved with commissioning the system:

1) How was commissioning of the control system accomplished?
   a) Automatic – little to no operator action required
   b) Manual setup by operator
   c) Other ____
   d) N/A

2) Was the commissioning simple and straightforward?
   a) Yes
   b) No (Please Describe) ____
   c) Somewhat (Please Describe) ____
   d) N/A

3) How long did the commissioning process take?
   a) Less than one hour at one time.
   b) 1 or more hours at one time. Please indicate approximate number of hours ______
   c) Multiple actions/activities over 1 or more days.
      Please indicate number of days involved_____
      Please indicate TOTAL number of hours_____
      Please indicate number of operators involved_____

4) Was any of the time needed for commissioning a result of a problem with the control system or any part of the system or process that was particularly challenging?
   If so, please describe ____

Thank you for taking the time to complete this important survey. If you would like to discuss any concerns or thoughts (good or bad) that you would like recorded as part of the installation experience, please feel free to leave contact information and when/how would be best to contact you.

____
____
____

Operator Survey

Your responses to these questions will help other GSA building managers that are considering LED lighting upgrades understand how well LED lighting and controls work and what's involved for their effective operation.

If you worked with products from more than one vendor, please complete a separate survey for each vendor. Thank You!

PLEASE return completed surveys in the pre-paid and pre-addressed envelope provided

____

Please identify which system THIS SET of questions refers to. PLEASE SELECT ONLY ONE:

___Philips (zone 6)
___RAB (zone 5)
___Intellilum (zone7)
___Energy Planning & Asscociates – Envirobrite (zone 4)
___Axis LED (zone 3)

Commissioning – if you were involved with commissioning the system:

1) How was commissioning of the control system accomplished?
   a) Automatic – little to no operator action required
   b) Manual setup by operator
   c) Other
      ____
   d) N/A

2) Was the commissioning simple and straightforward?
   a) Yes
   b) No (Please Describe) ____
   c) Somewhat (Please Describe) ____
   d) N/A

3) How long did the commissioning process take?
   a) Less than one hour at one time.
   b) 1 or more hours at one time. Please indicate approximate number of hours ______
   c) Multiple actions/activities over 1 or more days.

   Please indicate number of days involved _____
   Please indicate TOTAL number of hours _____
   Please indicate number of operators involved ____

4) Was any of the time needed for commissioning a result of a problem with the control system or any part of the system or process that was particularly challenging?
   If so, please describe
   ____

Controllability

5) How easy is it to make sure the lighting controls are operating as intended?
   a) Easy
   b) Medium. Please describe ____
   c) Challenging. Please describe ____
   d) N/A

6) What tasks did you need to perform most often (if any) to keep the controls functioning effectively?

   ____

7) How does operating this control system compare to operating the incumbent system?
   a) Easier. Please describe ____
   b) About the same
   c) More challenging. Please describe

      ____
   d) N/A

Reliability

8) How many system failures or malfunctions have you experienced with this system? ______ Please describe them and what, if any, resolution was reached.

   ____

9) How does this system's reliability compare to the past system?
   a) Better. Please describe ____
   b) About the same
   c) Worse. Please describe ____
   d) N/A

Maintainability

10) How easy was it to isolate control system problems?
   a) Better
   b) About the same
   c) Not as good. Please describe ____
   d) N/A

11) How easy was it to restore system function after a failure?
   a) Better
   b) About the same
   c) Not as good. Please describe ____
   d) N/A

12) How does maintaining this control system compare to the past system?
   a) Better
   b) About the same
   c) Not as good. Please describe ____
   d) N/A

13) Please describe any outside help needed to maintain the system.
   ____

Lighting Conditions

14) Were the lighting conditions produced by the system adequate for this building?
   ___Yes ___No (please describe) ____

15) How do the lighting conditions produced by this system compare to the past system?
   a) Better
   b) About the same
   c) Not as good. Please describe ____
   d) N/A

Occupant Acceptance

16) Were the lighting conditions produced by the system adequate for building occupants?
   ___Yes ___No (please describe) ____

Please describe any comments you received from occupants about the lighting system.
____

Zone by Zone Lighting Power Reduction Details

Figures A1 through A10 present details on the LPD reduction for each zone in sets of two figures per zone. The first figure in each zone set shows the LPD reduction from existing fluorescent baseline to the initial installation of the new LED lighting and then to final reduction from light-level tuning. In these figures, the project measurement points represented along the X-axis include:

- "Baseline (if all lamps working)" = old fluorescent (FL) system if all lamps were working.
- "Baseline (as found)" = old FL system as found with some lamps not working.
- "Initial LED fixtures" = new LED system as initially installed (typically with lower light delivery than the old system) but with no initial tuning and without any controls activated.
- "Tuned LED" = new LED system with light levels adjusted (light-level tuning) to meet occupant needs. This varied from no adjustment to varying adjustment in a zone to meet individual occupant requests.

The second figure presents the typical average load profile for an averaged 24-hour period showing the baseline profile (original as found fluorescent system), initial LED configuration profile (typically without controls), and the final tuned LED configuration with all controls activated .

For Zone 3, Figure A1 shows a 20% reduction in power density (0.82 to 0.66) from baseline to initial LED installation and an additional 14% reduction from light-level tuning to meet occupant needs. This is accomplished with a very small reduction in light level (1%). In this case, the reduction can be attributed primarily to LED efficacy and potentially more efficient light distribution.

