Ace Hardware LED High-Bay Lighting and Controls Project

ET Project Number: ET 12PGE3361

Photo Courtesy of Digital Lumens

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LEGAL NOTICE

ABBREVIATIONS AND ACRONYMS

IES	Illuminating Engineering Society
LED	Light Emitting Diode
LPD	Lighting Power Density
MH	Metal Halide
CEUS	California Commercial End-Use Survey

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EXECUTIVE SUMMARY

PROJECT GOAL

This project was intended to test the integration of Light Emitting Diode (LED) lighting technology in combination with an aggressive lighting controls strategy to realize the deepest energy savings possible within a warehouse space.

The study compared the energy consumption of a baseline metal halide (MH) lighting system with that of a LED retrofit lighting system and the integration of a variety of lighting controls establishing energy savings produced by each option. The changes were performed incrementally so that it is possible to quantify the contribution of each controls approach on the total energy savings for the project. Additionally, to determine cost effectiveness simple payback calculations were calculated for the LED retrofit lighting system and associated controls.

The study also collected subjective feedback from occupants in the space to help establish the relative visual quality of the incumbent and retrofit lighting systems.

The study was conducted in a discreet 44,800 square foot warehouse space within a much larger warehouse facility. This retrofit project is representative of lighting retrofits in warehouse spaces where the lighting systems are currently 'static' (with no daylighting or occupancy based controls) and for conditions where MH lighting is the incumbent light source technology.

This study found that the simple payback for this retrofit project, while using the full host of controls available was 3.6 years, and resulted in a predicted 93% reduction in the yearly energy consumption in the space.

PROJECT DESCRIPTION

This study was conducted on a lighting retrofit project in a discreet 44,800 square foot space within an Ace Hardware Distribution Center in Rocklin, CA. The space is used as the aerosol storage room, and contains inflammable and aerosol products that the company sells in its stores.

The existing high bay metal halide luminaires were replaced initially with LED luminaires and then with the addition of lighting controls to the replacement LED luminaires. The energy savings between the existing and retrofitted lighting was analyzed in addition to savings from occupancy and daylight harvesting controls of the new fixtures.

The occupancy of the warehouse does not follow a traditional Monday through Friday schedule. For this site, 'Weekday', 'Friday', and 'Saturday' have operating hours as follows:

- Sunday-Thursday - 4:00 AM through 11:00 PM. (five days a week)
- Friday – 8:00 AM through 5:00 PM.
- Saturday – No activity except possible maintenance or other facility work (rare).

Baseline Lighting System:

There were 102 existing 400 watt MH high bay luminaires mounted near the 25' ceiling. The luminaire connected load was approximately 460 Watt each including ballast losses for magnetic ballasts. The existing lighting system did not have local controls. The lighting in the space was controlled via the breakers at the panel, which are at least 250 feet away from the space with no direct line-of-sight to the lighting in the space. There are fourteen (14) 4'x8' skylights that provide a limited amount of daylighting in the space. No occupancy or daylighting controls were present in the baseline space.

Energy Efficiency Upgrade Opportunities:

The existing lighting in the space suffered from inconsistent maintenance and relatively low light levels, so as part of the retrofit project, the intent was to increase the lights levels from approximately 5 to 8 footcandles in the aisles to 15 footcandles.

There is often continuous occupation in the space during work hours, but at any given time, most of the aisles are not locally occupied. Therefore, implementation of an occupancy-based lighting control system with discrete control of individual aisles could allow lighting to be turned of during times when aisles are not occupied.

Further, there is adequate daylighting to permit reducing light output from electric lighting in portions of the space regardless of the occupancy patterns. When unoccupied, some of the lighting could be turned OFF completely. As a result, there is a strong opportunity to save energy with an aggressive lighting controls approach.

Metal halide light sources have several limitations that make them less than ideal as a platform for lighting controls. Warm-up and re-strike times (the length of time it takes from the initial ignition until they are producing maximum light output) range from several minutes up to about 15 minutes. This eliminates the possibility of turning 'OFF' the light during vacant periods. Further, it is possible to dim MH lamps, but the range of dimming is limited to approximately 40 to 50% of full light output, and the power input only drops by about 30%, so there is considerable efficacy penalty to achieve this dimming.

Recent LED technology advances have resulted in higher efficacy and lower costs, providing an opportunity to cost effectively replace MH luminaires with LED. The LED technology has the added benefit of instant warm-up and re-strike and a very wide range of dimming capability (down to 10% is common with many products) while still maintaining a high level of efficacy through the dim range.

Controls Strategies Studied:

This project evaluated the installation of an 'all-in-one' retrofit lighting solution employing LED light source technology, on-board occupancy sensors, daylight sensors, and wireless communication; combined to coordinate the activity, establish a control schedule, and enable status monitoring.

The study was structured into six control phases tested sequentially. Specific controls strategies were programmed into the controls system for each test segment. The control strategies were:

- **Pre-Retrofit Baseline (As Observed and Fully Operational)**

  This employed the lighting controls approach that was being used for the lighting system before the project initiation (manual lighting controls at the panel). This establishes the baseline energy consumption for the existing equipment and control strategy, and provides hours of operation information. During per-retrofit baseline monitoring, not all luminaires were operational; therefore, "As Observed" and "Fully Operational" baselines are reported. The 'Fully Operational' baseline has been adjusted by approximately 20% upwards from the 'As Observed' baseline to compensate for non-functional luminaires documented during the baseline energy measurements.

- **Post-Retrofit Strategy #1: LED Luminaires at 100%**

  This employed the same lighting controls approach that was being used for the pre-retrofit lighting system. The lighting was operated without integrated controls, and the light level was established at 100% of the luminaire output (full-ON) for this test segment.

- **Post-Retrofit Strategy #2: LED Luminaires at 70%**

  The second Post-Retrofit Baseline segment was collected after the lighting system was adjusted to reduce the light level to 17 fc average in the aisles, which is slightly higher than the target illuminance of 15 fc. All the additional controls were operated with the top lighting level established at this 70% value

- **Post-Retrofit Strategy #3: Occupancy Control Only, Coarse Zoning**

  This strategy employed the occupancy sensors as the only control device. The lighting was grouped into zones (one zone per aisle, and a zone for each cross-aisle or open area in the space), with a short delay time of 30 seconds. The lights were dimmed to approximately 10% of full output for unoccupied periods during the workday.

- **Post-Retrofit Strategy #4: Daylighting Control Only, Individual Control**

  In this approach, the regular schedule of operation for the facility was used to establish a long occupancy sensor delay time so that once the first occupancy event occurred in the morning, the lighting remained on until the end of the regular day. During the day, the only adjustment to the lights was the response to daylight availability.

- **Post-Retrofit Strategy #5: Combined Control, Coarse Zoning**

  This strategy employed both daylighting and occupancy controls in the space in an approach that is consistent with the typical warehouse lighting control system as currently designed for new construction in California.

- **Post-Retrofit Strategy #6: Combined Control, Fine Zoning**

  This strategy essentially employed fixture-level controls approach that is enabled by the built-in occupancy sensor and daylight sensor in each luminaire.

PROJECT FINDINGS/RESULTS

Results from the monitoring study show an annual energy consumption reduction up to 93% of the lighting energy consumed in this space from a combination of the LED technology and the controls strategy #6.

The LED light source replacement is shown to be responsible for an approximately 50% reduction in the energy use from the baseline. The most aggressive lighting control system (combined daylighting and fine granularity occupancy sensors – Strategy #6) added an additional 43% reduction in the energy use from the baseline.

The energy savings associated with the LED replacement should be considered a reasonable expectation for similar space type and baseline lighting system (MH fixtures).

The energy savings associated with the controls should be considered a reasonable expectation for a similarly occupied warehouse space, but may be somewhat decreased if the number of occupants or hours of operation are greater than those in this study space.

Figure 1 below shows the representative weekday (Sunday through Thursday) energy use curves for the various scenarios, including the 'Fully Operational' baseline, which is the basis for all energy comparisons in the report. This graph visually shows the amount of energy consumption through a typical weekday, with the baseline shown as a shaded region, and the relative values of the various controls strategies as lines below.

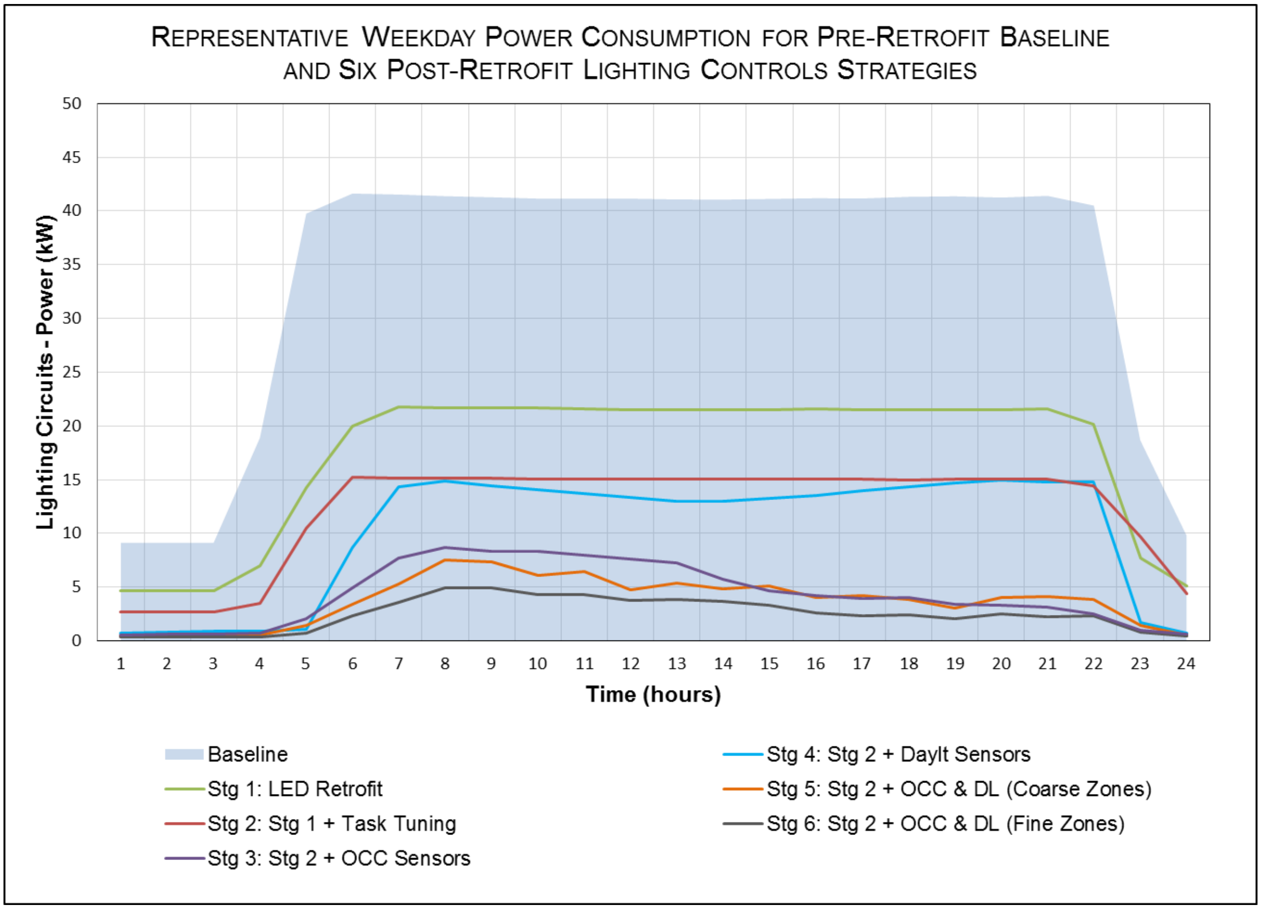


FIGURE 1. REPRESENTATIVE WEEKDAY POWER CONSUMPTION FOR PRE-RETROFIT BASELINE AND SIX POST-RETROFIT LIGHTING AND CONTROLS STRATEGIES

Table 1 below provides a breakdown of the lighting energy use estimates for the various scenarios compared to the baseline for an entire year. It also provides a comparison to current Title 24-2008 and 2013 lighting power density allowances to provide context for new construction limits. This comparison is important because a lighting replacement project in a warehouse is likely to cause a Title 24 review and inspection due to the much more aggressive thresholds for renovations and retrofit requirements.

Table 2 below provides information on the demand reduction that the lighting system exhibits in the afternoon for the representative use curves.

Table 1. Summary of Annual Energy Consumption for Baselines and Six Post-Retrofit Scenarios

	Lighting Power Density (W/sq.ft.)	Percentage of T24-2013 Allowance (0.6 W/Sq.Ft.)	Meets Title 24-2013	Estimated Annual Energy Use (kWh)	Percentage of Fully-Operational Baseline Value
Fully-Operational	1.05	175%	N	254,973	---
As-Observed	0.83	138%		202,991	80%
Strategy #1	0.52	87%	Y	129,603	51%
Strategy #2	0.37	61%	Y	92,038	36%
Strategy #3				29,388	12%
Strategy #4				71,638	28%
Strategy #5				25,653	10%
Strategy #6				16,929	7%

Table 2. Table of Representative 15-Minute Demand for Pre-Retrofit Baseline and Six Different Post-Retrofit Lighting and Controls Strategies

	Peak 15-Minute Average Demand (Kilowatts)	Percentage of Fully-Operational Baseline Value
Fully-Operational	41.8	---
Strategy #1	21.8	52%
Strategy #2	15.2	36%
Strategy #3	9.0	21%
Strategy #4	15.0	36%
Strategy #5	7.7	18%
Strategy #6	5.2	12%

Project Recommendations

The results of this study support several primary recommendations:

1. Promote the replacement of MH warehouse lighting systems with new LED-based lighting systems. Deep energy and demand savings of approximately 40 – 50% are possible by the replacement of the MH luminaires with high quality LED luminaires. This retrofit strategy is cost effective, and will reliably produce energy and maintenance savings to the owner for many years to come beyond the payback period.
2. Promote the inclusion of occupancy and daylighting controls with warehouse lighting retrofit measures to reduce or eliminate lighting under certain occupancy and/or daylighting conditions. If done properly, this is will increase the energy savings considerably, up to approximately an additional 40-45%. Demand will be less affected, but will typically be reduced by 35-40%. Even in higher traffic warehouse spaces, the energy savings will likely be approximately half of that found in this project, in the 20-25% range, but demand savings will likely be reduced somewhat more due to coincident activity within the space.
3. Promote the positive impact of establishing lighting controls settings (setbacks for unoccupied periods, delay times for setback, etc.) considerably more aggressive than that specifically mandated in Title 24-2013. That level of performance (requiring bi-level occupancy controls at 50% for the low setting), are the minimum performance to meet the Standard in construction. The high energy and demand savings in this report are not possible when applying the minimum performance approach to the controls. Note that the 2013 version of the Standard has much more aggressive requirements for additions, alterations, and repairs (Section 141.0), so it is likely that Title 24 needs to be consulted.
4. A lighting retrofit in a warehouse will save considerable energy, but the Title 24 additions, alterations, and repairs (Section 141.0) mandates are already effectively responsible for a considerable portion of the savings; the 0.6 W/sq.ft. allowance in the code has not changed in the latest revision. This is a fairly low lighting power density (LPD), but a lower LPD can be achieved with an effective, efficient lighting system. In addition, it is easily possible to exceed the minimum Title 24 performance levels for controls, and this is particularly where the savings in a warehouse retrofit program can be achieved.

INTRODUCTION

The advent of LED technology has changed the lighting industry in a number of ways. As LED technology improves, it is becoming more efficacious than many other technologies. In addition, the inherent ability to dim and switch on and off without the apparent life or energy penalties of other high efficacy sources provides additional benefits that have not fully been explored by the lighting industry yet.

The advances in the controls and wireless communications segments of the market have made it possible to integrate all of these products into a luminaire. Integrating the different controls options with a central control and sensors at luminaire levels, there is opportunity to switch luminaires individually, rather than in groups. This provides greater energy savings opportunities above and beyond what is currently being done with controls.

The product evaluated in this study is manufactured by Digital Lumens and is a 215W LED warehouse luminaire designed for both aisles and open areas. This luminaire includes an occupancy sensor and daylight sensor on-board, and a wireless node for connection to a central control system. The luminaire is capable of operating through the control system or independently, depending on the initial setup and programming.

The product line was developed specifically for warehouse retrofit situations. In these cases, the wiring in the facility is existing, and any real changes to the existing electrical system can be prohibitively expensive. As a result, the wireless approach employed by these products eliminates the need for any large scale wiring changes, and puts the primary effort of the retrofit project into the luminaire replacement and controls commissioning.

However, as the lighting industry and the technologies that support it advance, it is apparent that this approach may be viable for new construction as well. In specific situations where the lighting equipment density is low enough (through the relatively low illuminance requirements of the task), the possibility of integrated sensors, control system interface, and luminaire is a viable approach, especially as the cost of the non-luminaire technologies decrease.

As a result, while this study explores the possibilities for retrofit situations, the packaging of luminaire, controls, and communication technology into a single product is applicable for new construction situations as well.

BACKGROUND

This assessment was a retrofit project of an Ace Hardware Distribution Center in Rocklin, CA. The existing high bay metal halide luminaires were replaced with LED luminaires. The energy savings between the existing and retrofitted lighting was analyzed in addition to savings from occupancy and daylight harvesting controls added to the new fixtures.

This project was an evaluation primarily of the integration of LED light source technology with integral occupancy and daylighting controls capability, using an aggressive controls switching strategy to obtain the deepest reasonable energy savings while maintaining or improving the visual comfort and performance of the space for the employees.

EMERGING TECHNOLOGY/PRODUCT

This project explored a high efficiency LED light source technology and various controls applications, which can be applied in combinations to obtain deeper energy savings. The four technologies considered are:

- LED light source technology
- Occupancy sensor controls in warehouse spaces
- Daylighting controls in warehouse spaces
- Integration of these with an advanced wireless controls interface and controls protocol

None of these technologies are new in specific application by themselves. However, the difference is how these technologies are integrated (or not) in an effective manner. The product specified in this project was a LED light fixture that has an occupancy sensor, a daylight sensor, and a Wi-Fi enabled internet–based controls interface integrated into the unit. This controls interface is also capable of much higher levels controls flexibility than the traditional controls system, and reflects the future of lighting controls for many lighting systems, beyond warehouse applications.