Figure A1. Ft. Worth Zone 3 Lighting Power Density

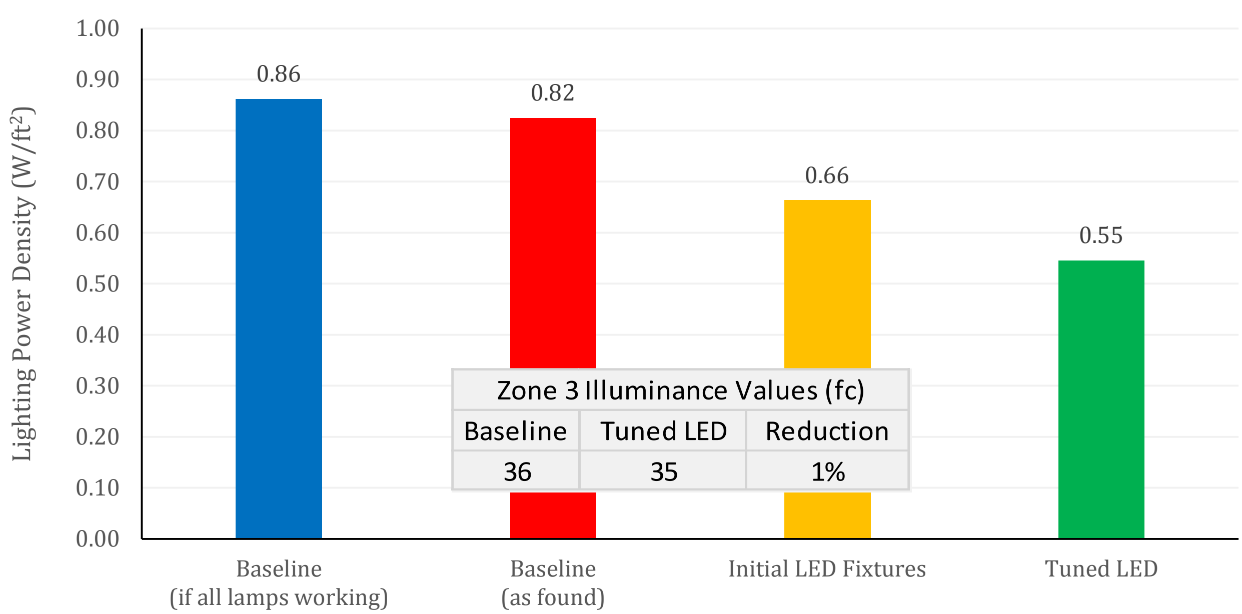
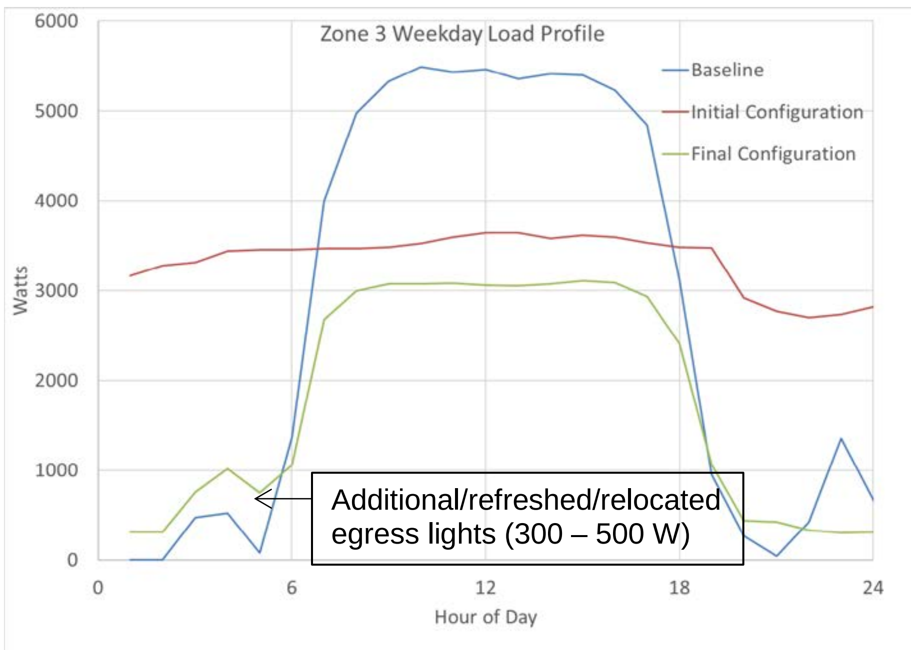


Figure A2 for Zone 3 presents profiles showing the baseline (fluorescent) weekday load profile, along with the initial (LED) fixture and final (tuned) profiles. These profiles appear as expected with the initial configuration showing a flat profile indicating no controls and a final configuration with activated advanced controls. Note that in this zone, the early morning and evening hours show more load from the final LED configuration (with advanced controls) than the baseline fluorescent system (with controls). After discussion with the site, this higher after-hours load was determined to be the result of a few additional fixtures being installed to meet nighttime egress needs, which were part of a separately funded project on egress lighting.

Figure A2. Fort Worth Zone 3 Weekday Load Profile



For Zone 3, Figure A2 shows a 59% reduction in power density (0.59 to 0.24) from baseline to initial LED installation and an additional 3% with light-level tuning. This also involved a large reduction in light level (76%). In this case, the reduction in power density is primarily a function of reduced light levels.

Figure A3. Ft. Worth Zone 4 Lighting Power Density

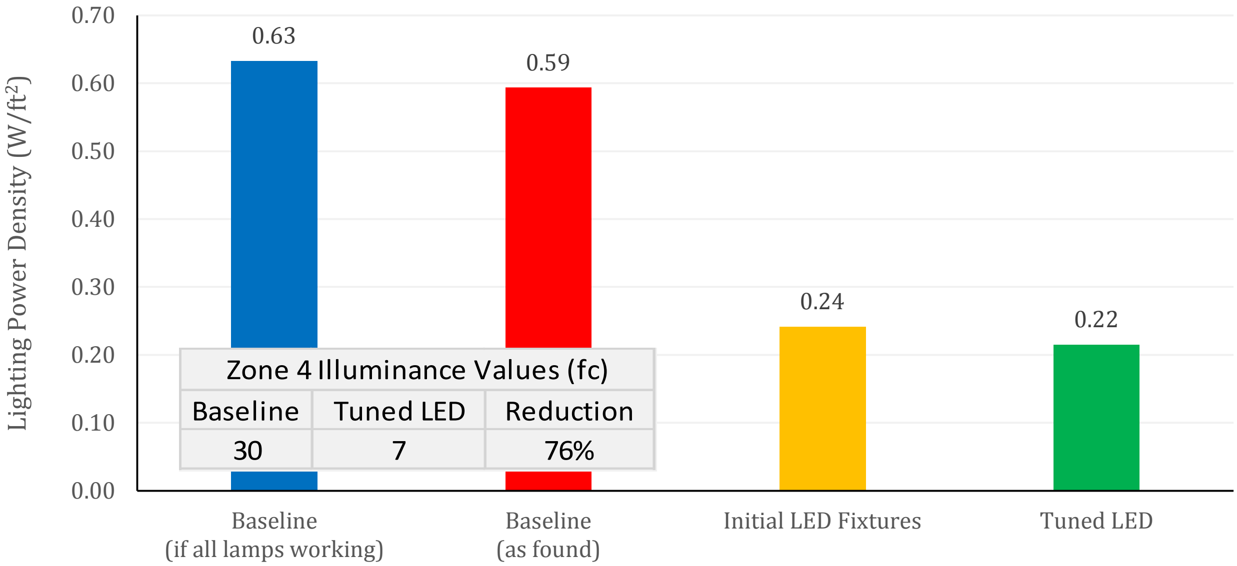
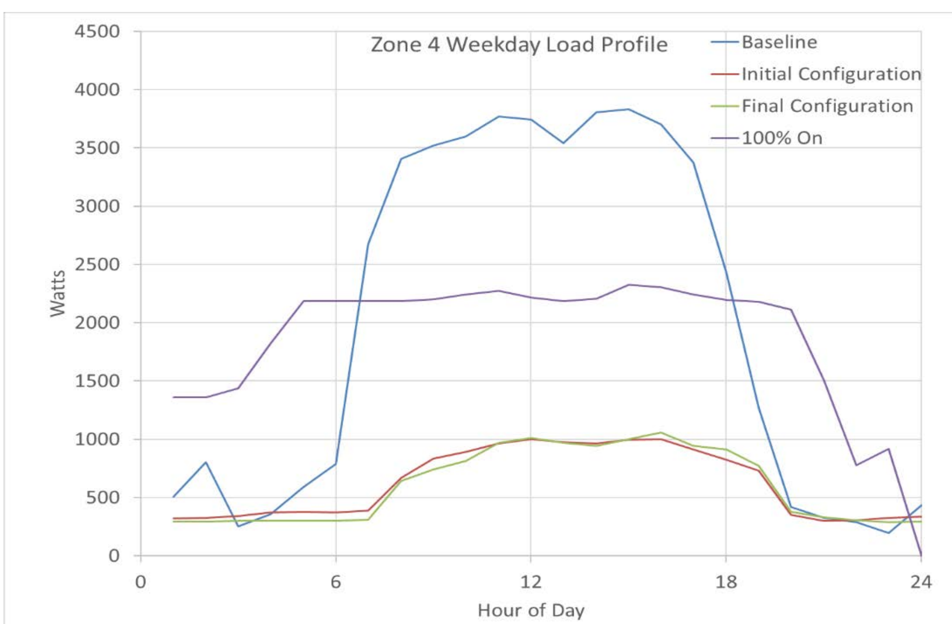


Figure A4 for Zone 4 also shows generally expected profiles, but the initial (LED) fixture and final (LED-tuned plus controls) profiles are almost identical. This is because the product had pre-set control levels activated directly out of the box. To compare this system to others without pre-set control levels, the 100% profile was specifically programmed within the system and measured after installation to capture savings without controls.

Figure A4. Fort Worth Zone 4 Weekday Load Profile



For Zone 5, Figure A5 shows a 50% reduction in LPD (0.86 to 0.43) from baseline to initial LED installation and another 26% reduction from light-level tuning to meet occupant needs. A significant reduction (pre-tuning) in light level (34%) also occurs with this zone retrofit. This reduction in LPD can be primarily attributed to reduced light levels.

Figure A5. Ft. Worth Zone 5 Lighting Power Density

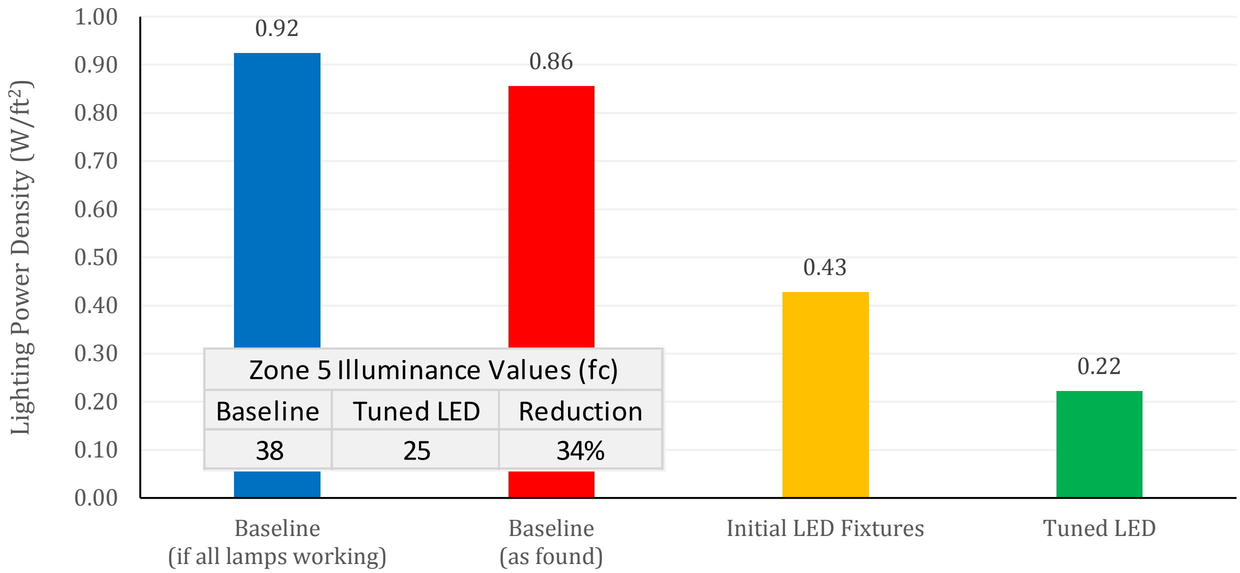
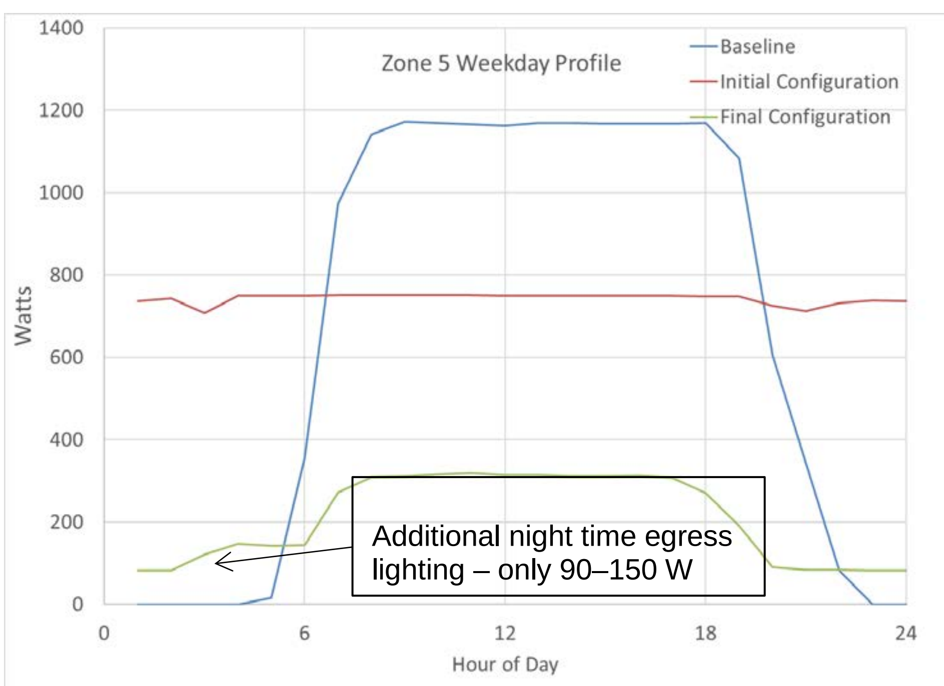


Figure A6 for Zone 5 also shows expected profiles, with the exception of early morning and evening hours where there is more load from the final LED configuration than the baseline fluorescent. This also was determined to be the result of separate project work on egress lighting that resulted in the installation of a few additional fixtures to meet nighttime egress needs.