The integration of the controls into the luminaire is a reflection of the primary market that this product was designed to address – retrofit warehouse spaces – which will likely have existing HID sources and no controls. However, this product can easily be specified for new construction, and is capable of meeting the lighting and controls requirements in the newly adopted Title 24 code, which requires bi-level lighting controls for warehouse spaces.

The cost of a product that includes all of these capabilities is likely to be a barrier in circumstances where there is no requirement for all of the capabilities.

ASSESSMENT OBJECTIVES

The light source technology replacement from Metal Halide (MH) to LED was expected to reduce energy consumption considerably. What was unclear at the onset is the amount of additional energy savings that can be gained through aggressive but effectively transparent lighting controls strategies. This project tests these opportunities and provides some baseline metrics for lighting controls when integrated into a warehouse lighting system with an aggressive controls strategy.

For this project, the Consultant collected data to evaluate the energy savings from LED high-bay lighting fixtures and controls products installed at the Ace Hardware site.

The incumbent lighting system was monitored, and then the lighting system replaced with the new luminaire and controls system. Further monitoring was done while the lighting was operated in the same manner as before the retrofit. Then, various levels of lighting controls were implemented to help provide attribution to individual control aspects.

Occupant feedback of the new lighting system was collected through subjective surveys. These were administered pre- and post- installation to document the occupant's level of acceptance of the new lighting system.

TECHNOLOGY/PRODUCT EVALUATION

SITE DESCRIPTION

For this project, the Ace Hardware Distribution Center (Figure 2) in Rocklin, CA was chosen for field evaluation of a high-bay LED lighting retrofit. It is an approximately one million gross square foot facility for the large hardware supply chain, and includes primarily high-bay warehousing and some office areas for management of the warehouse staff.

FIGURE 2. ACE HARDWARE DISTRIBUTION CENTER

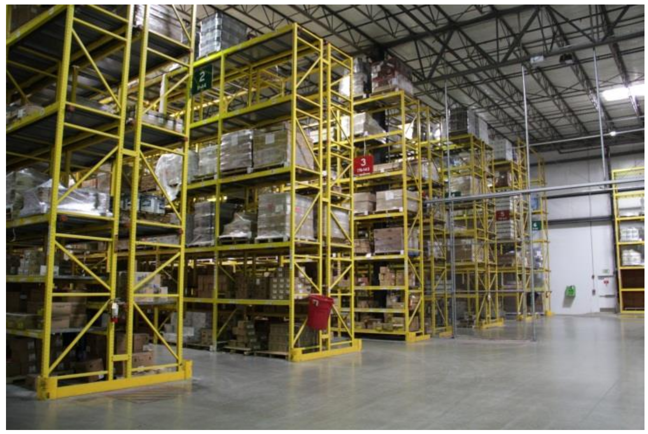


FIGURE 3. AEROSOL STORAGE ROOM

The specific room in the building that was the focus of this study is the aerosol storage room (Figure 3), which is a 44,800 square foot space dedicated to storage of hazardous materials that are sold through the stores, including spray paint, volatile solvents, and other potentially inflammable or explosively flammable products. As a result, there are special requirements for safety that the lighting system must meet to ensure that the lighting is not a potential source of ignition in the event of an volatile aerosol leak. These requirements are primarily electrical in nature, and do not affect the lighting performance of the system in any manner.

FACILITY OPERATING SCHEDULE

The occupancy of the warehouse does not follow the traditional weekday (M-F) and weekend (S-Su) schedule. For this site, 'Weekday', 'Friday', and 'Saturday' have typical operating hours as follows:

- Weekday - 4:00 AM through 11:00 PM. The days that follow this schedule are Sunday through Thursday (five days a week)
- Friday – 8:00 AM through 5:00 PM.
- Saturday – No activity except possible maintenance or other facility work (rare).

PRE-RETROFIT LIGHTING

The existing lighting equipment was 400 Watt high bay metal halide luminaires installed near the ceiling. There were 102 existing light fixtures in the space, distributed across 15 different circuits (Figure 4). The luminaire connected load was approximately 460 Watt each including ballast losses for magnetic ballasts. The existing lighting equipment was circuited in a typical 'A-B' alternating arrangement to avoid dark aisles if a single lighting circuit were to fail.

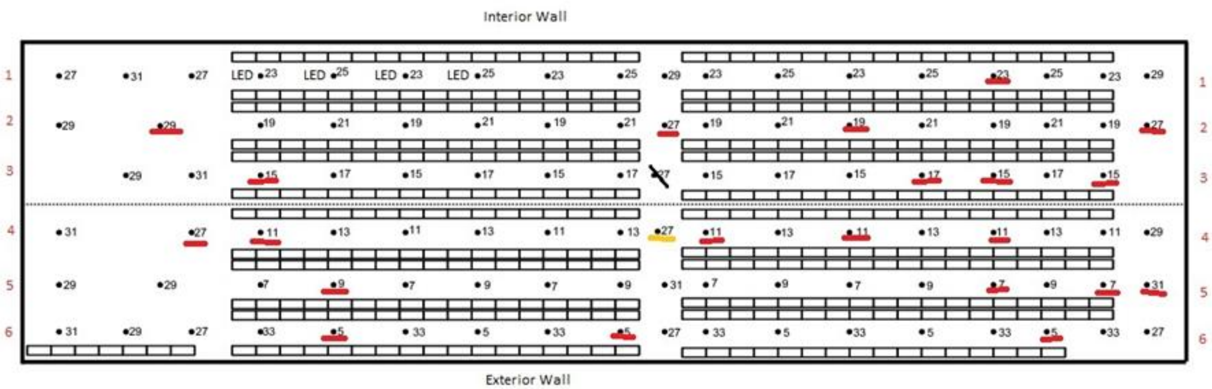
The existing lighting system did not have local controls. The lighting in the space was controlled via the breakers at the panel, which were at least 250 feet away from the space and around the corner with no direct line-of-sight to the lighting in the space.

Fourteen (14) 4'x8' skylights provide a limited amount of daylighting in the space when the conditions are favorable. The skylights are not ideally located; in one row the skylights are almost directly above the high racks rather than the aisle (Figure 5), so the light supplied is limited more than ideally would occur. When daylight is available, there is an opportunity to trim back nearby light fixtures to capture savings, but it must be done on a fixture-by-fixture basis, not through a larger circuit-wide approach. This does reflect the conditions of many California warehouse spaces; the shell of the building is often designed without full knowledge of the layout of the interior racks so perfect integration of the skylight into the rack layout is unlikely.

During the pre-retrofit monitoring period, twenty-one (21) of the luminaires were observed to be non-functional. The existing light levels were somewhat lower than recommended by the Illuminating Engineering Society (IES) when all the lighting equipment was functional; however, non-functional luminaires resulted in darker regions, especially when clustered in a row.

The lighting system was less than optimal in respect to maintenance, but it is presumed that once this retrofit project was planned for the space, regular maintenance was not performed, knowing that the whole system would be replaced shortly. Other areas in the warehouse had very good maintenance, which confirms that overall the facility has been maintained regularly.

Light levels measured in the space were approximately 11.5 footcandles (fc) in the open areas, and 5.0 to 8.0 fc in the aisles. Recommendations by IES are for 10.0 fc in warehouse spaces. Vertical light levels on the racks at approximately 5' Above Finished Floor (AFF) ranged from 0.5 fc to 3.5 fc. These values were measured in aisles without skylight influence, and with fully functional luminaires.



Missing fixture
Burnt out

The red underlined luminaire locations were not functional at the time of the site observations. This represents about 20% of the total lighting load in the space

FIGURE 4. PRE-RETROFIT CONDITIONS

FIGURE 5. SKYLIGHT LOCATION, ABOVE RACKS

PRE-RETROFIT ELECTRICITY USE

Lighting electricity use was monitored at the site between September 14 and October 15, 2012. Three circuits were logged for two weeks, and then the logger was switched to a second set of circuits for two weeks. The aerosol room was consuming approximately 653 kWh per weekday, 463 kWh per Friday, and 182 kWh per Saturday. Adjusting for the non-functional luminaires, the "fully operational" baseline usage was calculated to be 815 kWh per weekday, 591 kWh per Friday, and 243 kWh per weekend day.

Monitored data was combined with an annual work schedule to provide annual estimates of lighting energy use for the warehouse space. These energy consumption estimates are shown in Table 3.

TABLE 3. PRE-RETROFIT DAILY ENERGY CONSUMPTION ESTIMATES

	Weekday	Friday	Saturday	Annual
Fully Operational	815 kWh	591 kWh	243 kWh	254,973 kWh
As Observed	653 kWh	463 kWh	182 kWh	202,991 kWh

Lighting power densities (LPDs) were determined for both the incumbent installed lighting and the incumbent as observed operational lighting. The estimated incumbent installed LPD was calculated by multiplying the number of fixtures in the space by the connected load of each fixture; the incumbent as observed operational LPD was calculated by multiplying the connected load of each fixture by the number of actual functional fixtures in the space.

Table 4 below outlines the observed results for the warehouse space, as well as the estimated installed LPD and the statewide average energy use intensities (from CEUS-2006).

TABLE 4. SUMMARY OF ENERGY CONSUMPTION FOR BASELINE CONDITIONS

	AREA (SQUARE FEET)	LIGHTING POWER DENSITY (W/SQ.FT.)	ENERGY USE INTENSITY (KWH/SQ FT/YEAR)	ANNUAL ENERGY USE (KWH)	STATEWIDE AVERAGE ENERGY USE INTENSITY FOR THIS SPACE TYPE (FROM CEUS-2006) (KWH/SQ.FT./YR)
Fully-Operational	44,800	1.05	5.69	254,793	2.21
As-Observed		0.83	4.53	202,991	

The energy use in the warehouse area is substantially above statewide averages despite the fact that only 80% of the fixtures are functioning, because the hours of operation are very long (including substantial weekend operation hours) and the LPD of the space is considerably above what is now the design standard for an unconditioned warehouse space. Further, the lighting in the space lacks controls, and even though some of the lighting is turned off after hours, a considerable amount remains functioning.

The monitored effective hours of use are consistent with those reported by the customer in the initial site survey.

The observed LPD is less than the installed LPD due to the non-functioning fixtures. However, even the observed LPD is considerably above that in the current (2008) T-24 code document, which is set at 0.6 wsf for conditioned and unconditioned storage space. Table 5 provides a comparison of the existing conditions compared to the current Title 24 standards for design power density.

TABLE 5. DESIGN COMPARISON OF BASELINE CONDITIONS TO CURRENT T24 (2011) AND T24-2013 ALLOWANCES

	LIGHTING POWER DENSITY (W/SQ.FT.)	T24-2008 AND T24-2013 ALLOWANCE (W/SQ.FT.)	PERCENTAGE OF T24-2008/2013
Fully-Operational	1.05	0.60	175%
As-Observed	0.83		138%

There are fourteen (14) 4'x8' skylights in the space. Table 6 below provides a comparison of the as-built conditions and the current Title 24 (2008) for skylighting.

TABLE 6. COMPARISON OF BASELINE SKYLIGHT CONDITIONS TO CURRENT T24 (2008) REQUIREMENTS

	ACTUAL SKYLIGHT ROUGH OPENING AREA (SQ.FT.)	T24-2008 REQUIREMENT (3% OF FLOOR AREA) (SQ.FT.)	PERCENTAGE OF T24-2008
Skylights	448	1,344	33%

Title 24-2013 uses a different metric to determine the adequacy of the skylighting. In the newest revision, the skylights must cover 75% of the space with top-lighting per the calculation methods defined in the Standard. Each 4'x8' skylight calculates to produce 1,677 square feet of top-lighted area, for a total of 23,478 square feet. The space requires 33,600 square feet of top-lighted area, so using the dimensions of the existing skylights, an additional six (6) skylights would be required to satisfy that requirement; approximately 40% more than are installed.

The result of this comparison is that the skylighting benefits that may be expected in a new construction space will be substantially greater than can be observed in this space, because there will be substantially more skylighting area (and probably more individual skylights as well).

PRE-RETROFIT ENERGY CONSUMPTION PROFILE

The monitored lighting circuits also provide representative use patterns throughout the day. Daily use patterns for weekdays, Friday, and Saturday are shown in Figure 6.

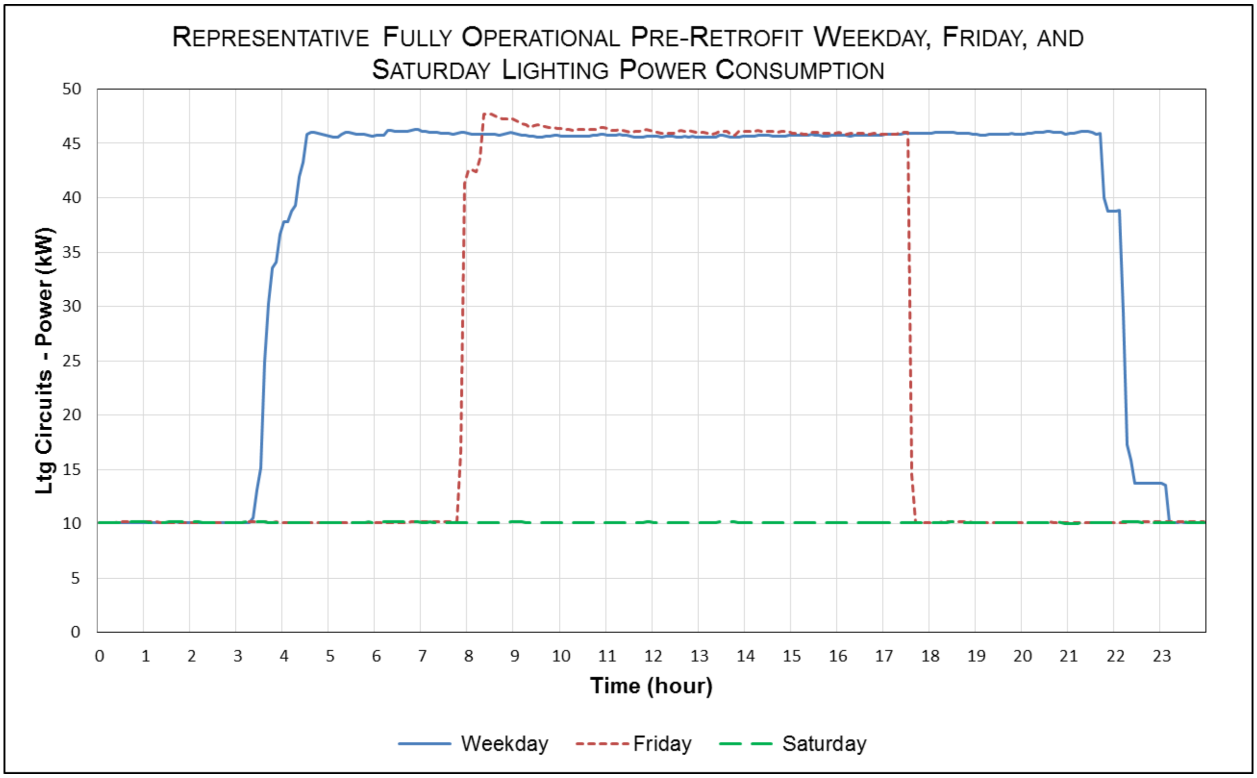


FIGURE 6. REPRESENTATIVE FULLY OPERATIONAL PRE-RETROFIT WEEKDAY, FRIDAY, AND SATURDAY LIGHTING POWER CONSUMPTION

The graph shows the power draw of the lighting system that is typically used during each hour of the day. As the charts illustrate, the lighting is used primarily during typical first and second shift work hours, starting at 4 AM and extending to about 11 PM. The lighting is turned on throughout the majority of the day, but at times, there may be a circuit or more turned off as a result of available daylighting from the skylights. This was done manually, and is not consistent.

Figure 7 below shows the weekday power draw for the lighting system, adjusted to compensate for the non-functional lighting equipment. This increases the total draw by approximately 20%. The non-functional equipment is distributed somewhat uniformly across the lighting circuits, so the lighting power draw was uniformly adjusted by this factor to compensate.

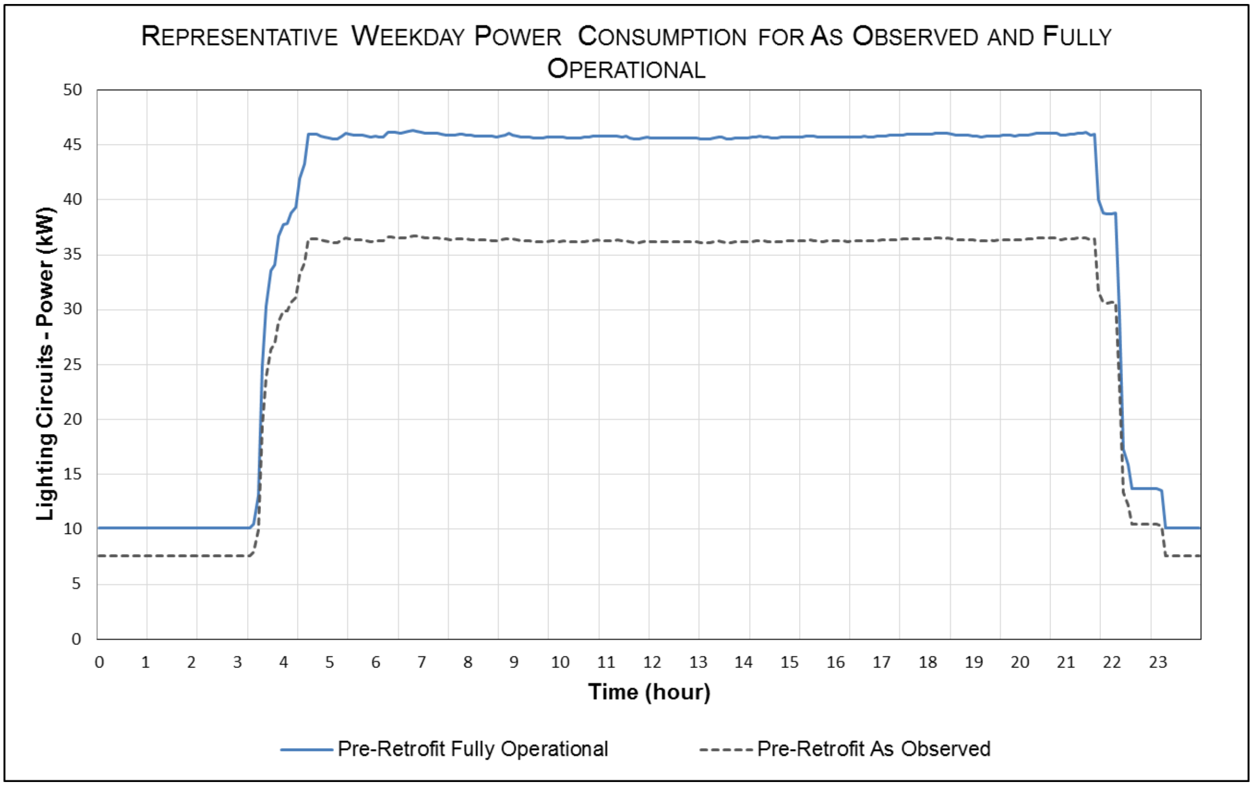


Figure 7. Representative Weekday Power Consumption for As Observed and Fully Operational

The "Fully Operational" results serve as a baseline for comparison to post-retrofit energy use because the post-retrofit conditions are all essentially fully operational as well, so this represents the most fair before to after comparison.

Lighting Retrofit

Lighting Equipment

The retrofit replaced all of the 102 existing 400W metal halide luminaires with LED luminaires that use 230 watts at full power setting. The replacement luminaires have built-in wireless interconnectivity, and include both an occupancy sensor and daylight sensor. The LED light source is dimmable as well, and the control system provides the flexibility to make adjustments to both the 'high' and 'low' level set points.

As a result, this retrofit is effectively two-pronged; 1. replace the light source with a substantially more efficacious light source and 2. add advanced controls capabilities to further reduce lighting energy consumption when the space is not fully occupied and when daylighting is ample.

CONTROLS

The installed LED luminaires have several built-in interconnected wireless control capabilities; these can be operated individually or as combined measures. These controls capabilities include:

- Occupancy - Occupancy sensors are integrated into the fixture to turn lights on when an area is occupied (Figure 9) and off when it is unoccupied (Figure 8). The actual target light level can be established for each condition, so the 'off' setting does permit the lights to remain functioning at a chosen setback level rather than fully off.

  Time delays are customizable to allow flexibility depending on the type of space and use. For example, during normal operating hours the facility manager may set the time delay to 10 minutes and during non-business hours the time delay can be set to 2 minutes. Shortening the time delay during non-business hours maximizes the energy savings during the typically unoccupied hours.

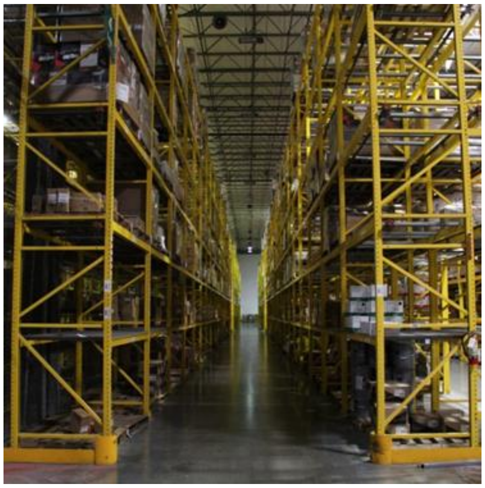


FIGURE 8. POST-RETROFIT CONDITIONS, FIXTURES OFF, UNOCCUPIED AISLE

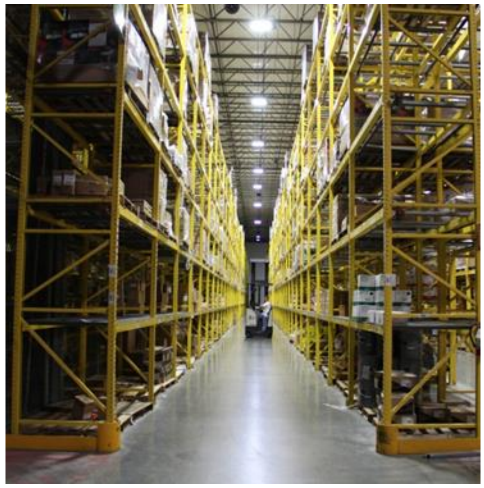


FIGURE 9. POST-RETROFIT CONDITIONS, FIXTURES ON, OCCUPIED AISLE

- Task tuning - Task tuning allows for reduction in light output to predetermined levels needed to maintain visual comfort or a minimum level required for task performance. This can be done for individual fixtures or a grouping of fixtures.
- Daylighting - Daylight harvesting is another integrated feature of the fixtures which reduces lighting levels based on the amount of available daylight. This feature is enabled by an ambient light sensor (Figure 10) detecting lighting levels which are then sent to the controller to dim the fixture based on daylighting levels.

FIGURE 10. INTEGRATED OCCUPANCY AND DAYLIGHITNG SENSORS (DAYLIGHTING - RED BOX)

- Zoning: Zoning of fixtures can be done in groups or individually and should be done based on viability of the space. Collecting groups of fixtures into zones of control will establish that each luminaire in a zone is controlled in the same manner. While individual zoning allows each fixture to become its own control zone operating independently of the rest.

The lighting controls system allows centralized management for facility managers through the LightRules™ control system. This system permits implementation of scheduling and operation of the above mentioned control capabilities for the entire system or individual fixtures.

RETROFIT DETAILS

The lighting equipment was replaced in the space over a period of about 10 days in October 2012. At the same time, the wireless gateways were installed and the lighting system commissioned.

Following a period of functional testing, the lighting system was put through a 'burn-in' period to ensure that all the luminaires were operational, and the control system operating correctly.

Finally, Dent DataLoggers (Figure 11) were installed on all 15 circuits of the lighting for the space for monitoring purposes. The Dent loggers use current taps (CTs) to measure the amperage of the load and establish a wattage load. Other information such as power factor and voltage, also were collected. The information was collected every 30 seconds continuously on all 15 circuits.

For normal occupancy conditions, it is possible to collect the status on possibly 5–minute or even longer intervals, but the occupancy patterns in this test space are somewhat unique.

There are two patterns of activity that commonly occur in the space; night stocking and the daytime order fulfillment.

FIGURE 11. DENT DATA LOGGERS ON EXTERIOR OF CIRCUIT BREAKER BOX

The night stocking will have an occupant moving through areas of the racks with a pallet of materials, pulling from the staging area and placing in the appropriate locations in the racks. This often involves a period of occupation of an hour or more, and sometimes the occupancy is limited to a small area of the space for an extended period; for example, when resupplying spray paint cans, the various colors are all restocked in one area of the racks, and this takes considerable time to do for each stocked color.

The daytime order fulfillment is very different in nature. Mostly, this activity is fast and short. The picking truck will drive through to the pick location and the worker will typically step off the truck to select the correct product and place it in the order bin at the back of the truck. Then, the picking truck will depart for the next product location. The entire duration of occupancy in the aerosol room may be a short as 30 seconds and most picking activities are less than a minute.

There are two entry points to the Aerosol Room, one on the NE corner and one on the SE corner. It appears that most traffic uses the NE corner. The staging area is located on the

North side of the racking. There are six aisles for truck traffic, and midway through the space there is a cross aisle.

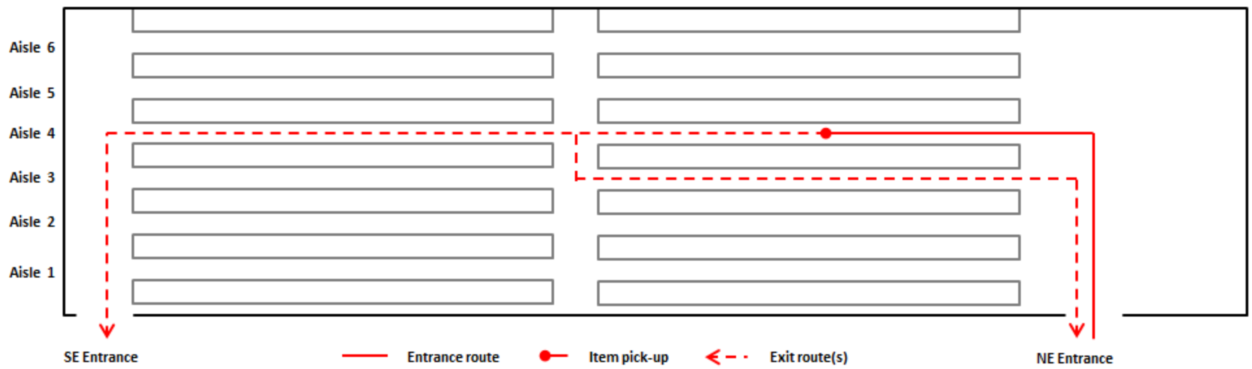


FIGURE 12. EXAMPLE ENTRANCE AND EXIT ROUTES

The picker trucks are not capable of easily reversing direction in the aisles, so once a picker has committed to entering the aisle, they must continue to at least the mid-point cross aisle to turn and leave via a different aisle (this is faster than putting the truck in reverse). As a result, every truck entry into an aisle results in an occupancy event for the ½ aisle length and at least one other ½ aisle length.

ANTICIPATED IMPACTS

The retrofit to LED will save approximately 50% of the pre-retrofit Fully Operational baseline energy consumption due to the light source technology change.

The controls integration is a much less clear benefit. While the light source technology change will result in a substantial energy savings that has considerable precedence to support the expectation, the controls savings opportunity is less clear. There is considerable potential for savings through controls, but where the savings may settle are dependent on a number of factors, including occupancy patterns, controls settings, and general aggressiveness of the owner towards saving energy. A rule of thumb in the industry is that the controls can save an additional 50% of the remaining energy consumption after an LED retrofit is complete.

As a result, based on basic expectations, the energy savings for this space are approximately 75% of the Fully Operational baseline, or about 69% of the As Observed baseline values.

This project intends to challenge that level and establish that the potential may be greater given the conditions to permit an aggressive energy savings approach.

Further, the lighting retrofit is anticipated to be a lighting performance upgrade in several aspects. The visual quality of the lighting is superior to the MH system, especially in terms of vertical illuminance on the racking and products. There is more light produced with the new system, which offers the opportunity to dim back and extend the LED life. The color rendering is superior with the LED sources as well.

TECHNICAL APPROACH/TEST METHODOLOGY

The aerosol room was monitored for a period of four weeks to establish the pre-retrofit hours. At that point the lighting upgrades were made, and once fully operational, the lighting was monitored for a period of eight months. During that time, two initial post-retrofit segments were completed to establish the difference in load and energy consumption that is associated with the replacement of the MH luminaires with LED technology.

The first step employed the lighting at the full output level (no consideration for the actual light levels delivered to the work plane in the space). The second was done once the lighting system was adjusted downward to reduce the light level to the target illuminance (15 fc). Subsequently, the lighting system controls were then employed in phases to assess the impact of each control step on the overall energy consumption of the space.

POST-RETROFIT MONITORING

SCHEDULE

The schedule of the post-retrofit monitoring phases was as follows:

- Pre-retrofit Baseline: September 14 through September 30
- Post-Retrofit Strategy #1: November 29 through December 9
- Post-Retrofit Strategy #2: December 21 through January 4
- Post-Retrofit Strategy #3: March 5 through April 10
- Post-Retrofit Strategy #4: April 11 through May 8
- Post-Retrofit Strategy #5: May 9 through June 21
- Post-Retrofit Strategy #6: June 22 through July 15

Due to some controls commissioning problems and observed performance issues, the schedule of the post-retrofit monitoring was delayed approximately 2 months between the Post-Retrofit Baseline 2 and the Post-Retrofit 3 segments. These issues are discussed in the Problems and Solutions section at the end of the report.

CONTROL STRATEGIES

There are specific controls strategies that were programmed into the controls system for each test segment. Additionally, a period of time at the beginning was monitored to establish an energy baseline for the retrofitted lighting system.

All of the control strategies had a night operation mode that turned off all the lights in the space after the occupancy sensor 30 second delay time, with the exception of eight luminaires, which were set to operate at 25% output all night long as nightlights. While in the night mode, all of the lights would function if occupancy was detected, but the normal status was that the majority remained off for most of the night.

The control strategies are:

- **Pre-Retrofit Baseline** (two separate measurement segments)

  This employed the lighting controls approach that was being used for the lighting system before the project initiation (manual lighting controls at the panel). This establishes the baseline energy consumption for the existing equipment and control strategy, and provides hours of operation information.

  The two segments were operated the same, but the circuits connected to the DataLoggers was changed to sample another representative segment of the space.

- **Post-Retrofit Strategy #1; LED Luminaires at 100%**

  This employed the same lighting controls approach that was being used for the pre-retrofit lighting system. This establishes the baseline for energy consumption for the new lighting equipment only, with no additional controls employed. The lighting was operated without integrated controls, and the light level was established at 100% of the luminaire output (full-ON) for this test segment.

- **Post-Retrofit Strategy #2; LED Luminaires at 70%**

  The second Post-Retrofit Baseline segment was collected after the lighting system was adjusted to reduce the light level to 17 fc average in the aisles, which is slightly higher than the target illuminance of 15 fc.

  Since the lighting system is brand new, a little bit of overage was designed into the system to account for lumen depreciation as the system ages. This is a setting of 70% output on the luminaires, which will result in a lower connected load and energy consumption. It represents the right lighting load to meet the design illuminance target, and the most equivalent 'pre- to post-' light source technology comparison that can occur.

  All the additional controls were operated with the top lighting level established at this 70% value.

- **Post-Retrofit Strategy #3; Occupancy Control Only, Coarse Zoning**

  This strategy employed the occupancy sensors as the only control device. The lighting was grouped into zones (one zone per aisle, and a zone for each cross-aisle or open area in the space), with a short delay time of 30 seconds for the aisles, cross aisles, and open areas was applied to the system. The lights were dimmed to approximately 10% of full output for unoccupied periods during the workday.

  After hours, the lights were set to turn completely off. This level of dimming was established with feedback from Ace Hardware regarding their level of comfort with the light levels in the unoccupied areas.

- **Post-Retrofit Strategy #4; Daylighting Control Only, Individual Control**

  In this approach, the regular schedule of operation for the facility was used to establish a long occupancy sensor delay time so that once the first occupancy event occurred in the morning, the lighting remained on until the end of the regular day. At that point, the occupancy sensor delay time was switched back to 30 seconds, so that if the facility were running extended hours, the lights would work to accommodate the activity.

  During the day, the only adjustment to the lights was the response to daylight availability since the occupancy sensor delay time was set to a long time period. Light level design criteria are explained in the below section on commissioning.

- **Post-Retrofit Strategy #5; Combined Control, Coarse Zoning**

  This strategy employed both daylighting and occupancy controls in the space in an approach that is consistent with the typical warehouse lighting control system as currently designed for new construction in California.

  For occupancy sensor control, the lighting was grouped into zones (one zone per aisle, and a zone for each cross-aisle or open area in the space), with a delay time of 30 seconds for all luminaires in the space. The occupancy sensors dimmed the lights to 10% when no activity is detected in the zone. At night, the lights were turned off when no activity is detected.

  The photocell did individually override lights near the skylight locations and dim when there was adequate daylighting. At any given time, individual lights may have been turned off or set to the 'unoccupied' setting depending on the availability of daylight and the occupancy status.

  The daylight control forced the lights to drop below the 10% minimum during the daytime if the daylight is sufficient to lower the electric light output.

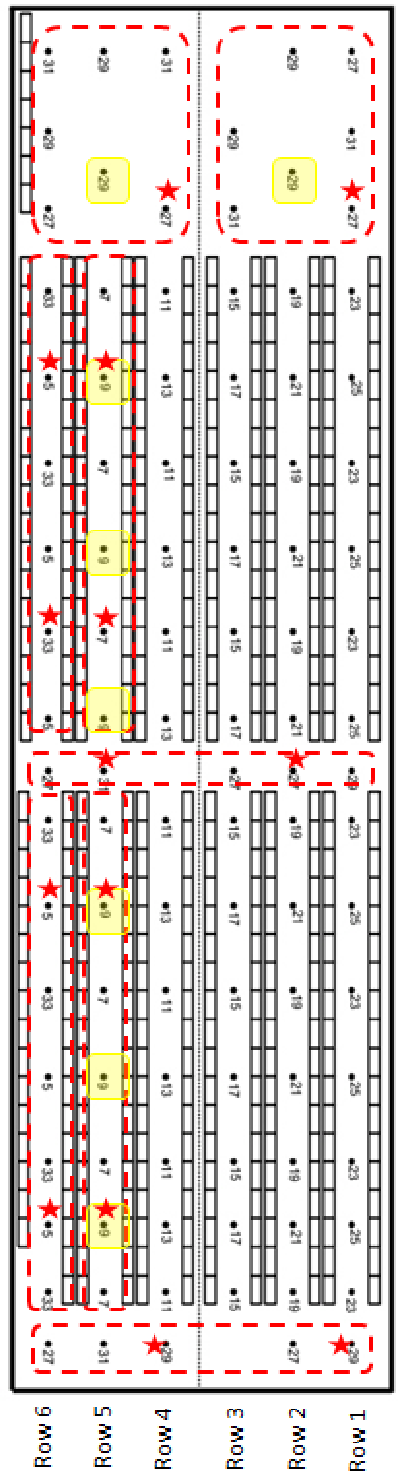
- **Post-Retrofit Strategy #6; Combined Control, Fine Zoning**

  This strategy essentially employed the 'one for one' approach that is enabled by the built-in occupancy sensor and daylight sensor in each luminaire.

  For occupancy sensor control, each luminaire operates independently; taking occupancy status from its own sensor, with a delay time of 30 seconds for all luminaires in the space. The occupancy sensors dimmed each light to 10% when no activity is detected. At night, the lights were turned off when no activity is detected.