Figure A6. Fort Worth Zone 5 Weekday Load Profile



For Zone 6, Figure A7 shows a 34% reduction in power density (0.90 to 0.59) from baseline to initial LED installation and another 9% reduction from dimming to meet occupant needs. This also is accompanied by a significant reduction in light level (41%). The reduction in power density can be primarily attributed to reduced light levels.

Figure A7. Ft. Worth Zone 6 Lighting Power Density

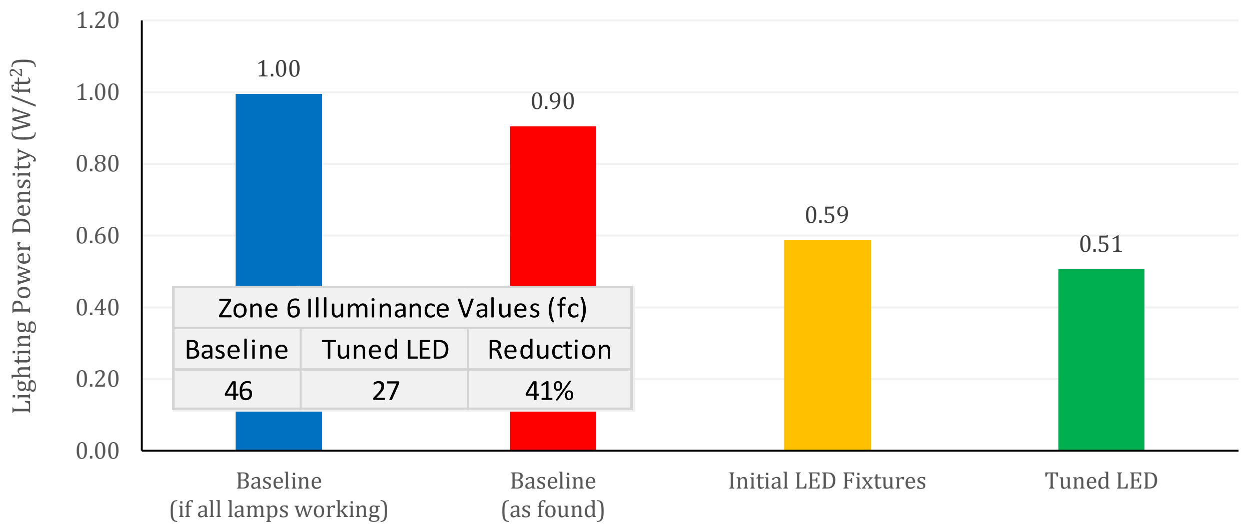
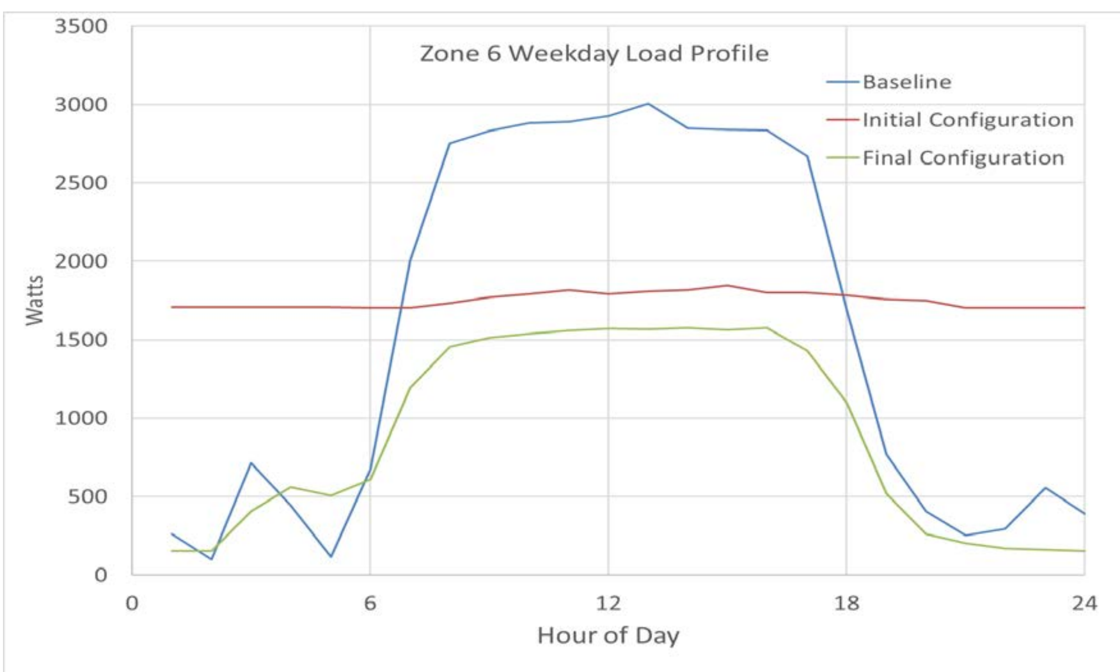


Figure A8 shows lighting power profiles for Zone 6.

Figure A8. Fort Worth Zone 6 Weekday Load Profile



For Zone 7, Figure A9 shows a 70% reduction in LPD in the occupied mezzanine areas (1.34 to 0.41) from baseline to initial LED installation and another 2% reduction from light-level tuning. In this case, the mezzanine was originally lighted with much less efficacious T12 fluorescent lighting, which greatly contributed to the large reduction in LPD. Hallway lighting power was only reduced by 7% by design. This was accomplished by purposely installing new LED lighting to match existing light levels to ensure egress lighting needs were maintained.