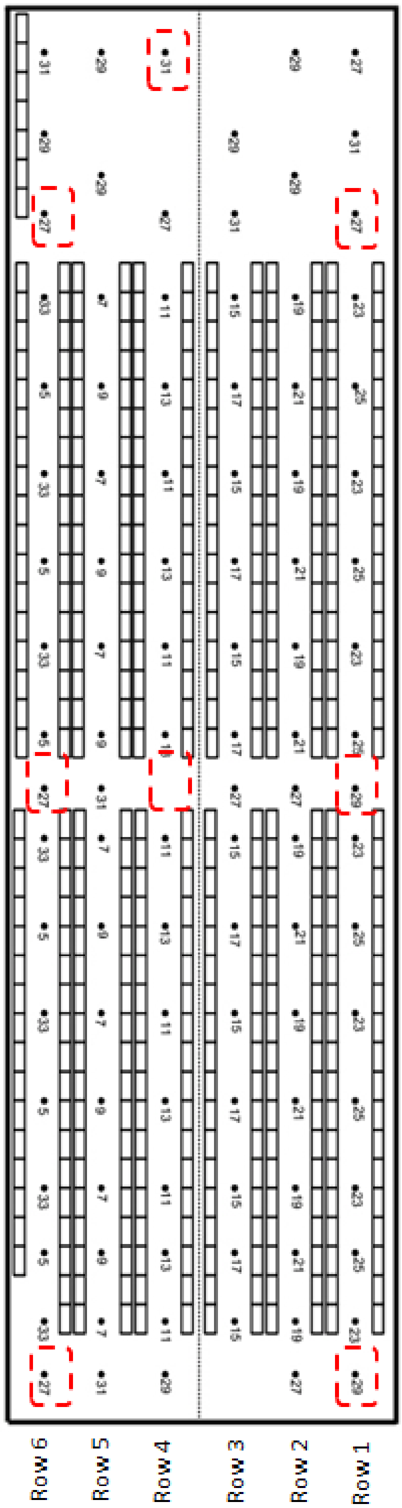
  The photocell did individually override lights near the skylight locations and dim back when there was adequate daylighting. At any given time, any individual light may have been turned off or set to the 'unoccupied' setting depending on the availability of daylight and the occupancy status.

Figure 13 below shows the zones of control for the test space while in the 'coarse' zoning control strategy. Figure 14 below shows the night lighting control layout. When the lighting is in the 'coarse' zoning control, the daytime zones applied to the lighting at night as well, so an occupancy event at night will cause the whole zone to turn on.



Note: Each Row will be similar to one of the two representative Rows. Rows 1, 3, and 4 will be the same as Row, 6, and Row 2 will be the same as Row 5.
The daylight fixtures are sub-zones within the larger occupancy-sensor zone, so they will be controlled by the occupancy sensor in the zone they are contained within, but will also have daylight controls that the other fixtures in the zone do not.

FIGURE 13. COARSE ZONING CONCEPT



Note: ALL lights will be operational and can turn ON based on the occupancy sensors, but a small number will be set to operate at 25% power all night for security purposes. There is a fixture in the middle aisle that is not shown on this plan, and is designated as a night light fixture (note the red box with no fixture inside).

FIGURE 14. ‘NIGHT LIGHT’ LAYOUT

Initial Commissioning

The Illuminating Engineering Society recommends approximately 10 footcandles (horizontal) and 5 footcandles (vertical) in warehousing situations where most visual tasks are not highly detailed (labels are larger, or the nature of the visual task is not critical). In this space, the visual tasks are not critical because the labels on the racks are reasonably large and the bar code readers ultimately make the determinations regarding product selection. Ace Hardware has requested 15 footcandles, so this study will use that as the target horizontal illuminance.

- Occupancy sensor settings

  All the occupancy sensors were set to 30 second delay time. As the products were specified with appropriate aisle coverage patterns, no other commissioning was required.

- Daylight sensor settings

  The lighting equipment controlled by daylight sensors was commissioned to ensure that the approximate light level under the skylight area remains greater than or equal to the average illuminance in the space once the new lighting system is operational, or 15 fc. The daylighting was actually set up to satisfy 20 fc, which results in slightly lower energy savings, but ensures that the light levels do not drop too low in any condition where the photo sensor in the luminaire may be affected by high illuminance levels in the racks above the work plane. This setting is manually done at each luminaire, not as part of the LightRules™ controls programming, so it must be completed in the field at the time of installation.

- Time-of-day settings

  After normal operation hours (plus 30 minutes), the controls reduced the minimum light setting for unoccupied zones to 0% (fully 'off'). This remained in effect until the anticipated start of operation hours the next day. Figure 14 shows a layout for the arrangement of 'night lights' in the space for security purposes. These luminaires remained at 25% all night long and also functioned with the occupancy sensor. For all lights, the occupancy sensors remained active and turned the lights 'on' at any time in the day or night when the space is occupied. Planned 'Occupied' time is 3:30 AM to 11:30 PM Sunday through Thursday, 3:30 AM to 5:30 PM Friday.

Monitoring Plan

Energy Monitoring

The energy monitoring for the post–retrofit controls testing employed two distinct methods. Each method served as verification for the other, and combined, provides a complete picture of the energy consumption of the lighting system during the test periods.

The first method is to monitor the lighting circuits in the space using the Dent loggers. This will collect data on power, energy consumption, voltage, volt-amps and other variables. The data will be collected at 30-second intervals throughout the survey period.

The Dent loggers were also used as verification for the second monitoring method; the reported energy consumption and hours of operation data that is collected by the lighting control system attached to the lighting equipment.

The lighting control system software, LightRules™, is capable of reporting in 15 minute intervals. It provided information on energy consumption, hours of operation, and other operation information regarding the use of the lighting system and the status of the individual lights or zones at any given time.

ILLUMINANCE MEASUREMENTS

Two types of illuminance measurements were collected:

- Horizontal Illuminance Measurements

  Horizontal illuminance measurements were taken at pre-determined points along the center line of selected stack aisles, as well as at pre-determined points in the open areas. Measurement points were located approximately every 17 feet, corresponding to every second vertical support for the shelf stacks. Horizontal measurements were taken at standard workplane height, 30" above the floor.

- Vertical Illuminance Measurements at Eye-Level

  Vertical illuminance measurements were taken to measure the amount of light arriving on the vertical surfaces of the shelf stacks. These measurements were taken at every second vertical support for the shelf stacks on both sides of the stack aisles, corresponding to the horizontal measurement locations described above. Vertical measurements were taken at a representative eye-level of 5' above the floor. Vertical measurement points at eye level are shown with orange X's in the diagram in Figure 14.

The diagram in Figure 15 below, shows the locations of illuminance measurements in the space. Existing luminaires in the space are indicated by black dots, with numbers indicating the lighting circuit each fixture is on. Black rectangles represent the shelf stacks in the space. Horizontal illuminance measurement locations are indicated in the diagram with orange triangles, and vertical illuminance measurement locations are indicated with orange X's.

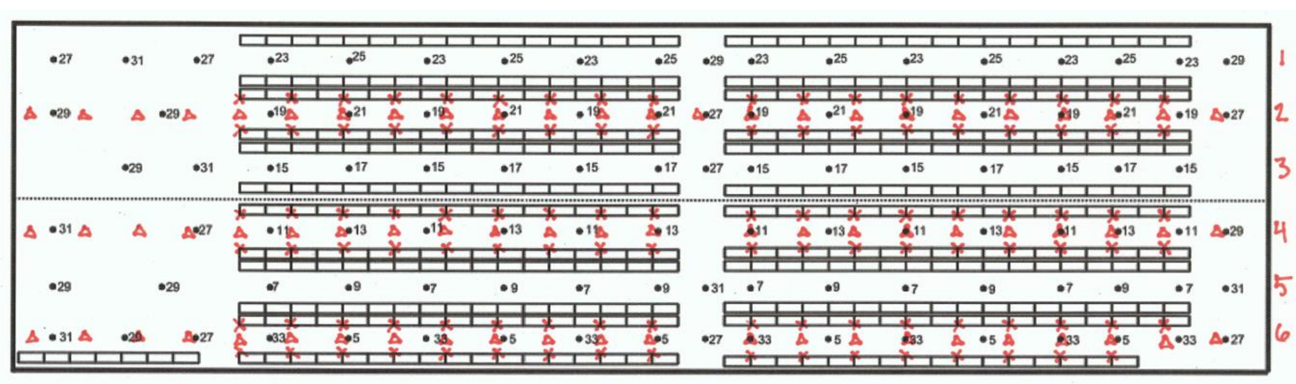


FIGURE 15. DIAGRAM OF ILLUMINANCE MEASUREMENT LOCATIONS.

RESULTS

The retrofit lighting system demonstrated a substantial reduction in the energy consumption for the space in a variety of conditions.

Representative daily power graphs for each phase of the testing from pre-retrofit through all control scenarios are shown in Figure 6, Figure 16, Figure 17, Figure 18, Figure 19, Figure 20, Figure 21, and Figure 22.

The lighting system has a reduced connected load of approximately 23,460 Watts, (50% reduction) for the LED technology replacement. Further, the load is reduced another 30% from the initial level based on the task-tuning process in Strategy #2. These can be identified on the graphs as the Strategy #1 and Strategy #2 plots; Figure 17, Figure 18. The rest of the graphs represent the increased savings associated with the introduction of various levels of dynamic control.

Strategy #1 was the LED Replacement approach and saves 50% of the energy consumption in a typical year due to the reduced wattage per luminaire. Strategy #2 is the LED Replacement and Task-Tuning and saves 64% of the energy consumption in a typical year due to the reduced wattage per luminaire associated with dimming the luminaire.

Strategy #3 was the Occupancy-Only (plus LED Replacement and Task-Tuning) approach. This saves energy throughout the work day, in an irregular manner related to the patterns of occupancy in the space. The savings from this approach are erratic; however, do show greater savings in the afternoon than in the morning. Additionally, even in the morning, considerable savings are occurring because at any given time, the majority of the space is not in an 'occupied' status. Therefore, many of the lights are set back into to 'unoccupied' mode, where they operate at 10% of full output. This controls category saves 88% of the energy consumption in a typical year due to the reduced load that occurs on a daily cycle.

Strategy #4 was the Daylighting-Only (plus LED Replacement and Task-Tuning) approach. This saves energy in the middle of the day, causing a characteristic inverted bell curve in the load on the graphs. This controls category saves 72% of the energy consumption in a typical year due to the reduced load that occurs on a daily cycle.

Strategies #5 and #6 were combined daylighting and occupancy sensor (plus LED Replacement and Task-Tuning) approaches. Strategy #5 uses a group approach to the occupancy sensors that reflects a typical approach to grouping lighting equipment to use a single sensor that would be commonly employed in a warehouse of this design. Strategy #6 places every luminaire under its' own control, since every luminaire has a sensor.

Strategy #5 saves 90% of the energy consumption in a typical year due to the reduced load that occurs on a daily cycle. As expected, Strategy #6 had the highest energy savings of all of the Strategies. This controls category saves 93% of the energy consumption in a typical year due to the reduced load that occurs on a daily cycle.

ILLUMINANCE MEASUREMENTS

Table 7 below provides the average illuminance measurements in the aisles Pre- and Post-Retrofit.

TABLE 7. AVERAGE ILLUMINANCE IN THE WAREHOUSE AISLES IN PRE-RETROFIT AND POST-RETROFIT CONDITIONS

	AVERAGE LIGHT LEVEL IN AISLES (FOOTCANDLES)	IES RECOMMENDATION FOR WAREHOUSE SITUATIONS (FOOTCANDLES)	ACE HARDWARE DESIRED LIGHT LEVEL (FOOTCANDLES)
As-Observed	5-8	10	15
Post-Retrofit (Strategy #1 Readings)	22		
Post-Retrofit (Strategy #2 Readings)	17		

Strategy #1 is the Post-Retrofit condition with all the LED lighting products operating at full power. As is apparent, this results in much higher light levels than is desired or necessary for the space.

Strategy #2 is the same circumstance, but the upper limit of the lighting has been adjusted downward so that about 70% of the power is established as the upper limit. This reduces the light level by approximately 23% to 17 footcandles. This change establishes the ideal initial light level to meet Ace Hardware's preferences and still provide for lumen degradation as the system gets dirty and ages.

While there is clearly a dramatic increase in the light levels with the LED lighting system, there is also marked improvement in color rendering, uniformity, and overall visual comfort that should help reduce eye fatigue for workers in the space.

BASELINE PERFORMANCE

Figure 16 provides representative information on the baseline energy performance of the lighting system. In Appendix A, Figure 42 and Figure 35 represent the Friday and Saturday graphs of the same Pre-Retrofit conditions.

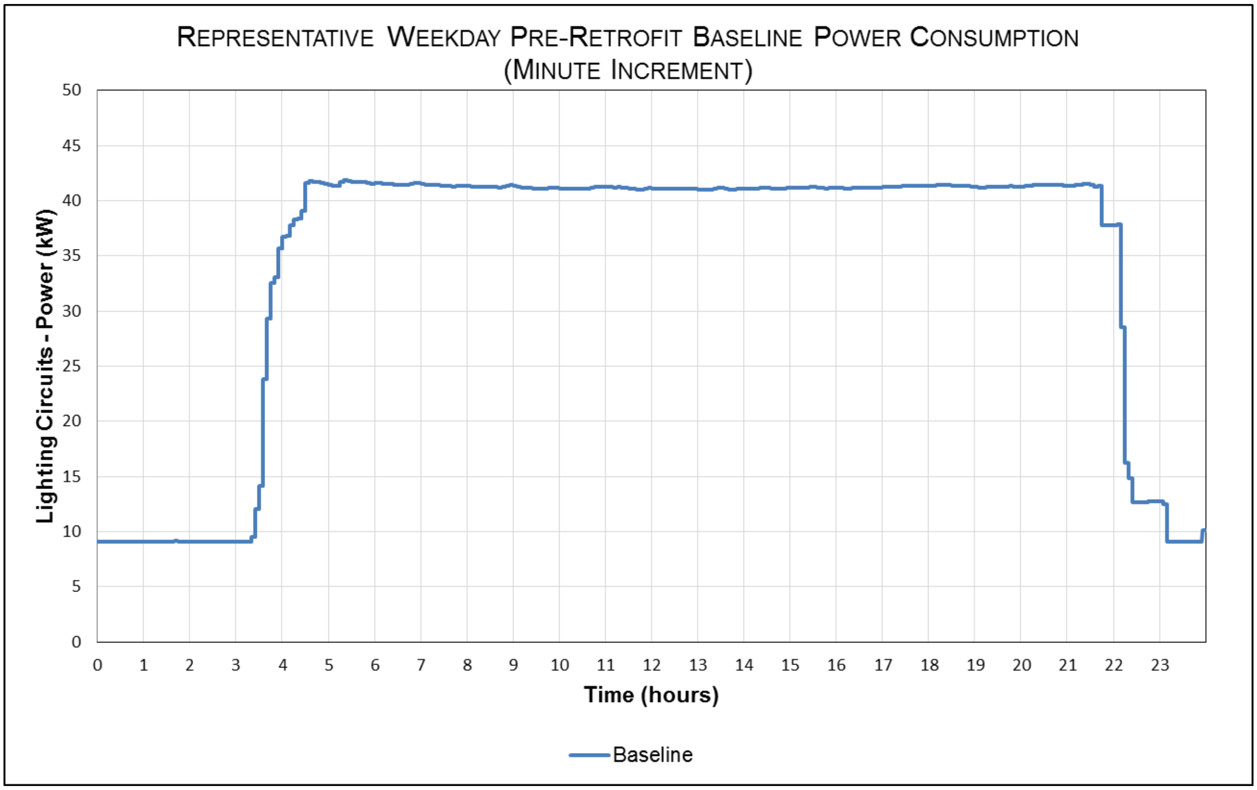


Figure 16. Representative Weekday Pre-Retrofit Baseline Power Consumption (Minute Increment)

POST-RETROFIT STRATEGY #1 PERFORMANCE

Figure 17 provides representative information on Strategy #1 energy performance of the lighting system. Figure 36 and Figure 44 represent the Friday and Saturday graphs of Strategy #1.

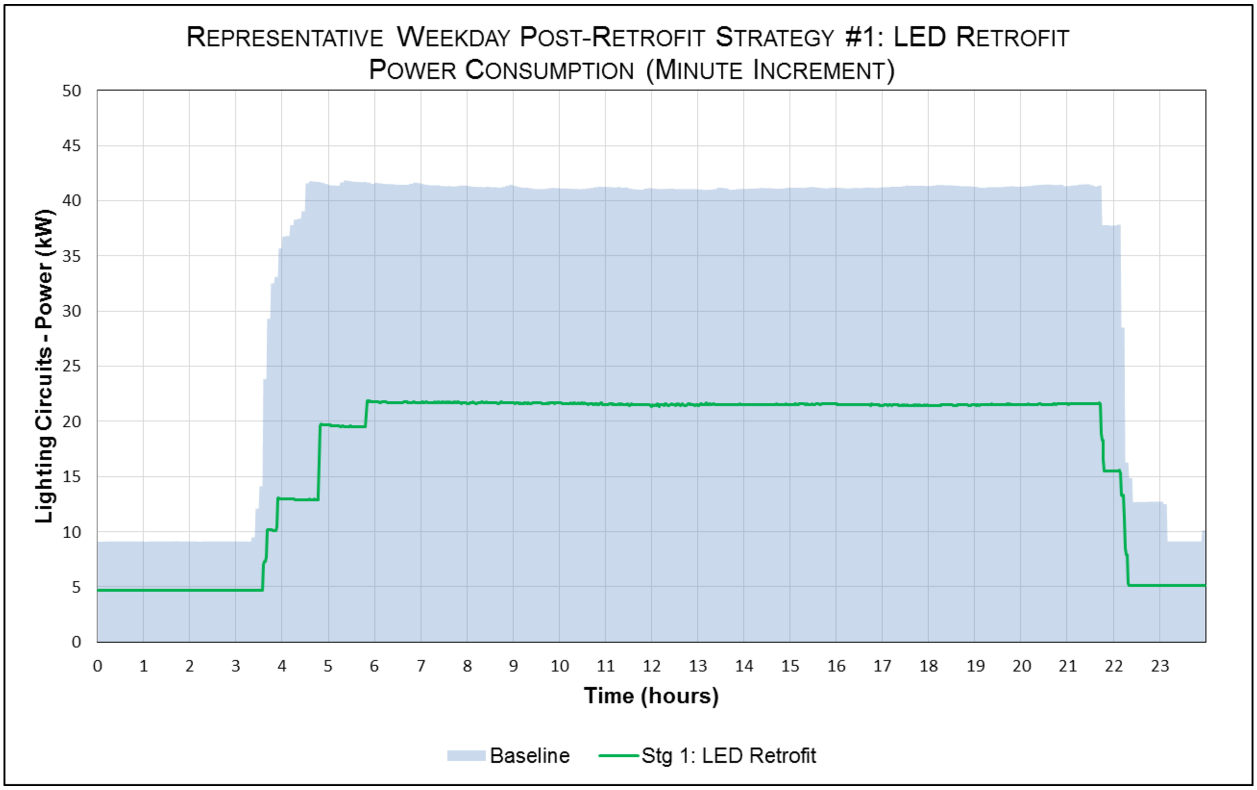


FIGURE 17. REPRESENTATIVE WEEKDAY POST-RETROFIT STRATEGY #1: LED RETROFIT POWER CONSUMPTION (MINUTE INCREMENT)

POST-RETROFIT STRATEGY #2 PERFORMANCE

Figure 18 provides representative information on Strategy #2 energy performance of the lighting system. Figure 37 and Figure 45 represent the Friday and Saturday graphs of Strategy #2.

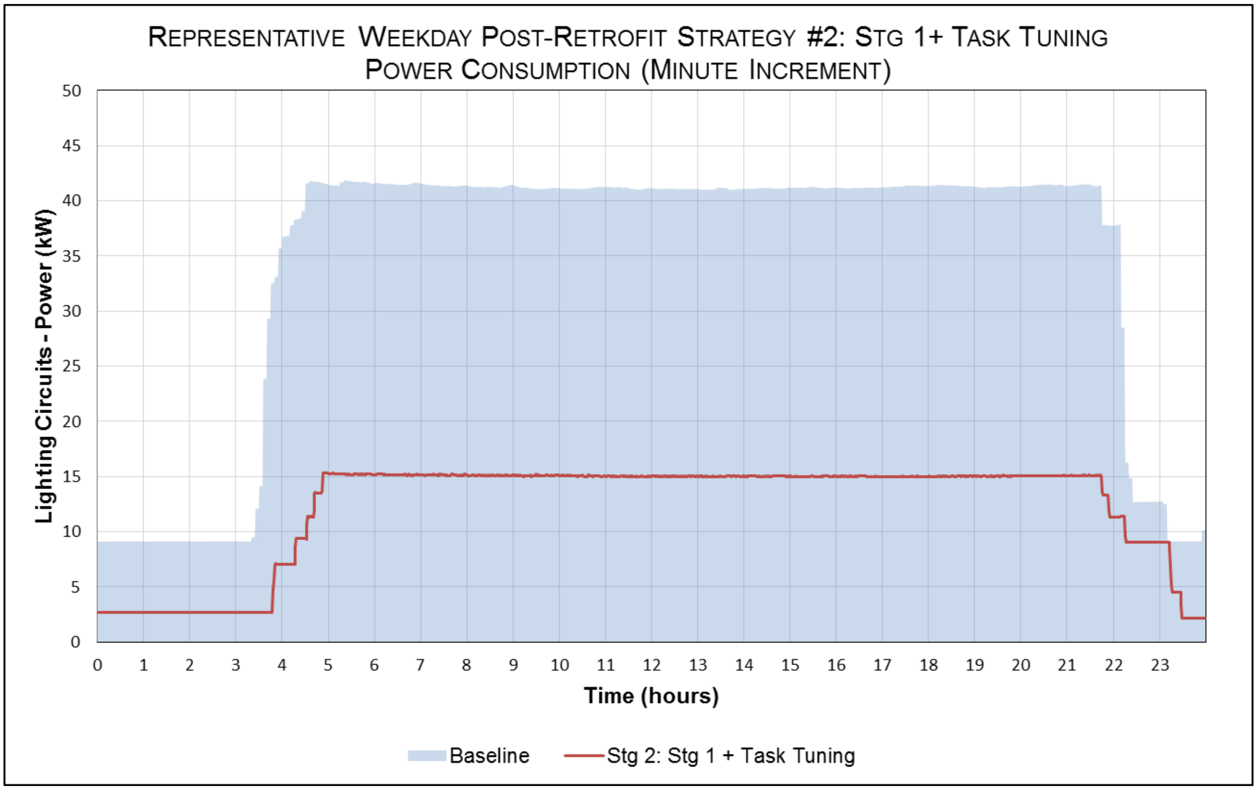


FIGURE 18. REPRESENTATIVE WEEKDAY POST-RETROFIT STRATEGY #2: STG 1 + TASK TUNING POWER CONSUMPTION (MINUTE INCREMENT)

POST-RETROFIT STRATEGY #3 PERFORMANCE

Figure 19 provides representative information on Strategy #3 energy performance of the lighting system. Figure 38 and Figure 46 represent the Friday and Saturday graphs of Strategy #3.

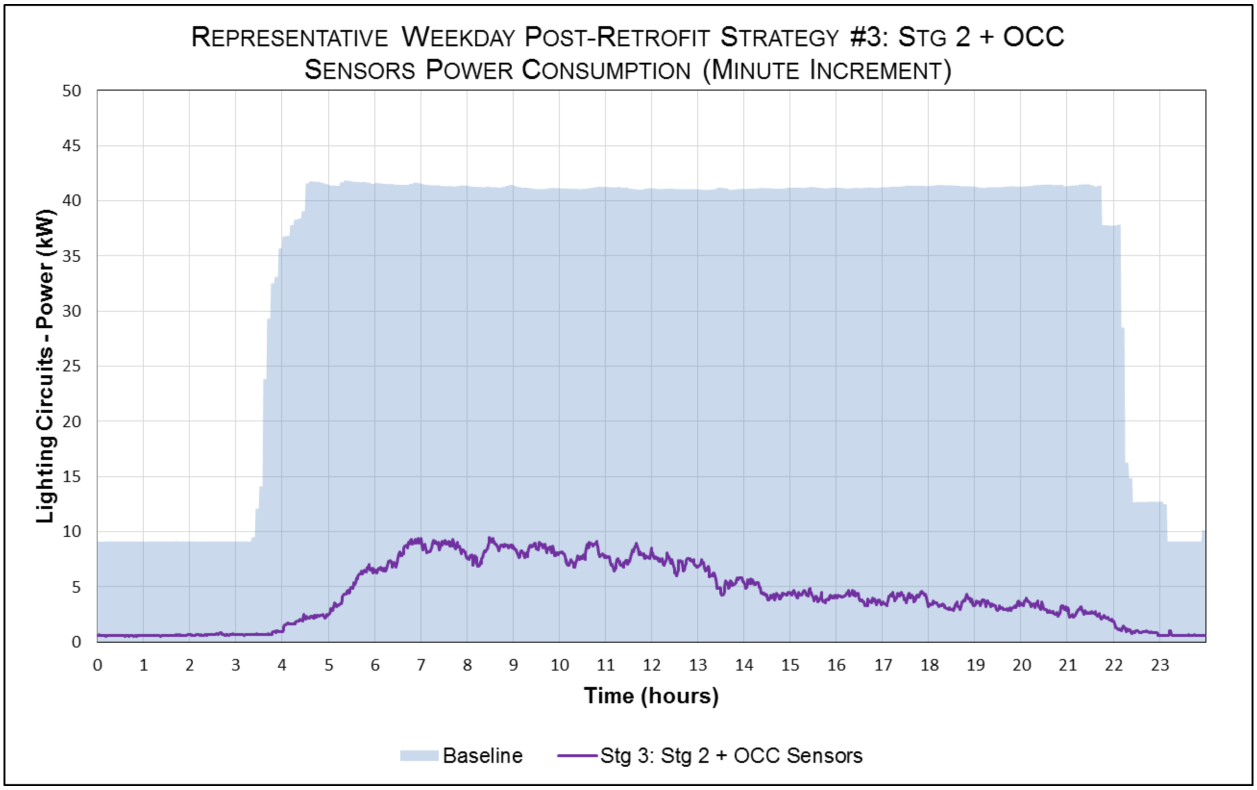


FIGURE 19. REPRESENTATIVE WEEKDAY POST-RETROFIT STRATEGY #3: STG 2 + OCC SENSORS POWER CONSUMPTION (MINUTE INCREMENT)

POST-RETROFIT STRATEGY #4 PERFORMANCE

Figure 20 provides representative information on Strategy #4 energy performance of the lighting system. Figure 39 and Figure 47 represent the Friday and Saturday graphs of Strategy #4.

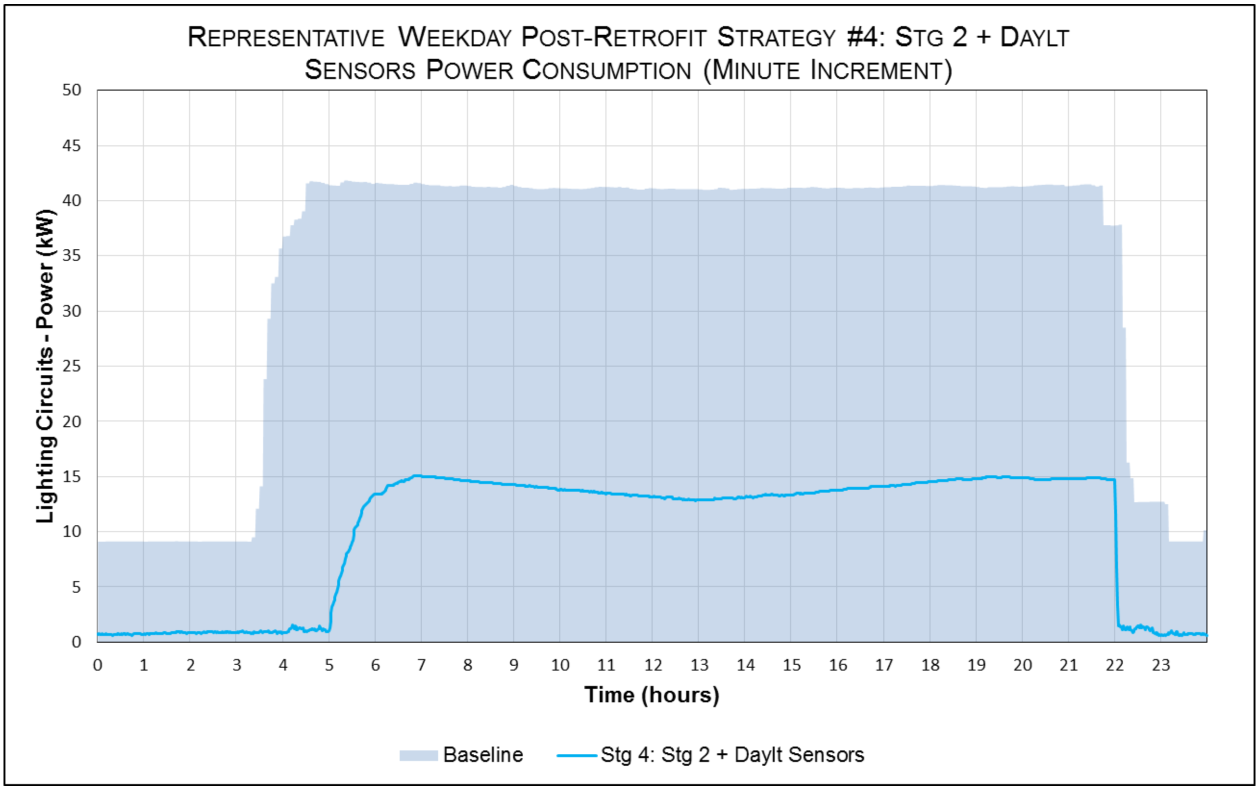


FIGURE 20. REPRESENTATIVE WEEKDAY POST-RETROFIT STRATEGY #4: STG 2 + DAYLT SENSORS POWER CONSUMPTION (MINUTE INCREMENT)

POST-RETROFIT STRATEGY #5 PERFORMANCE

Figure 21 provides representative information on Strategy #5 energy performance of the lighting system. Figure 40 and Figure 48 represent the Friday and Saturday graphs of Strategy #5.

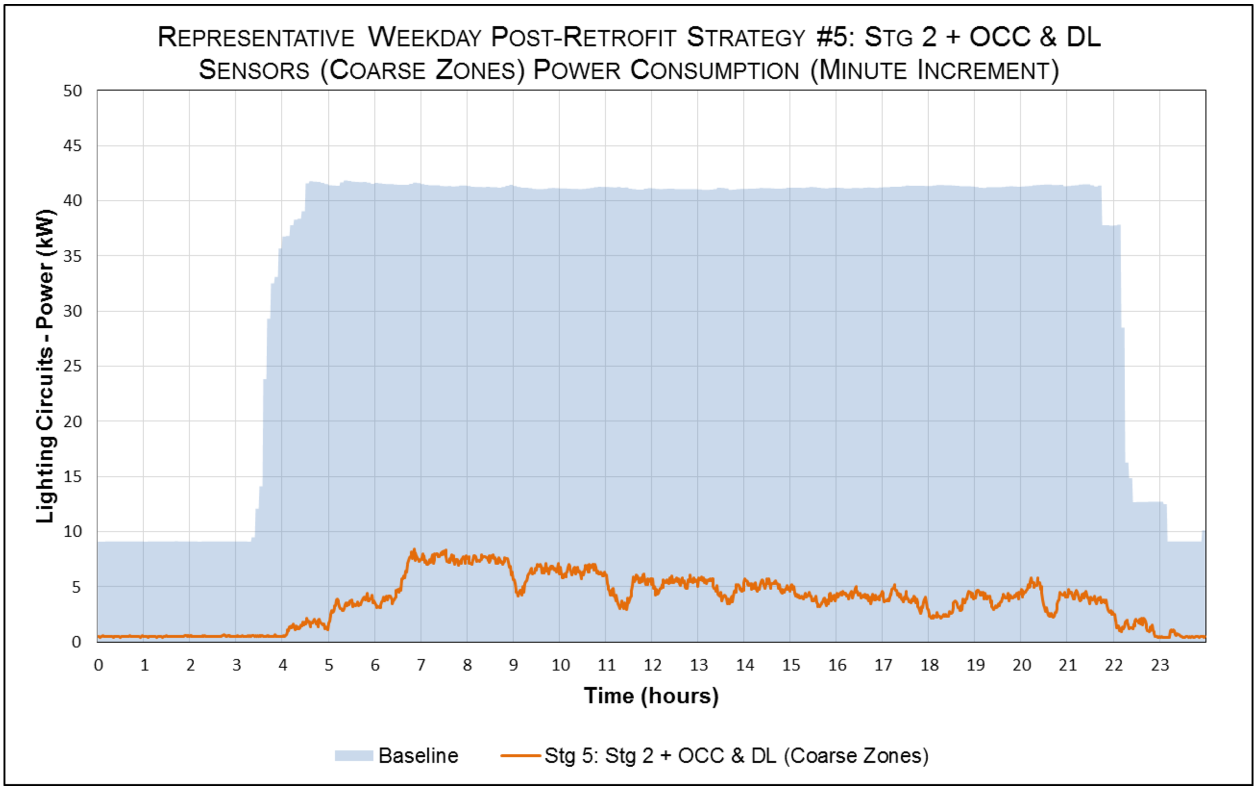


FIGURE 21. REPRESENTATIVE WEEKDAY POST-RETROFIT STRATEGY #5: STG 2 + OCC & DL SENSORS (COARSE ZONES) POWER CONSUMPTION (MINUTE INCREMENT)

POST-RETROFIT STRATEGY #6 PERFORMANCE

Figure 22 provides representative information on Strategy #6 energy performance of the lighting system. Figure 41 and Figure 49 represent the Friday and Saturday graphs of Strategy #6.

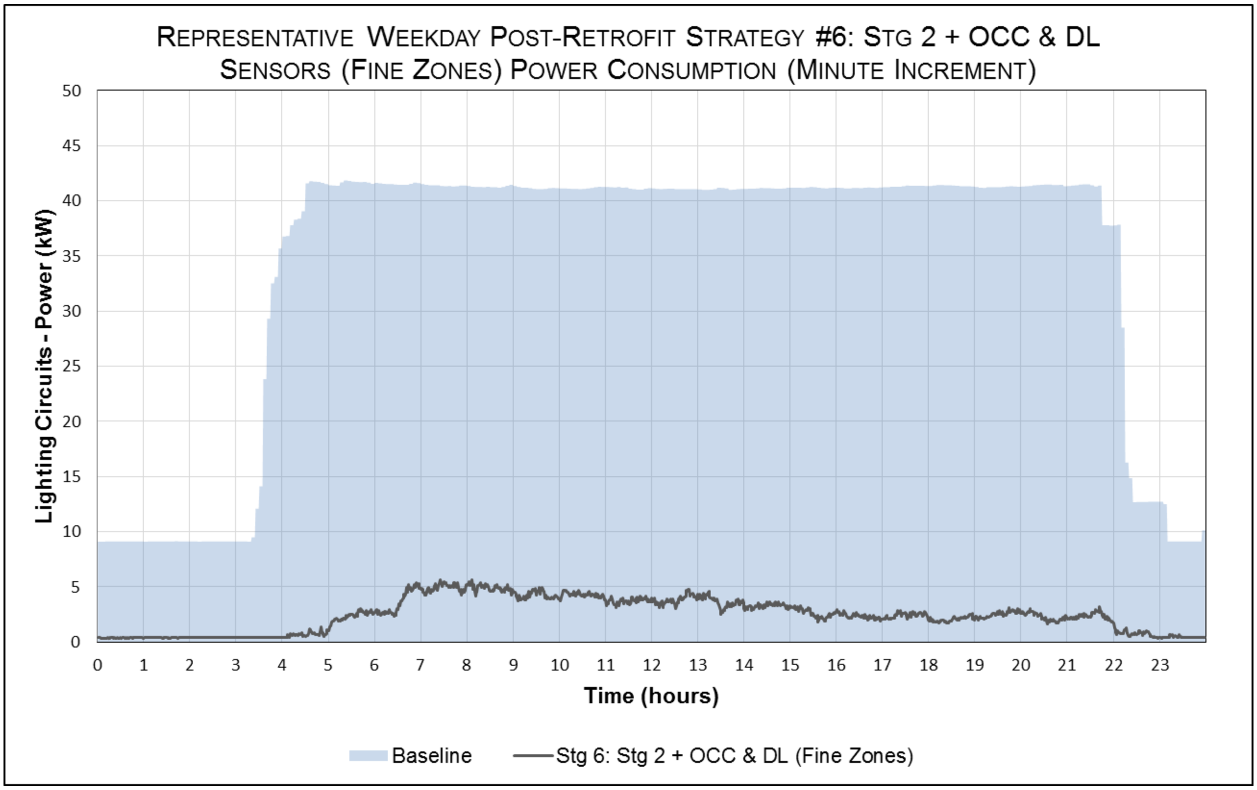


FIGURE 22. REPRESENTATIVE WEEKDAY POST-RETROFIT STRATEGY #6: STG 2 + OCC & DL SENSORS (FINE ZONES) POWER CONSUMPTION (MINUTE INCREMENT)

ANALYSIS OF RESULTS

OCCUPANT SURVEYS

METHODOLOGY

Interviews and surveys with installers, occupants, the facilities manager and warehouse supervisors were conducted to evaluate satisfaction with baseline and retrofit conditions. The survey instrument used to collect the data for occupant satisfaction is located in the Appendix. The same survey was used for pre- and post- retrofit conditions. Occupant surveys were administered pre-and post- lighting retrofit to warehouse employees of the aerosol room during their shift. Interviews with installers occurred in an informal manner during the lighting retrofit. Facilities manager and warehouse supervisor evaluations were ongoing throughout the entire project period (September 2013-July 2013).