Figure A9. Ft. Worth Zone 7 Lighting Power Density

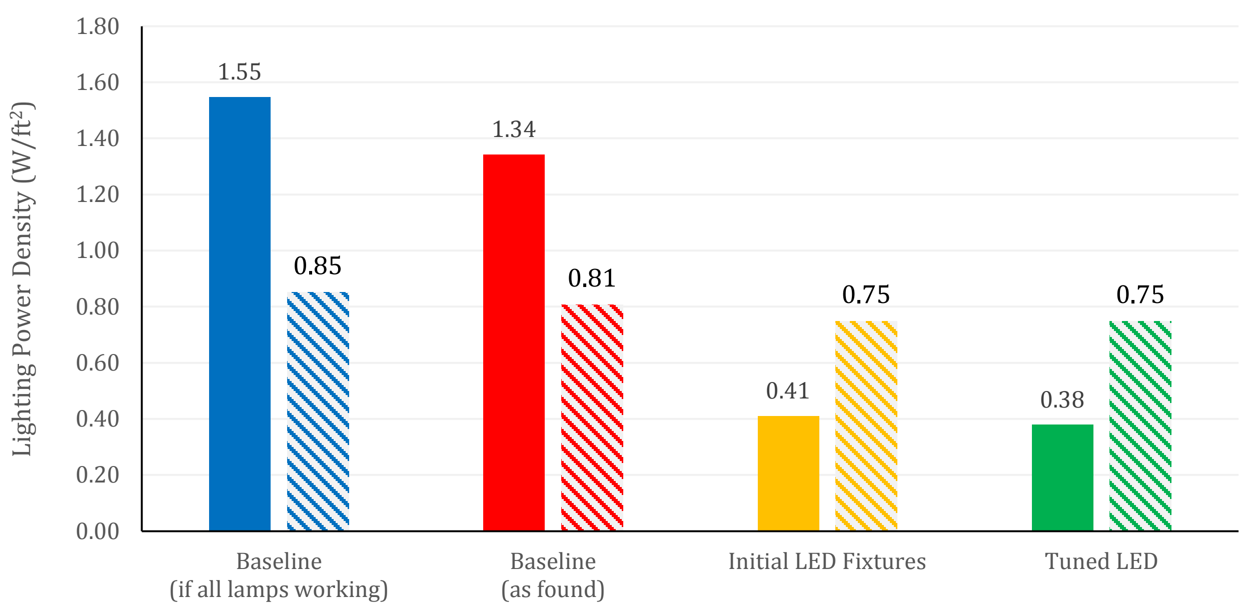
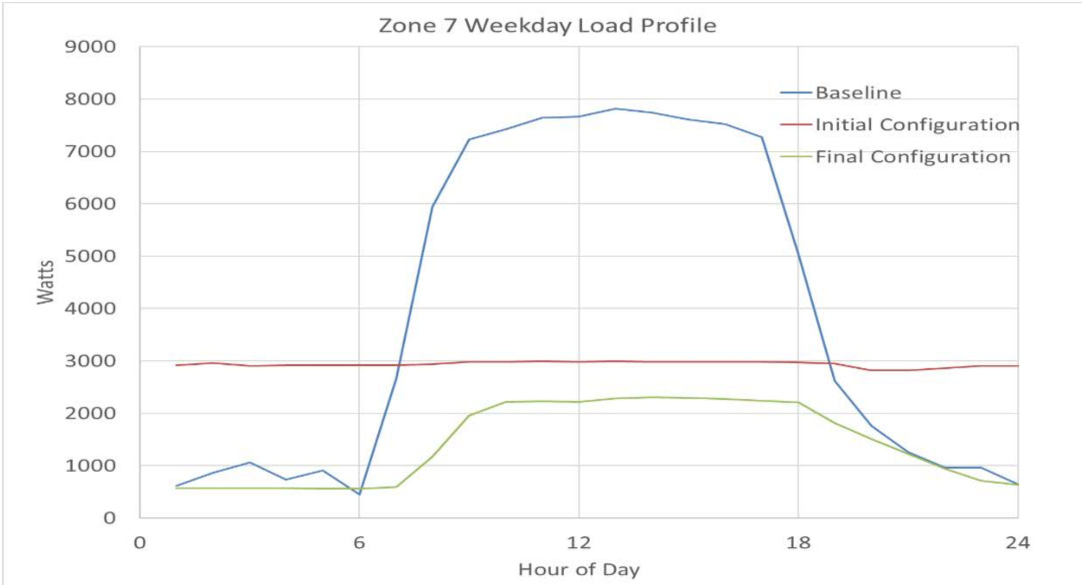


Figure A10 for Zone 7 also shows expected lighting power profiles.

Figure A10. Fort Worth Zone 7 Weekday Load Profile



Installer Responses

A list of all the responses from installers about their experience on this project is presented here related to the general question area of the survey. These responses are specific to this evaluation project and are not anticipated to necessarily apply to any other projects.

Instructions complete and effective:

Zone 5 – "Typical lay in fixtures"

Zone 3 – "The fixture was simple in design but we had to modify the junction box to accept all the cables several times (not enough knock outs)"

Zone 6 – "There was no wiring diagram to connect the control components with the emergency ballast/battery. This caused a significant delay on one occasion while I had to examine the wiring of all the components and draw out my own schematic. Because of the complexity I could not have multiple installers working on these but had to wire them myself"; "wiring schematic was not available for the egress lights."

Difference in time to install compared to standard fluorescent fixture:

Zone 7 – "Initially there was an issue with the size of the fixture but the manufacturer listened to my feedback and actually made changes to make the fixture more installer friendly, which was impressive and unexpected"; "at first but the manufacturer/vendor updated the design and made them faster to install."

Zone 4 – "The box was a tight fit in the grid and we had to pry it in place while hitting it with a rubber mallet. It would be wise to ask if the flaw has been corrected before ordering any new (complete) fixtures"; "The housing was too large and we had to use force to get them in place"; "We had difficulty with the fixture housing. It was slightly too large."

Zone 6 – “The placement of the connection point is at the end of the fixture, which made it difficult to fit in the grid with nearby obstructions. The junction box is also very small so additional time is required to fit the cable in place. The retrofit kits were complicated and had too many separately packaged parts, which eat up much more time than the other products we installed”; “The fixture was designed in a way that caused it to hit the support wires increasing the difficulty in installation.”

Zone 5 – “The fixtures being a 2x2 required the installation of a new 2’ grid cross section to support the fixture as well as a 2x2 ceiling tile. Additionally, some fixtures required that a box be installed in the new 2x2 tile to hold the test button for the fixtures that had a battery backup. This increased the time to install beyond the other manufacturers”; “We had to place a box next to the fixture cut into the celling for the test button”; “had to modify the ceiling and install test buttons for the egress lights in the ceiling.”

Zone 3 – “Due to the design we had to drill ½” holes several times to connect the cable. Additional knock outs should be added. Also later product revisions received had a junction/splice box on top that was undersized. When everything worked though the install was fairly simple”; “We had to drill holes to make cable connections to the fixture.”

Controls built in to fixtures and/or the controls configuration requiring any difference in installation:

Zone 7 – “built in”

Zone 4 – “We had an issue with the wires coming out of the optical sensor while installing. The sensor is mounted to the door. Additionally, the plastic locknut that secures the sensor came of easily and was difficult to put back in place.”

Zone 6 – “ For the egress lights, a specific schematic was missing this applies to the retrofit kits.”

Zone 5 – “The controls were separate and had to be installed first before installing the fixtures”; “We had to install them which added 10 or 15 minutes per light”; “we had to install them so more time was needed.”

Zone 3 – “We had to drill additional holes in the splice box to add in the Lutron devices on at a majority of the fixtures provided. The control device was a separate product”; “The control device was separate and added about 10 to 15 minutes per fixture to set up install and clean up”; “We had to install them in the field and it added time to the installation.”