RESULTS

Of the occupants surveyed pre-retrofit, the majority of occupants reported a neutral experience with the overall lighting conditions in the aerosol room. Indicating they did not strongly like or dislike the lighting conditions in the space.

Of the occupants surveyed post-retrofit, the majority of occupants indicated a positive experience with the new LED lights and associated controls. Comparing the responses from the pre-retrofit conditions indicates the occupants prefer the lighting conditions of the post-retrofit. The results of the pre-retrofit survey indicated a very neutral opinion of the lighting, while the post-retrofit responses had a majority of strong liking of the new lighting. During the post-retrofit occupant surveys, occupants expressed verbally their liking of the new lighting conditions. Most comments involved the ability to more easily read labels on racks, as compared to the pre-retrofit conditions.

During site visits, the consultant also conducted check-ins with the facilities manager and warehouse supervisors. The facilities manager expressed satisfaction with the installation process, operation and lighting conditions of the new fixtures. The warehouse supervisors, typically on the warehouse floor more frequently, also relayed positive feedback from the ground crew working in the aerosol room.

The site surveys of the employees provides positive reinforcement regarding the quality and quantity of light in the space after the retrofit, and further provides useful information regarding the acceptance of a dimming system with aggressive (short) delay times on the occupancy sensors.

The pre-retrofit surveys were taken in October before the work was done in the space. The post-retrofit surveys were taken at the end of the evaluation process in June, while Strategy #6 was in operation (combined daylight and occupancy controls with fine zoning). This is the most aggressive and highest energy saving strategy, so the surveys should provide fair input if the controls were too aggressive.

Several questions in particular show marked improvement, and none showed a decrease in response.

The questions that show an improvement are (on a scale from 1-9):

- #8 – "The lighting conditions are comfortable."

  The respondents for this question were neutral to very slightly negative in the pre-retrofit condition, with an average response of 4.3. The post-retrofit response is fairly strong agreement, with an average response of 7.6.

- #9 – "I am satisfied with the amount of light in the space."

  The respondents for this question were neutral to very slightly negative in the pre-retrofit condition, with an average response of 4.3. The post-retrofit response is fairly strong agreement, with an average response of 7.2.

  Both Question #8 and #9 are reflective of a positive change in the response to the lighting changes in a general, holistic sense, and were intended to gauge the lighting conditions in a broad sense.

- #14 – "I can comfortably read labels on packages and racking in this room."

  The respondents for this question were neutral to slightly positive in the pre-retrofit condition, with an average response of 5.3. The post-retrofit response is strong agreement, with an average response of 8.4.

  Question #14 is specifically asking about reading the labels, and response to this improved significantly. This indicates that the workers may be able to function more reliably, with less eye fatigue than before, so this appears as a very positive measure of actual task conditions in the space.

- #15 – "I do not find the changing light level conditions to be distracting."

  This question was not applicable in the pre-retrofit condition, so the responses were either "n/a" or neutral. The post-retrofit response is general agreement, with an average response of 7.0.

  This is an attempt to gauge the general impression about whether the occupancy sensors are distracting. The sensors will turn on light in front of the occupant in the space, and will follow behind them as well, although those changes may be unnoticed. The positive response to this question indicates that the employees are not bothered by the changing light conditions, and it is probably not impacting their productivity.

- #16 – I am satisfied with the lighting control systems in this space."

  The respondents for this question were neutral to very slightly negative in the pre-retrofit condition, with an average response of 4.3. The post-retrofit response is strong agreement as well, with an average response of 8.4.

  This indicates that overall, the new lighting system produces a higher level of satisfaction with the controls, and that they are not perceived as problematic by the employees at all. As a result, they are effectively conserving energy without negatively affecting the work environment.

Several conditions make these surveys difficult to treat as anything but slightly more than anecdotal. There is a small number of workers qualified to use this area, and at any given time there may only be a few working. We surveyed three in the pre-retrofit portion, and five in the post-retrofit portion.

The period of time between the surveys was approximately 8 months. A lot of changes were made to the lighting in that time, and long-term employees were able to see the changes happening. That may influence the survey results.

All of the employees were thoughtful and willing to participate. Since it was impossible to perform the surveys and all of the evaluation work with them unaware, they knew the reasons and potential benefits of this project, which may influence the responses.

The responses are overall positive, and suggest that the lighting retrofit has not only energy savings benefits, but additionally provides an improved visual environment for the employees.

EVALUATIONS

The LED light source technology performed predictably, with a substantial savings representing approximately 50% of the pre-retrofit energy consumption for a typical week. As this is a somewhat mature technology, this result is expected. This technology change also results in a higher light level (the owner requested a higher light level than was previously delivered by the MH lighting system) and improved color rendering that makes the space more comfortable to work within.

Further, the technology change will considerably reduce the lighting system maintenance. The technology change to the LED light source also permits a host of other benefits, including much greater applicability of effective controls strategies than a MH system offers.

As a result, the lighting system introduces a host of controls options that were used to explore the possibility for a more integrated approach to lighting and controls, with a goal of deep energy savings and high lighting quality for the visual tasks in the spaces. This has proven to be the case. The first layer of controls added into the testing is task tuning, which resulted in 24% additional energy savings beyond the LED technology replacement.

Occupancy sensor controls were tested next. This level of control resulted in an additional reduction in the lighting energy consumption of 24% in addition to the task tuning. Independently, daylight sensing shows an additional reduction in the energy consumption of 8% in addition to task tuning. Combined, these daylighting and occupancy sensors show a reduction of 26% to 29% in addition to task tuning.

The greatest energy savings are demonstrated by the combined occupancy and daylight sensor controls with the fine level of control (each fixture operating independently of the rest). This approach demonstrates a reduction in energy consumption of approximately 93% from the baseline Pre-Retrofit condition.

Figure 23 and Figure 24 show the weekday energy use profile for the baseline and the six different controls scenarios, one in minute resolution, and one in hourly resolution.

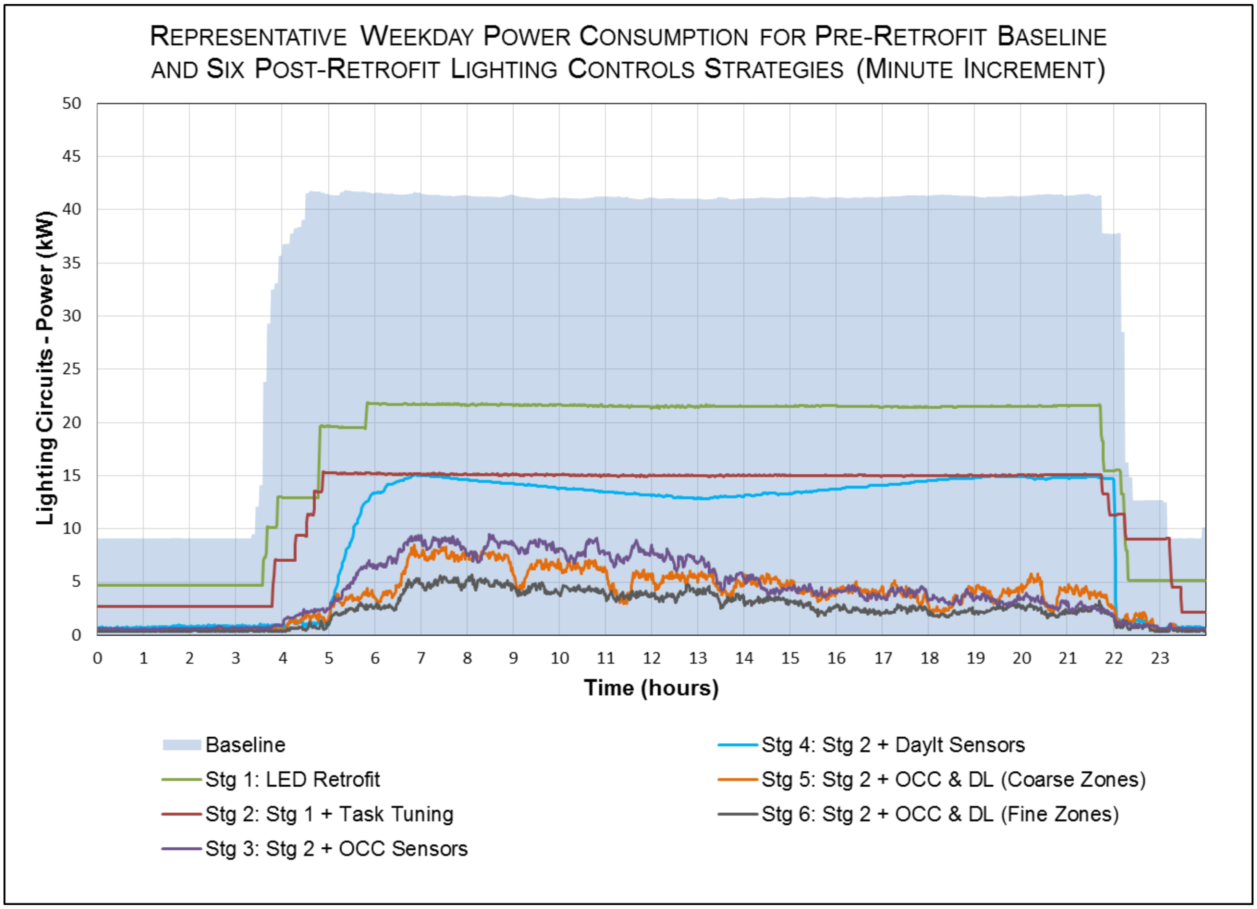


Figure 23. Representative Weekday Power Consumption for Pre-Retrofit Baseline and Six Post-Retrofit Lighting Controls Strategies (Minute Increment)

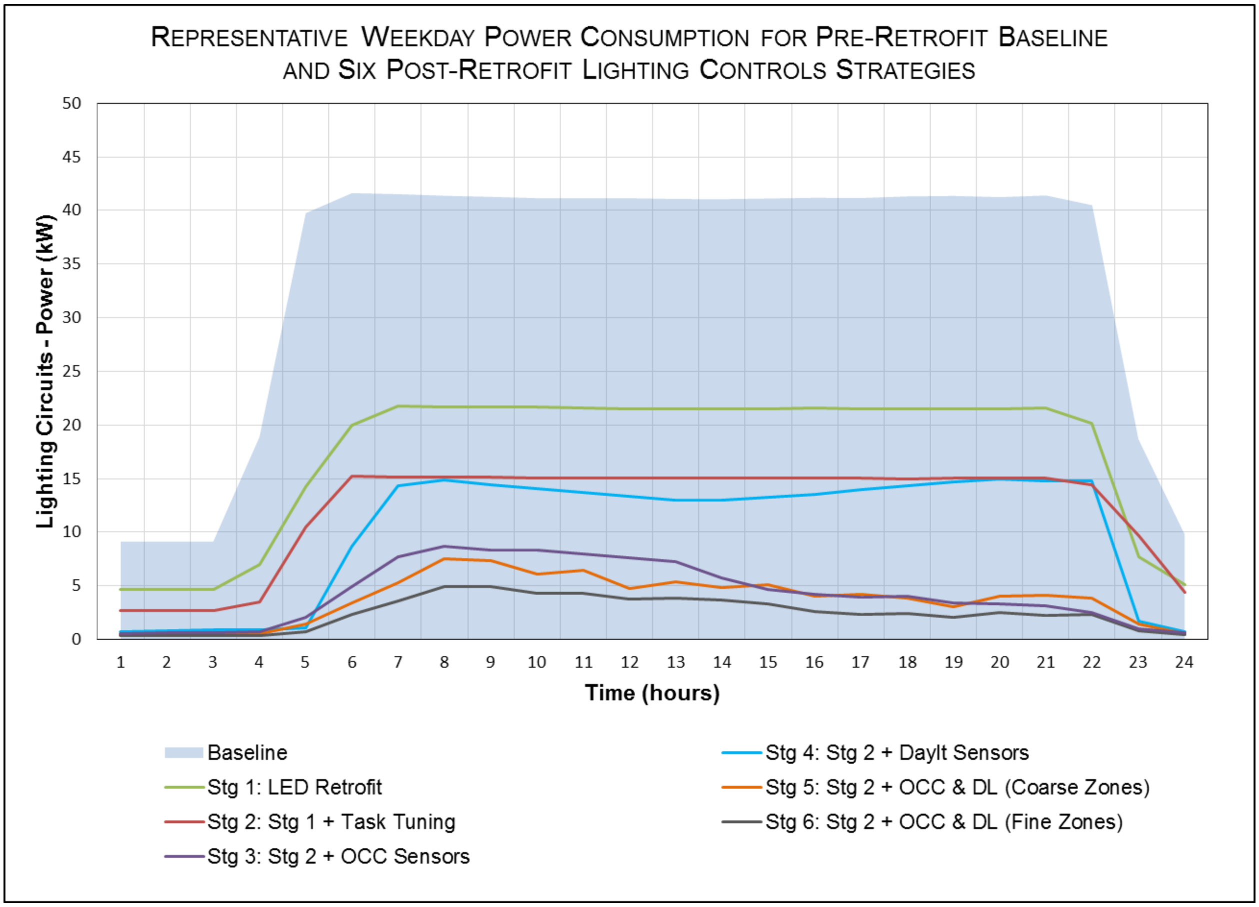


FIGURE 24. REPRESENTATIVE WEEKDAY POWER CONSUMPTION FOR PRE-RETROFIT BASELINE AND SIX POST-RETROFIT LIGHTING CONTROLS STRATEGIES

Table 8 below shows the energy use of the two baseline conditions and the six lighting strategies after the retrofit. The comparison to Title 24-2013 is based on the lighting power density allowance in the Area Category Method approach, which defines different allowance based on the function of the area.

Since the lighting power density allowance is based on the full output power of the lighting system, the reduction in the light level that occurs between Strategy #1 and Strategy #2 is not permitted to officially be employed as an approach to meet the limits in the energy code. However, it does permit a decent baseline for the estimation of the power density if this were a new construction project and the lighting equipment were spaced ideally for the conditions in the space.

The California Commercial End-Use Survey (CEUS) comparison reflects that the warehouse space is performing at a level much superior to those present during the last CEUS survey period, which was in 2006. While Title 24 has tightened on new construction and there is a good chance that some older warehouses have had energy retrofits, this warehouse is still expected to be performing much better than the average existing stock. Note that the space went from being 258% of the CEUS average kWh/sf/yr to only 17%, so the improvement is considerable.

It is important to note that the LED retrofit alone still produces a result higher than the CEUS average value. This it primarily due to the fact that the lighting system is delivering 50% more light than is considered the industry design standard.

TABLE 8. TABLE OF REPRESENTATIVE ENERGY USE AND ENERGY USE INTENSITY FOR PRE-RETROFIT BASELINE AND SIX DIFFERENT POST-RETROFIT LIGHTING AND CONTROLS STRATEGIES

	LIGHTING POWER DENSITY (W/SQ.FT.)	PERCENTAGE OF T24-2013 ALLOWANCE (0.6 W/SQ.FT.)	ESTIMATED ANNUAL ENERGY USE (KWH)	ENERGY USE INTENSITY (KWH/SQ FT/YEAR)	PERCENTAGE OF CEUS AVERAGE VALUE (2.21 KWH/SQ FT/YEAR)
Fully-Operational	1.05	175%	254,973	5.69	258%
As-Observed	0.83	138%	202,991	4.53	205%
Strategy #1	0.52	87%	129,603	2.89	131%
Strategy #2	0.37	61%	92,038	2.05	93%
Strategy #3			29,388	0.66	30%
Strategy #4			71,638	1.60	72%
Strategy #5			25,653	0.57	26%
Strategy #6			16,929	0.38	17%

Table 9 below shows similar information as a comparison of the baseline and energy consumption.

TABLE 9. SUMMARY OF ANNUAL ENERGY CONSUMPTION FOR BASELINES AND SIX POST-RETROFIT SCENARIOS

	LIGHTING POWER DENSITY (W/SQ.FT.)	PERCENTAGE OF T24-2013 ALLOWANCE (0.6 W/SQ.FT.)	ESTIMATED ANNUAL ENERGY USE (KWH)	PERCENTAGE OF FULLY-OPERATIONAL BASELINE VALUE
Fully-Operational	1.05	175%	254,973	---
As-Observed	0.83	138%	202,991	80%
Strategy #1	0.52	87%	129,603	51%
Strategy #2	0.37	61%	92,038	36%
Strategy #3			29,388	12%
Strategy #4			71,638	28%
Strategy #5			25,653	10%
Strategy #6			16,929	7%

The estimated demand reduction that this space is experiencing is considerable as well. Table 10 below provides information on the calculated demand based on 15-minute periods in the afternoon for the representative use curves calculated in Figures 23 & 24.

TABLE 10. TABLE OF REPRESENTATIVE 15-MINUTE DEMAND FOR PRE-RETROFIT BASELINE AND SIX DIFFERENT POST-RETROFIT LIGHTING AND CONTROLS STRATEGIES

	PEAK 15-MINUTE DEMAND (WATTS)	PERCENTAGE OF FULLY-OPERATIONAL BASELINE VALUE
Fully-Operational	41.8	---
Strategy #1	21.8	52%
Strategy #2	15.2	36%
Strategy #3	9.0	21%
Strategy #4	15.0	36%
Strategy #5	7.7	18%
Strategy #6	5.2	12%

OBSERVATIONS ON RESULTS COLLECTED

The use patterns of the picker trucks will defeat some of the benefits of the fully autonomous controls capability of this luminaire. This is an issue because while it is theoretically a benefit for some circumstances, this space does not demonstrate an ideal application for the technology. Although, there are considerable reasons to apply it, even in this space where the energy savings may not be too substantial.

The routes that the picker trucks must traverse effectively create zones of activity rather than discreet pockets. Therefore, even though the lights are capable of smaller segments of control, it is unlikely that this occurs in many of the occupancy events that occur in a day. This demonstrates that a lighting design that was done with zoning for individual half-rows as might be typically done with a traditionally hard-wired lighting control system should be able to achieve similar energy savings results without the need for a retrofit to a sensor per head approach.

Furthermore, the energy consumption graphs for the lighting system in a row with the skylight in close proximity demonstrates that the sensors will work effectively for each fixture, but ultimately, because of the distance for the light from the luminaires to overlap, even this is unnecessary for the success of a daylighting system. It does make the commissioning easier to achieve, but ultimately a single photocell for a zone in a closed-loop arrangement, or a single for the entire space in an open-loop arrangement can be employed effectively to achieve similar results.

However, this product is designed primarily as a retrofit luminaire for existing warehouse situations. In these circumstances, the benefits of the individualized control capability per head outweighs the relatively small cost penalty of the added sensor capability even if relatively small incremental savings are gained from that infrastructure.

These benefits include:

1. Ease of introduction of a control system in a previously uncontrolled space.
2. Ability to designate that each fixture operate autonomously.
3. Ability to coordinate controls wirelessly, so no control wiring required.
4. The one-for-one arrangement of controls and luminaires is likely to produce the highest energy savings possible.

COST EFFECTIVENESS CALCULATIONS

The lighting retrofit project saves considerable energy, as is shown in Table 8 above. As a reasonably new technology (at least in a form where it makes a viable alternate to a MH high bay lighting system) the cost of this system is considerable. The approximate unit pricing for the luminaires used in the retrofit is $1,000. The total installed price for the lighting system is $117,935.

However, because of the substantial energy savings possible, this retrofit strategy provides a reasonably favorable economic analysis. The simple payback period calculations for an electricity consumer with similar rates to Ace Hardware ($ 0.138 per kWh) are shown in Table 11 below.

TABLE 11. TABLE OF SIMPLE PAYBACK CALCULATIONS FOR ALL SIX STRATEGIES

	ESTIMATED ANNUAL ENERGY USE (KWH)	ESTIMATED ANNUAL ENERGY COST ($)	SIMPLE PAYBACK (YEARS)
Fully-Operational	254,973	$35,299	---
Strategy #1	129,603	$17,942	6.8
Strategy #2	92,038	$12,742	5.2
Strategy #3	29,388	$4,068	3.8
Strategy #4	71,638	$9,918	4.6
Strategy #5	25,653	$3,551	3.7
Strategy #6	16,929	$2,344	3.6

The controls strategy that saves the most energy (Strategy #6) pays back the fastest and as long as there are no issues with the system operating in this manner, this approach will produce a simple payback period of 3.6 years.

However, this does not take into account deferred and then reduced maintenance in the space, which could result in considerably shorter payback estimates. In this project where the ceilings are high and the existing MH luminaires have a relatively short lamp life expectancy (as compared to HPS or the replacement LED products) this savings will be considerable.

Assuming a typical 400 Watt lamp (non-specialty position-oriented lamp), with a horizontal life of approximately 15,000 hours, about 42 lamps were required to be replaced annually in the baseline system. Add in ballast failures of an older lighting system and the maintenance savings it is likely to be approximately $15,000 annually. Table 12 provides these payback estimates including maintenance savings.

TABLE 12. PAYBACK CALCULATIONS FOR ALL SIX STRATEGIES INCLUDING MAINTENANCE ESTIMATE

	ESTIMATED ANNUAL ENERGY USE (KWH)	ESTIMATED ANNUAL ENERGY COST ($)	PAYBACK WITH MAINTENANCE ($15,000) (YEARS)
Fully-Operational	254,973	$35,299	---
Strategy #1	129,603	$17,942	3.6
Strategy #2	92,038	$12,742	3.1
Strategy #3	29,388	$4,068	2.6
Strategy #4	71,638	$9,918	2.9
Strategy #5	25,653	$3,551	2.5
Strategy #6	16,929	$2,344	2.5

OCCUPANCY SENSOR PROGRAM DESIGN CONSIDERATIONS

The occupancy sensors are set to use a short delay time of 30 seconds. Since the activity in the space is highly transient, a short delay time can be employed because normal activity will regularly be resulting in positive sensor responses, unlike more sedentary occupancy, which may need a longer delay time to avoid nuisance 'off' triggers.

The typical occupancy event in the space is represented by one of two different activities.

1. Restocking. This activity involves taking a pallet of materials from the staging area and either placing it in an upper location in the racks as a whole, or breaking the pallet into smaller units and placing these in the low shelves in preparation for picking. It will be slower more deliberate, and the occupancy in an aisle may last several minutes, especially when restocking from a broken pallet. The restocker will normally use a pallet truck for this activity, but there is a lot of manual hand work when stocking broken pallets.
2. Picking. This activity is much higher speed, and typically an employee driving a picking truck with trailer to the location of a specific product, stepping off the truck to retrieve the desired quantity of the product, and place it in the trailer. The picker truck will then continue down the aisle to turn around at the mid- cross aisle, or continue through to the other end of the space to leave through the opposite door. This is often a very short duration, sometimes less than 30 seconds in total, unless there are multiple items to pick in the space.

The overall effectiveness of an occupancy sensor system is heavily dependent on the patterns of occupancy in the space; the volume of traffic and the duration of each occupancy event. If a space experiences high volume during the occupied hours, an occupancy sensor will save less energy, but in most cases, the occupancy sensor will act as the 'nighttime sweep' to turn off lights after the last occupant has left for the evening.

This space is a lower volume segment of the warehouse. It is intended for the aerosol products and the employees that enter there must have specific training for the eventual spills or can punctures. As a result, the lighting does have extended portions of the workday where lower activity occurs, and the control system it effectively setting back the lighting for these durations. A busier portion of the facility will experience lower savings.

During the day, the lighting in the space does not turn completely off when it senses unoccupied conditions. It will set the lights to 10% during the day when unoccupied. This reduces the energy savings slightly, but it ensures that at no time, regardless of the lighting status, will it deliver light levels lower than prescribed as part of the egress lighting recommendations.

At night, the majority of lights will turn off completely, but about six will remain on at a 25% level to ensure that basic nightlight levels are available as well, regardless of the lighting system status.

Figure 25 shows a typical day load for a single circuit. It reflects that at approximately 4:00 AM the lights will go into the daytime mode, where they operate at 10% minimum, and will go up as occupancy events occur. This mode extends to 9:00 PM.

During the day, the activity in the space has several peaks and valleys.

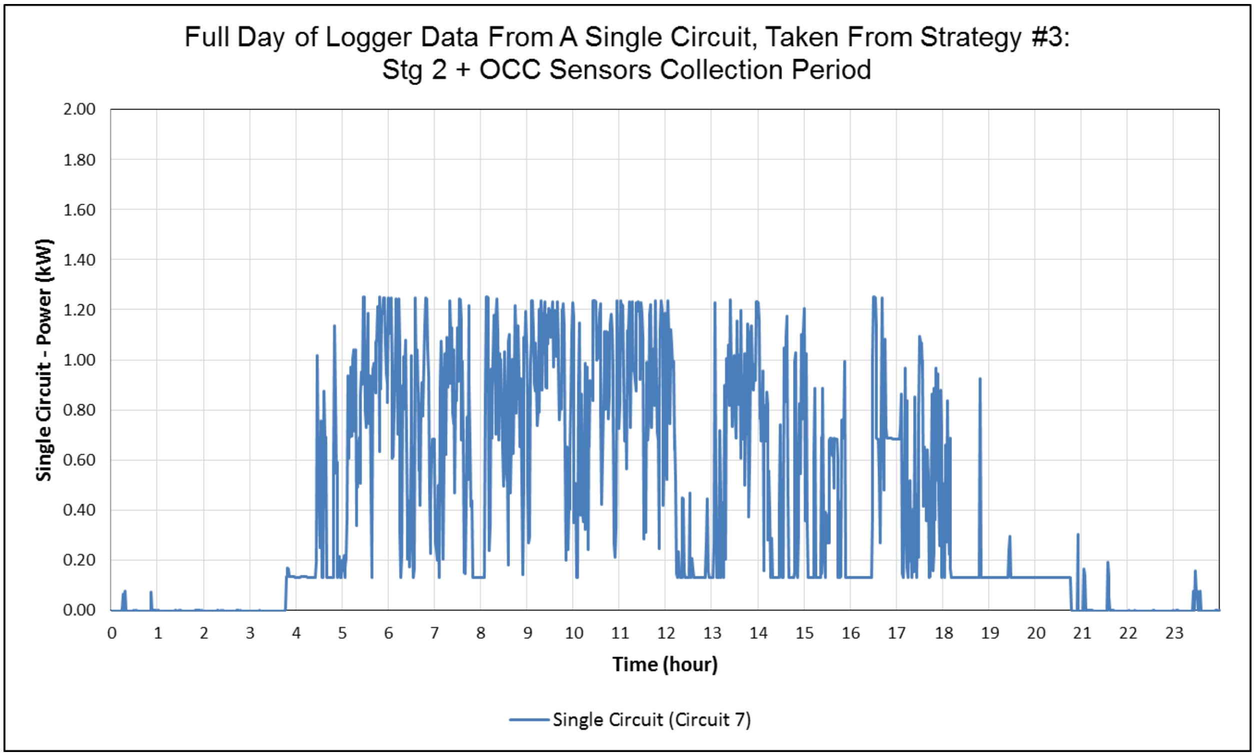


FIGURE 25. FULL DAY OF LOGGER DATA FROM A SINGLE CIRCUIT, TAKEN FROM STRATEGY #3: STG 2 + OCC SENSORS COLLECTION PERIOD

The 12:00 PM to 1:00 PM hour is when the shift change occurs, and a low activity period can be seen in the graph at that time. The afternoon is the time that the restockers will come through and place new products on the shelves. The activity is lower in the second shift for that reason, and as the evening progresses, the activity may end, depending on the amount of restocking that is required.

Figure 26 below shows the same graph expanded in time for only the period from 11:00 AM to 1:00 PM. There is constant activity and energy consumption in the aisle before 12:15, but even so, the circuit is rarely at full power (full power is approximately 1.2 kW when the lights are dimmed to 70% as they are currently established). This indicates that while the activity is heavy, all seven of the luminaires on this circuit are rarely all fully operating at the same time.

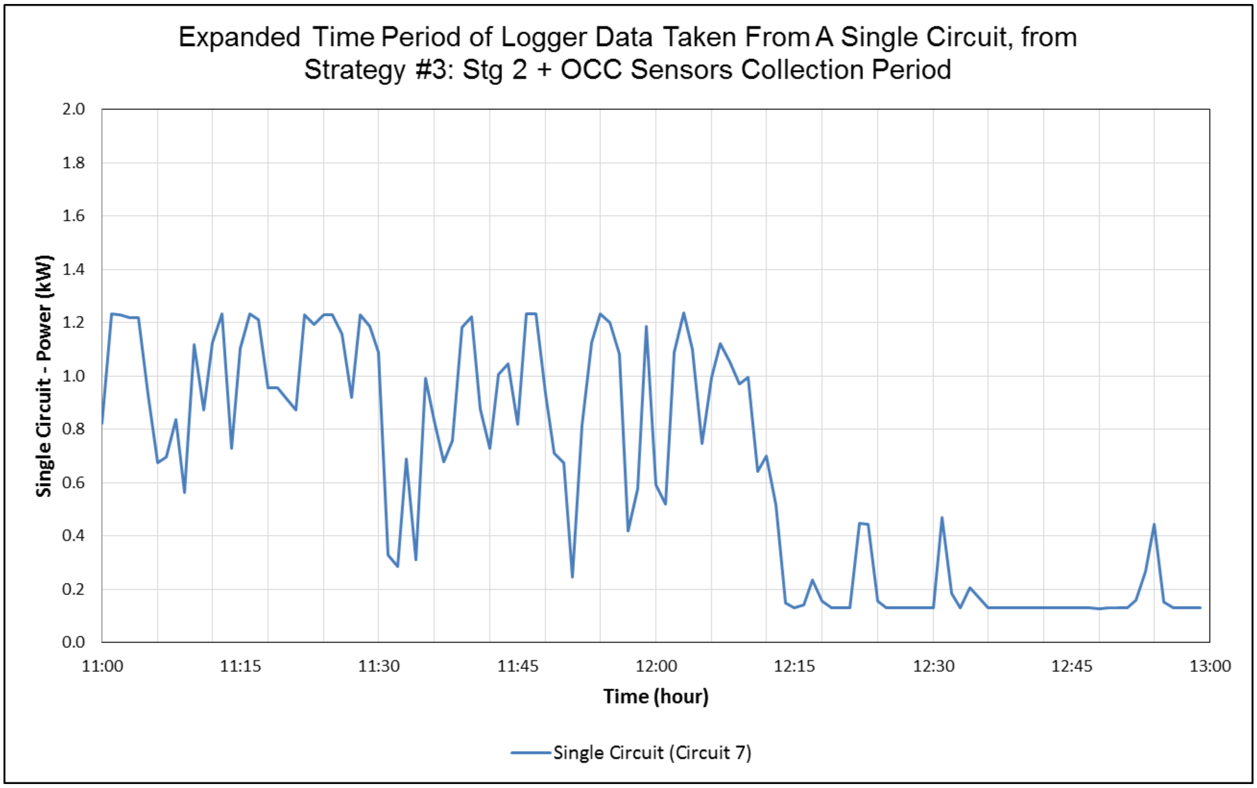


FIGURE 26. EXPANDED TIME PERIOD OF LOGGER DATA TAKEN FROM A SINGLE CIRCUIT, FROM STRATEGY #3: STG 2 + OCC SENSORS COLLECTION PERIOD

DAYLIGHT SENSOR PROGRAM DESIGN CONSIDERATIONS

The daylight sensors are integrated into the luminaires. They rely on reflected light to establish a dimming setpoint for the electric lighting system.

This approach is influenced by the reflectivity of objects in the space surrounding the luminaire and photocell sensor. This does have the potential to lead to some variability in the delivered light levels in the space, especially if there is a large light colored pallet of material high in the racks near the luminaire, or in close proximity to a skylight.

In this circumstance, the variability is not visible to any observer. The lights are high enough overhead that they overlap in coverage at the ground, so a single light could be influenced by a reflection, but the impact is minimal at best.

The daylight sensor was calibrated to start dimming the lights at 20 footcandles. This results in somewhat lower energy savings than might be possible if the sensor were calibrated to 15 footcandles, but this ensures that the lighting system does not over-dim at times.

Figure 27, Figure 28, and Figure 29 show a typical day load from a single circuit, under full sun, partly sunny, and cloudy days. The characteristic inverted bell curve from the daylight availability is clearly visible in both the full sun and partly sunny days. The cloudy day shows some periods of full sun, but not enough to clearly see the inverted bell curve.

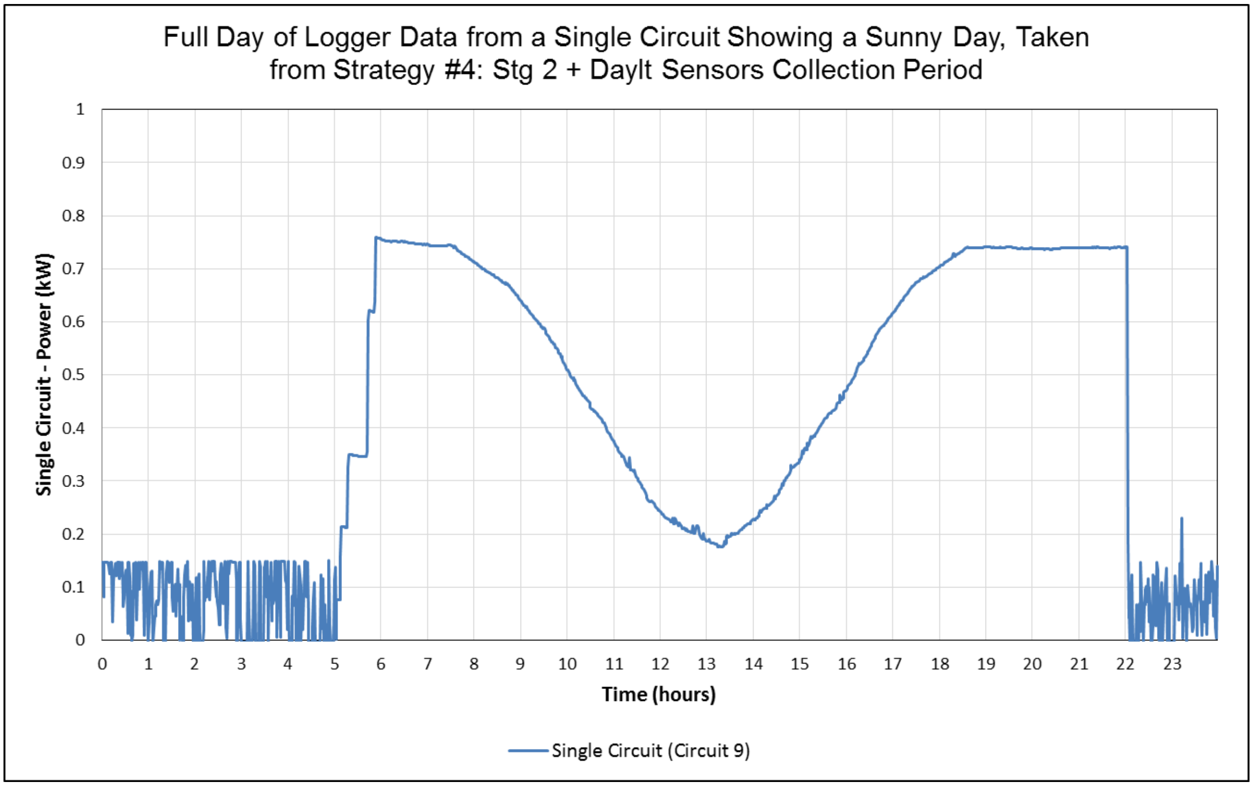


FIGURE 27. FULL DAY OF LOGGER DATA FROM A SINGLE CIRCUIT SHOWING A SUNNY DAY, TAKEN FROM STRATEGY #4: STG 2 + DAYLT SENSORS COLLECTION PERIOD