For complete fixture - time estimate to install:

Zone 7 – “Same as a traditional fluorescent fixture”; “Same as standard fluorescent”; “Same as a standard fluorescent.”

Zone 4 – “Besides pounding the fixture housing in place it was the same as a standard fluorescent”, “Same as a standard fluorescent”; “This fixture (once the box size is corrected) is as fast if not faster than a traditional fluorescent fixture.”

Zone 6 – “ Pretty much the same as a fluorescent but the connection point got in the way. Also the end of the fixture hangs over the grid and hits support wires (frustrating)”; “Took slightly longer than a standard fluorescent due to the fact that it was hitting support wires”; “The full fixtures took the same and sometimes slightly longer than a traditional fluorescent fixture (due to wiring connection points being on the end causing it to hit obstructions and be difficult to work with). The retrofit kit took longer than the other manufacturers due to the number of individually packaged parts, the off shape of the parts and the lack of any instructions on how to wire the control components with the emergency battery pack and ballast."

Zone 5 – "Same as a standard fluorescent plus the time to adjust the grid from 2X4 to 2X2 plus installing the box for the push buttons"; "Same as a fluorescent plus the time to change the ceiling tiles and add the buttons"; "This fixture takes longer than a traditional 2x4 fixture but would be comparable to a standard 2x2 fluorescent with the exception of the time required to install the test buttons in the ceiling in the adjacent tile (increase of time)."

Zone 3 – " The same as a standard if you don't factor in the Lutron. We did have to drill holes for the cables so that added a little more time"; "Same as a standard fluorescent plus the time to install the control device"; "This fixture (without external control devices) is as fast if not faster than a traditional fluorescent fixture."

For retrofit kit – time estimate to install:

Zone 7 – "Slightly faster and cleaner than pulling a whole (old) fixture out and placing in a new one. The cleanup time was significantly reduced due to not having to open the ceiling"; "About 5 minutes plus cleaning and setup"; "(about) 5 minutes."

Zone 4 – "5 minutes but there is additional time required tin set up, parts handling, disposal of the old parts, clean up, and so forth"; "5 minutes plus set up and cleaning"; "4 to 6 minutes."

Zone 6 – "I would estimate that it was faster than pulling a fixture out and replacing it with a complete fixture but there was a long setup time and a long cleanup time due to the design and packaging "; "We had a lot of boxes to open and the parts took time to sort out. Maybe 5 minutes without all the other steps"; "4 to 6 minutes."

Other input on fixture install:

Zone 7 – "The product is simple and straightforward to install."

Zone 4 – "Bring a small pry bar and a rubber mallet (hopefully the box size will be corrected in the future). For the retrofit kits I would suggest using small self-tapper screws to secure the LED strip, the existing screws are difficult to work with some things."

Zone 6 – "Be certain the proper schematics are provided"; "You may need to add time in planning to move the ceiling grid support wires a little so the fixture doesn't hit them;"

Zone 5 – "For all of the emergency light fixtures a gangable box with clamps will be required that is not provided by the manufacturer"; "Boxes for the test button need to be supplied by the installer;"

Zone 3 – "For the standard 2x4: Have a ½" carbide bit available to add holes in the junction box for cable connection. For the architectural: The Connection box is in the center of the top of the fixture, you will have to extend the existing MC whips in order to reach the connection point. I have notified the manufacturer regarding this design flaw as well as the undersized connection boxes on the revised fixtures"; "You may have to drill holes for your cable unless the product is updated."

Any Separate Instructions needed for control installation:

Zone 7 – "In fixture control system factory installed (wall switches required no wiring)"; "Fully integrated control system."

Zone 4 – " Factory installed inside fixture."

Zone 6 – " Was built into the fixture – for the wall switches no wiring required so we didn't need wiring instructions."

Estimate of time to install the controls:

Zone 7 – " Depends on how many access points are required. This system is comparable to the other LED products in the time required to install the access points. It is faster that installing power packs in most cases but close due to potential other requirements such as power outlets that could come up, this is the same for all the products being reviewed"; " 2 to 3 days; one day for the network cables plus one day for nums and switches – *similar to fluorescent system*"; "1 day for switches (blanks & new switches)."

Zone 4 – "Factory installed so no time required other than 4 or 5 hours to set up a cabinet for the hum and networking line for the access point"; "(Switches) 1/2 day, 1/2 day for 1 access point – *2 days for fluorescent.*"

Zone 6 – "Faster since the wall switches did not require wiring"; "1 day for the switches."

Zone 5 – " Installing the individual units took longer than a traditional wired power-pack occupancy sensor system installation. It is a superior set up though when compared to the traditional system. If these are not factory installed then expect triple the time required, or a minimum of 5 minutes per fixture plus set up time, clean up time, and fixture handling"; "10 to 15 minutes each."

Zone 3 – " N/A Installing the individual units took longer than a traditional wired power-pack occupancy sensor system installation. It is a superior set up though when compared to the traditional system. If these are not factory installed then expect triple the time required, or a minimum of 5 minutes per fixture plus set up time, clean up time, and fixture handling"; "10 to 15 min per fixture."

Other input on controls install:

Zone 6 – "You will need to blank off all switches in the area."

Zone 3 – "Have small wire nuts on hand, the wire nuts provided by Lutron are too large and result in loose inferior connections."

Observation on commissioning done by others (manufacturer):

Zone 7 – "They had to update the firmware to correct a few minor issues but that was typical among all vendors"

Zone 4 – "the technician was quick and effective."

Zone 5 – "Lutron had many problems getting their products to work properly. I was told this is not typical and was caused by a firmware issue that has since been resolved."

Length of time for commissioning:

Zone 7 – "Due to the size of the area plus the firmware update."

Zone 4 – "4 to 5 hours."

Zone 5 – "at least 3 – 4, 2 Lutron Technicians."

Zone 3 – "At least 3 – 4, 2 Lutron Technicians."

Additional comments:

Zone 6 – "…shipped dozens of incorrect fixtures to the site which were mixed in with the correct fixtures which caused some of them to get installed (and later replaced). The products provided for the east wing surface mount fixtures were not appropriate for the existing electrical which caused severe delays. The controls provided for that area (east surface mount area) were not appropriate as well which caused us to have to improvise and install the receiver switches (intended for the wall) on the ceiling (one for each row). The retrofit kits which included batteries did not have an appropriate schematic that showed how to install both the piece with the controls and the battery together. This caused a significant loss in time. This was disappointing coming from such a large manufacturer."

Zone 5 – "A firmware bug resulted in several trips by Lutron technicians to sort it out."

Figure A11. Fort Worth Zone 3 Estimated Annual Energy Use

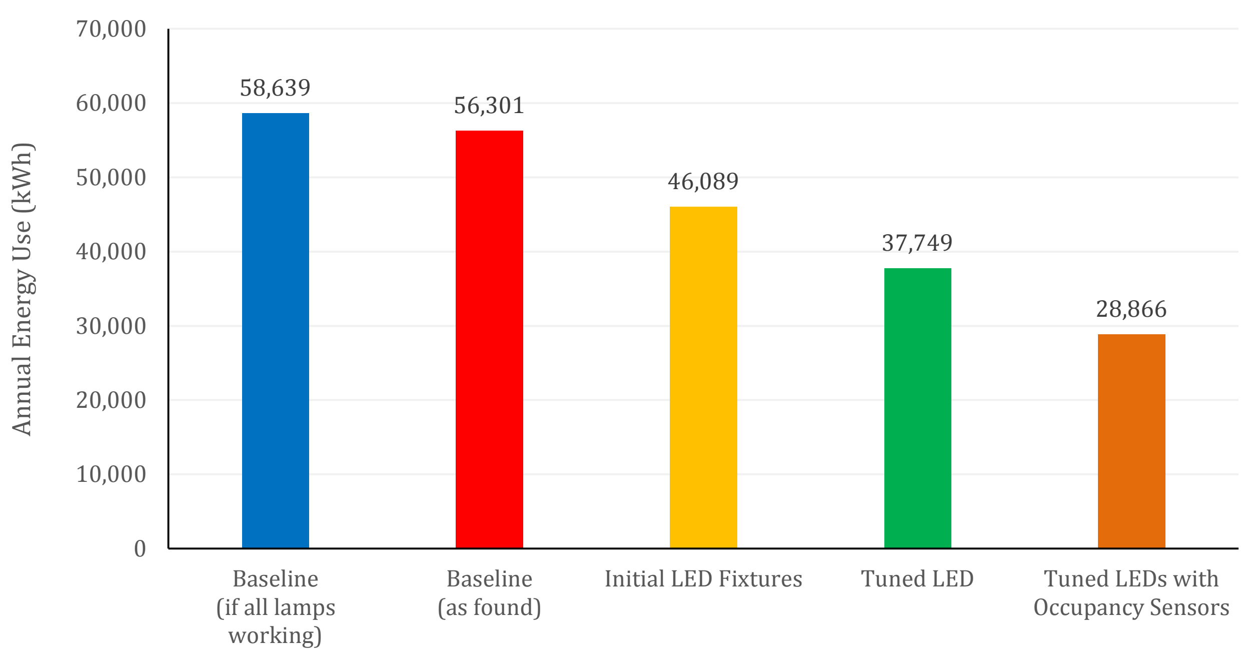


Figure A12. Fort Worth Zone 4 Estimated Annual Energy Use

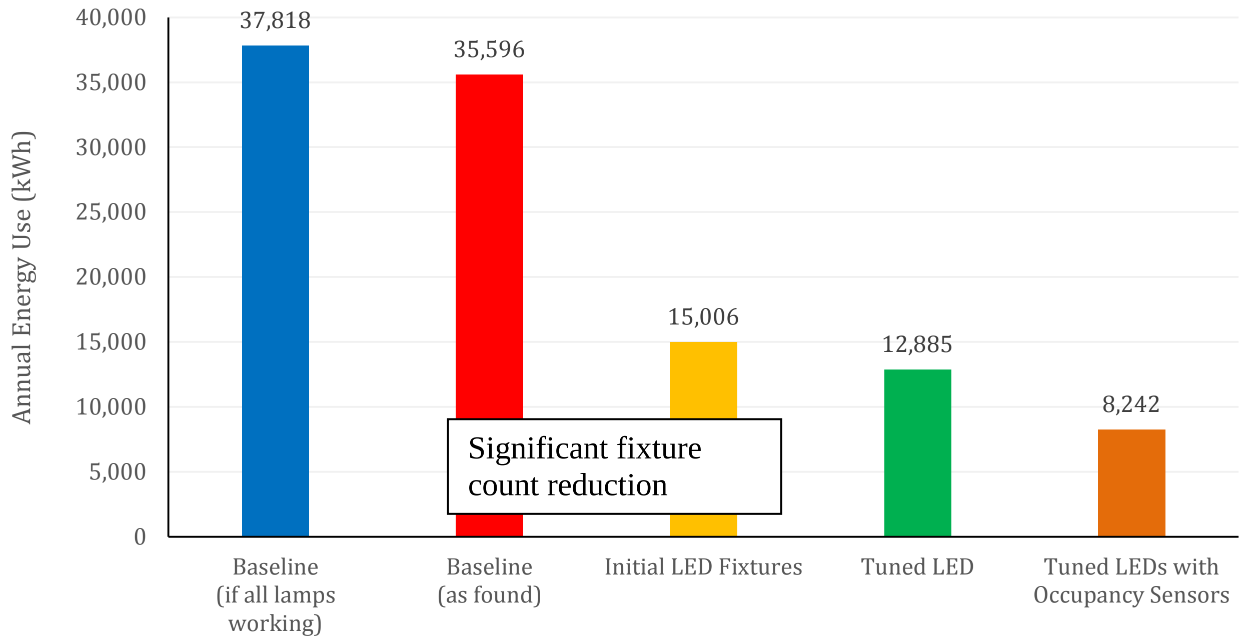


Figure A13. Fort Worth Zone 5 Estimated Annual Energy Use

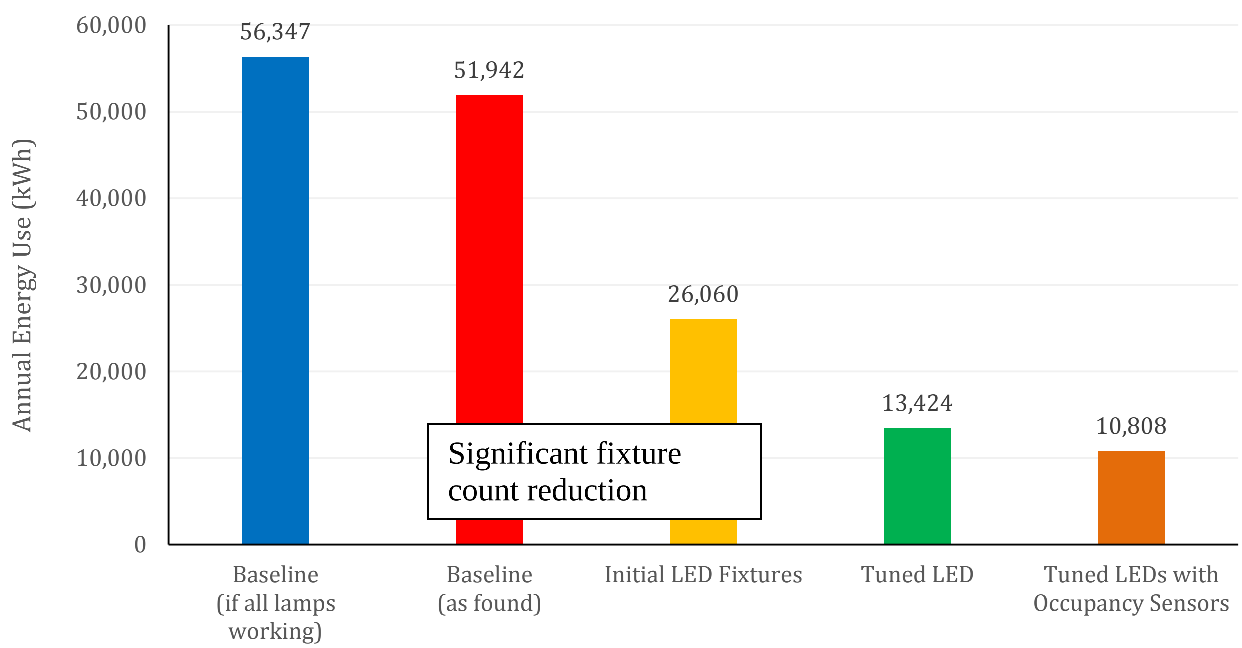


Figure A14. Fort Worth Zone 6 Estimated Annual Energy Use

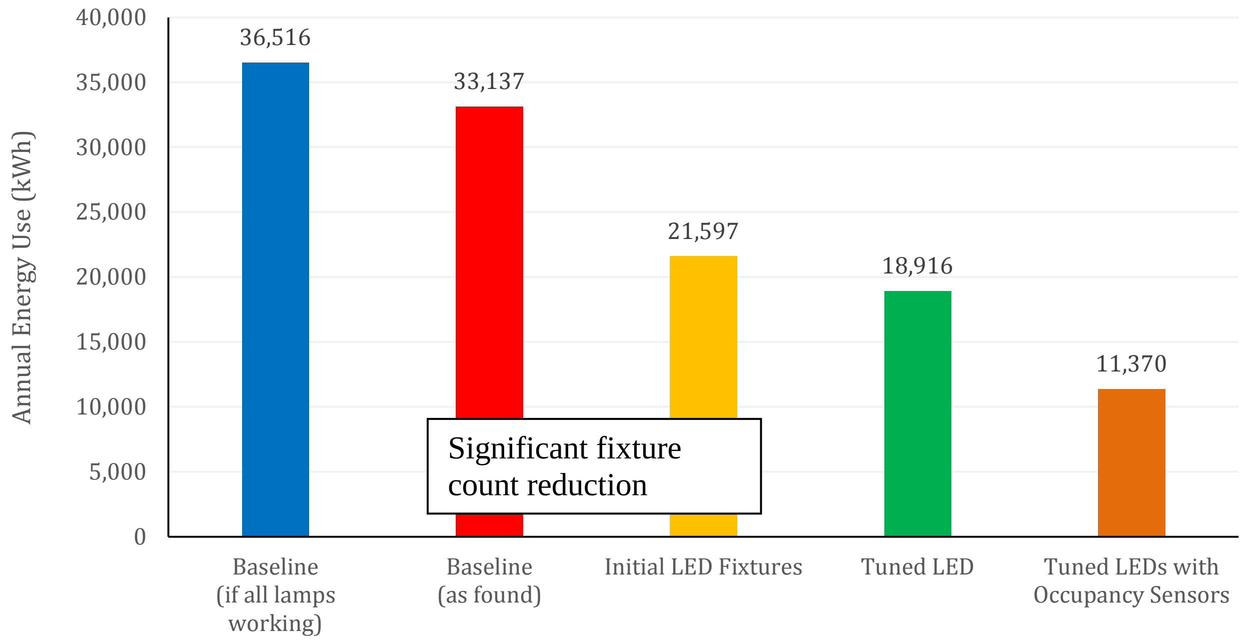
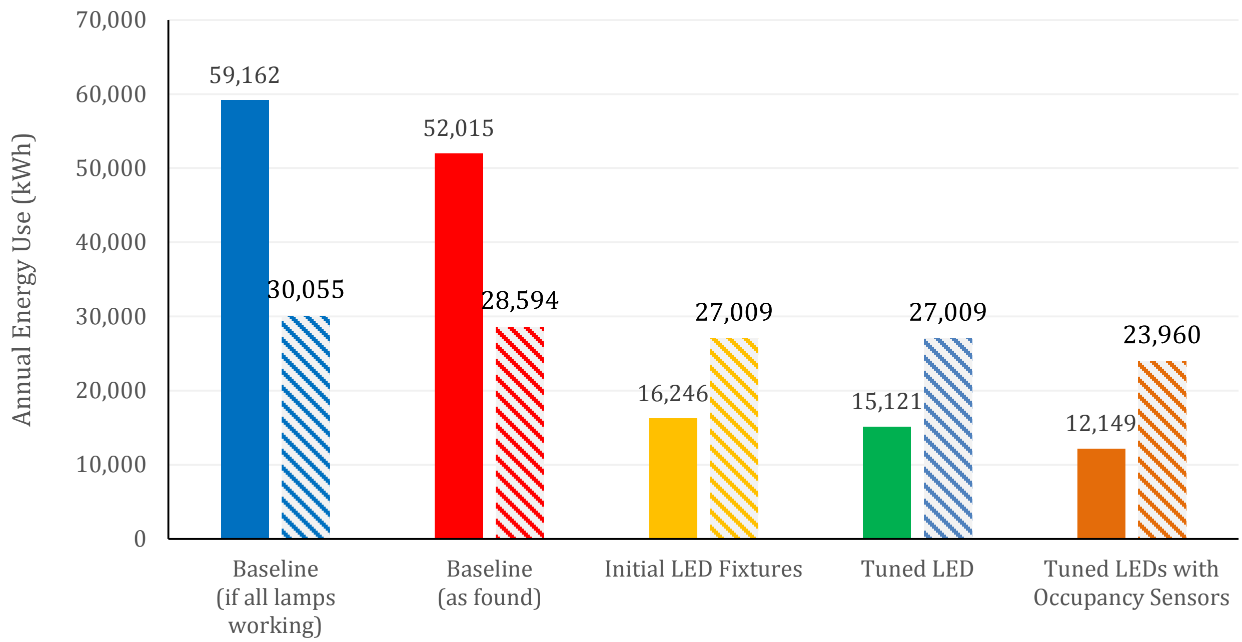


Figure A15. Fort Worth Zone 7 Estimated Annual Energy Use



B. GLOSSARY

ballast	A device that regulates the current and voltage supplied to a gaseous discharge lamp or lamps *(*e.g., a fluorescent lamp).
daylight harvesting	A control strategy that reduces electric light levels in the presence of available daylight, “harvesting” the daylight to save electrical lighting energy.
light-level tuning (high–end trim)	A control strategy typically accomplished as part of commissioning that reduces electric light levels to match occupant, task, or other operational needs. This is typically completed as a one-time setting and is not the same as active dimming, which is commonly accomplished at the whim of space occupants.