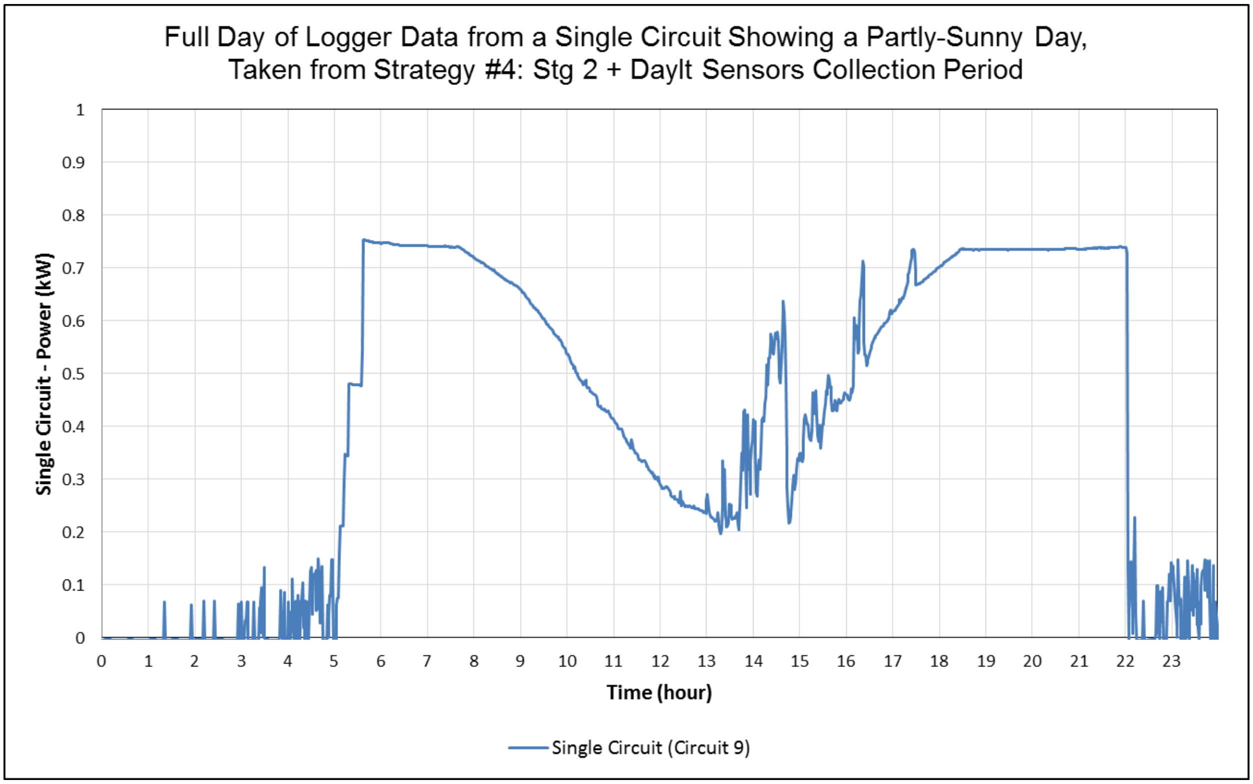


FIGURE 28. FULL DAY OF LOGGER DATA FROM A SINGLE CIRCUIT SHOWING A PARTLY-SUNNY DAY, TAKEN FROM STRATEGY #4: STG 2 + DAYLT SENSORS COLLECTION PERIOD

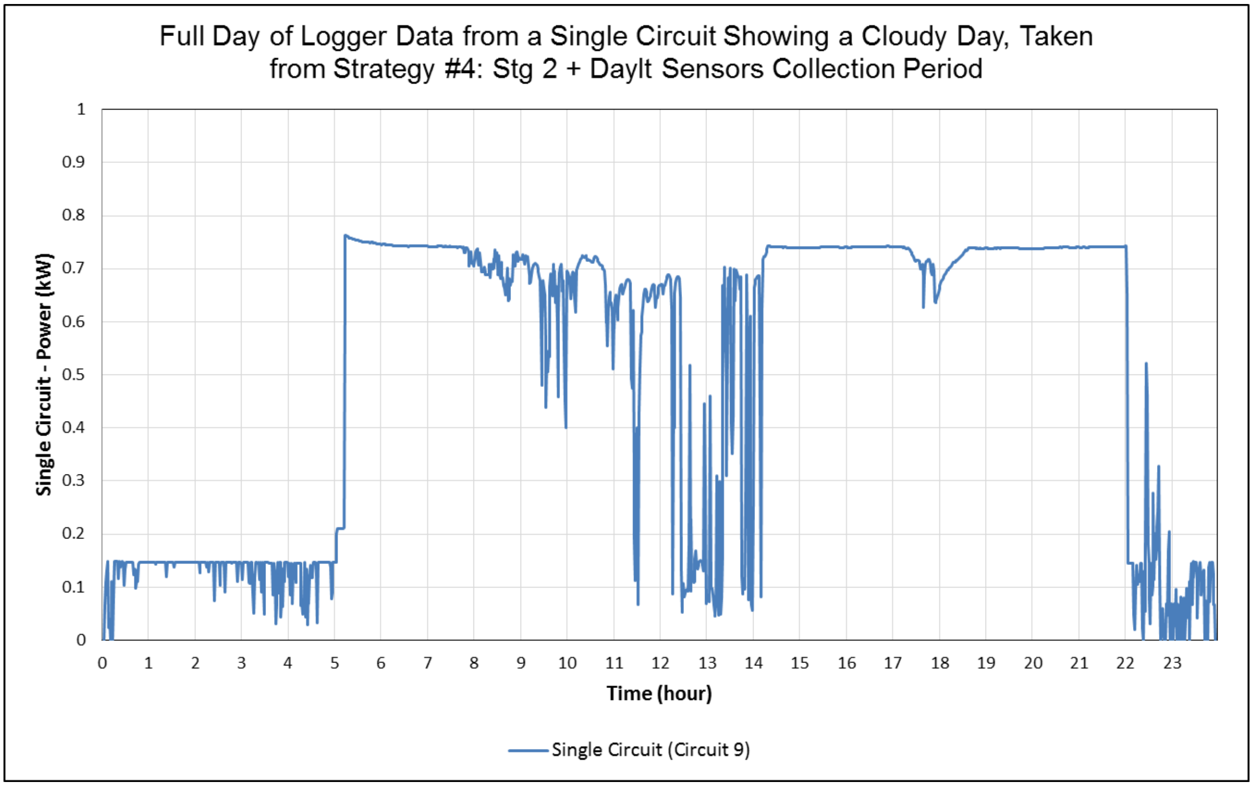


FIGURE 29. FULL DAY OF LOGGER DATA FROM A SINGLE CIRCUIT SHOWING A CLOUDY DAY, TAKEN FROM STRATEGY #4: STG 2 + DAYLT SENSORS COLLECTION PERIOD

Most of the lighting equipment in the space is not located in as close proximity to the skylights as this particular circuit of luminaires is, so most will have much lower energy savings as a result of the daylighting. Because of the high racking, most of the luminaires may show little or no benefit.

MULTIPLE CONTROLS INTEGRATION

The integration of daylight and occupancy sensing with the basic time of day settings and the overall definition of the range of dimming is important to understand and appreciate because it causes differing results depending on how the hierarchy is programmed into the control software.

Figure 30 below shows the combination of both daylight and occupancy sensors in action. This is also a single circuit from the space so that the impact of the daylight is visibly apparent.

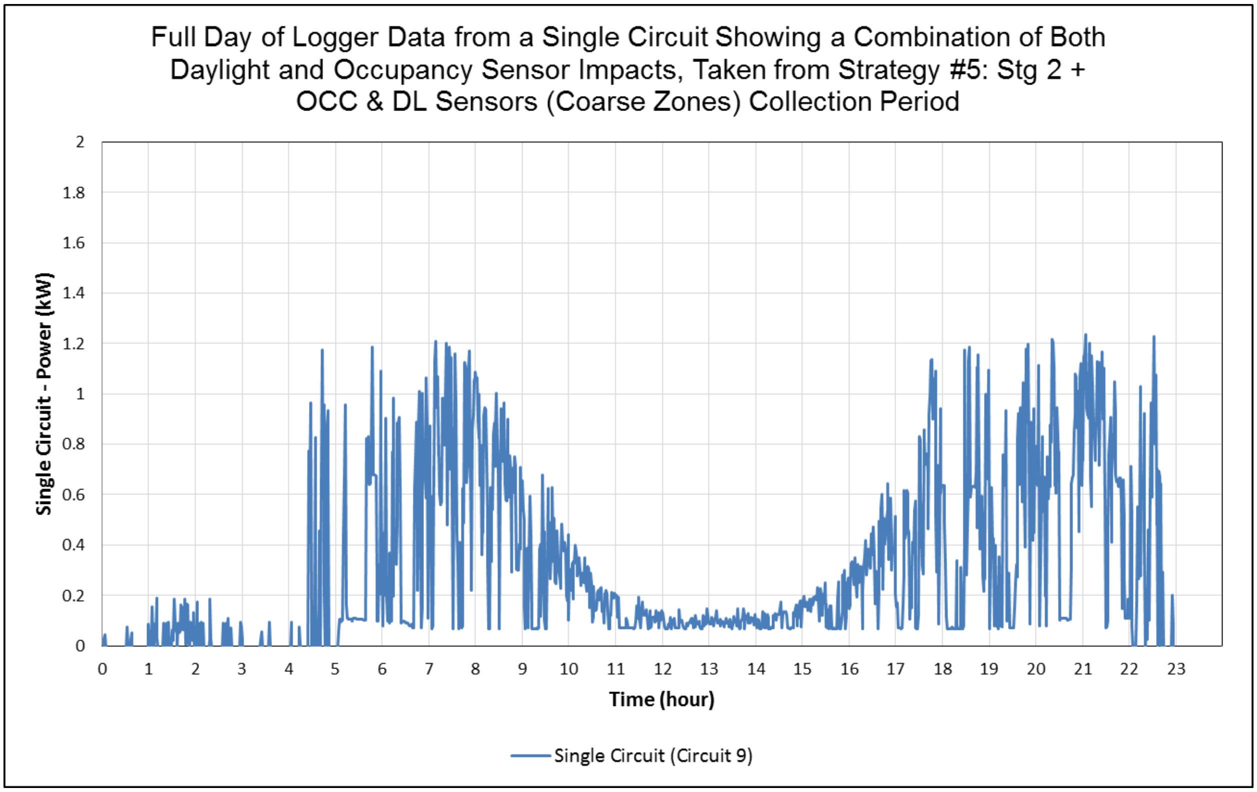


Figure 30. Full Day of Logger Data from a Single Circuit Showing a Combination of Both Daylight and Occupancy Sensor Impacts, Taken from Strategy #5: Stg 2 + OCC & DL Sensors (Coarse Zones) Collection Period

Two items are clearly apparent in the graph. The first is that the daylight control is functioning, as the characteristic inverted bell curve is readily visible in the peaks that are achieved during the daytime. The second is that the occupancy sensors are working, resulting in a sequence of peaks and valleys in the graph that show both the upper limit of the lighting load and also indicate where the minimum setting is located during periods of inactivity.

A few other details can be collected from this graph. This particular circuit is one that contains a luminaire that is experiencing a 'night noise' issue, and this activity can be seen in the early morning hours as small spikes that never reach 0.2 kW.

Second, someone came onto the space about 45 minutes before the lighting system was programmed to switch to the daytime mode. This activity can be seen from about 4:00 AM to 5:00 AM in the morning as high peaks close to full power, but there is no minimum setting (10% floor setting), so the lights went completely OFF between the activity. At 5:00 AM, the lights switch over to daytime setting, and a minimum power draw is established.

Third, there is a subtle, but perceptible reduction in the minimum setting (slightly lower than 10%) that occurs when daylighting becomes more available, The lighting control program overrides the minimum setting to dim further back when there is sufficient daylight. This shift is subtle, but is present, and indicates that the integration of all of these controls strategies (task tuning, occupancy sensors, and daylight sensors) is functioning effectively to maximize the potential energy savings.

Problems & Solutions

There were several problems observed during the post-retrofit monitoring period that created some delays in the monitoring while the project team attempted to resolve them effectively.

- Fixture Failures:

The first problem observed was the failure of two luminaires. These were observed quickly, and replacement luminaires were sent from the factory to replace these. These failures occurred during the initial burn-in period on the lighting (while the luminaires were operating 24/7 for a period of about two weeks), so the failures did not influence the testing.

These failures represent typical early failures of products, and may have had nothing to do with the LED technology. Regardless, once the two luminaires were replaced, the system operated properly.

As second failure that occurred early on was the inability of the installers to get one of the light fixtures to properly synchronize with the rest of the light control system. This was resolved by reprogramming the device at a later date to function correctly.

- Commissioning Issues:

One other issue that occurred at the beginning of the automatic controls strategies was coordination of the behind-the-scenes programming to ensure that the lighting system is functioning as intended. After initial programming, a round of data showed deviations in the anticipated power draw at times, and this was traced back to minor deviations in the programming. These were eliminated, and the monitoring process was begun with a control system functioning as anticipated. This caused an approximately 2-week delay at the beginning of the monitoring period for Strategy #3.

- Phantom Occupancy:

The last, and largest, problem that was encountered in the loggers was not observed until the first round of occupancy sensor controls was employed; in Strategy #3. In this strategy, the occupancy sensors were turned on for the first time, and at that time, the monitoring for Strategy #3 was begun.

When the first data from Strategy #3 was brought back and reviewed, nighttime noise was observed in the logger data. This noise looks like occupancy spikes in the lighting system, and are actually occupancy events.

However, at the times that the noise is being observed, there were not supposed to be any occupants in the space (the facility is secured at night, and there is no access after-hours). As a result, there was concern that there might be rodents or birds in the space that were triggering the sensors.

Figure 31 shows a typical overnight period with some noise in the afternoon and evening on the day before (a Saturday when the facility is closed), and considerable noise in the 4 to 5 AM period before the workday begins. At times, this night noise was fairly consistent at night, but seemingly random. Each occupancy event appeared to last only a 30-second period.

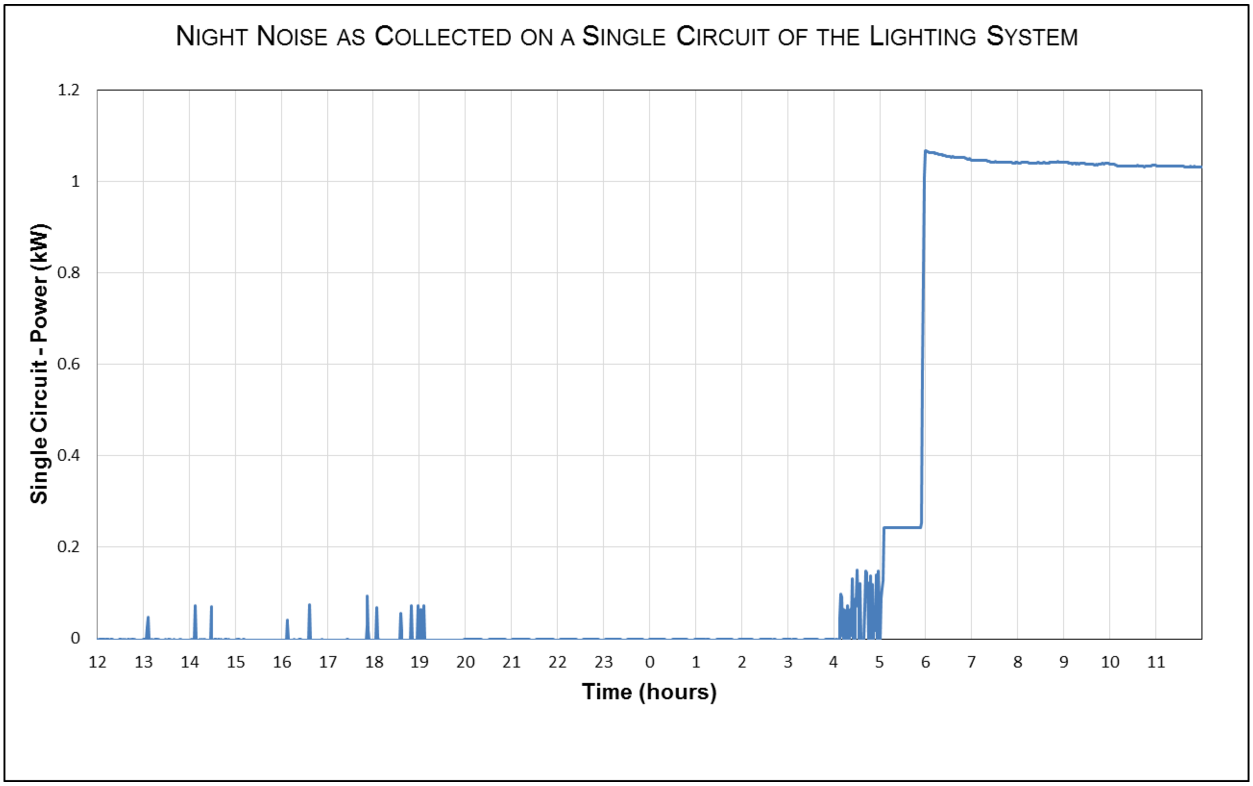


FIGURE 31. PHANTOM NIGHT NOISE AS COLLECTED ON A SINGLE CIRCUIT OF THE LIGHTING SYSTEM

Queries to Digital Lumens produced some additional information in the form of an animation of the lighting system time-coded through an overnight period. This proved that there were about six luminaires at night that were sensing occupancy and turning on, and then turning off once the occupancy was no longer detected. Of those, three of them were fairly heavily triggering in the unoccupied period, and the other three were much less so. A variety of other luminaires in the space will trigger in a seemingly random but very occasional pattern at night. These were rare enough to not be considered abnormal.

Investigation of the conditions showed no rodents or birds active in the space. At that point, Digital Lumens sent out replacement occupancy sensors to see if the occupancy sensors were tripping through faulty relays. The replacement sensors continued to show the night noise, so this was ruled out as the likely cause.

Next, the Ace Hardware facility staff took effort to stiffen the mounting bracket of the most affected luminaires in the space. This may have shown some positive impact, but not in a clear manner that would indicate the luminaires were moving in the air currents and tripping because of the movement.

As a result of these investigations, the monitoring process was delayed for approximately 60 days. An analysis of the energy consumption data that was collected at the time indicated that the night noise was increasing the total energy consumption by about 1% over a week, and about 3-5% over a nighttime period.

The final cause of the observed night noise is undetermined, but the leading theory offered by Digital Lumens is that the luminaires are experiencing a thermal gradient from exterior vents located nearby that are causing the infrared occupancy sensors to false trigger.

Since a satisfactory solution to the night noise was not discovered and the overall impact deemed to be relatively small, the monitoring continued with the night noise, however, the modeling of the energy consumption for the space was completed with circuits that did not exhibit the worst of the night noise problem to mitigate the impact of the issue on the calculations.

DATA COLLECTION COMPARISON

A comparison of the data collected through the Dent DataLoggers at 30-second intervals with the data collected through the Digital Lumens LightRules™ software produces some difference in calculated results.

Figure 32 below shows the graphs of the collected 30-second data and the 15-minute data overlaid. While there is a clear similarity in the graphs, it is impossible to determine what the differences are without looking at a second graph of the accumulation of kWh by both measurement methods.

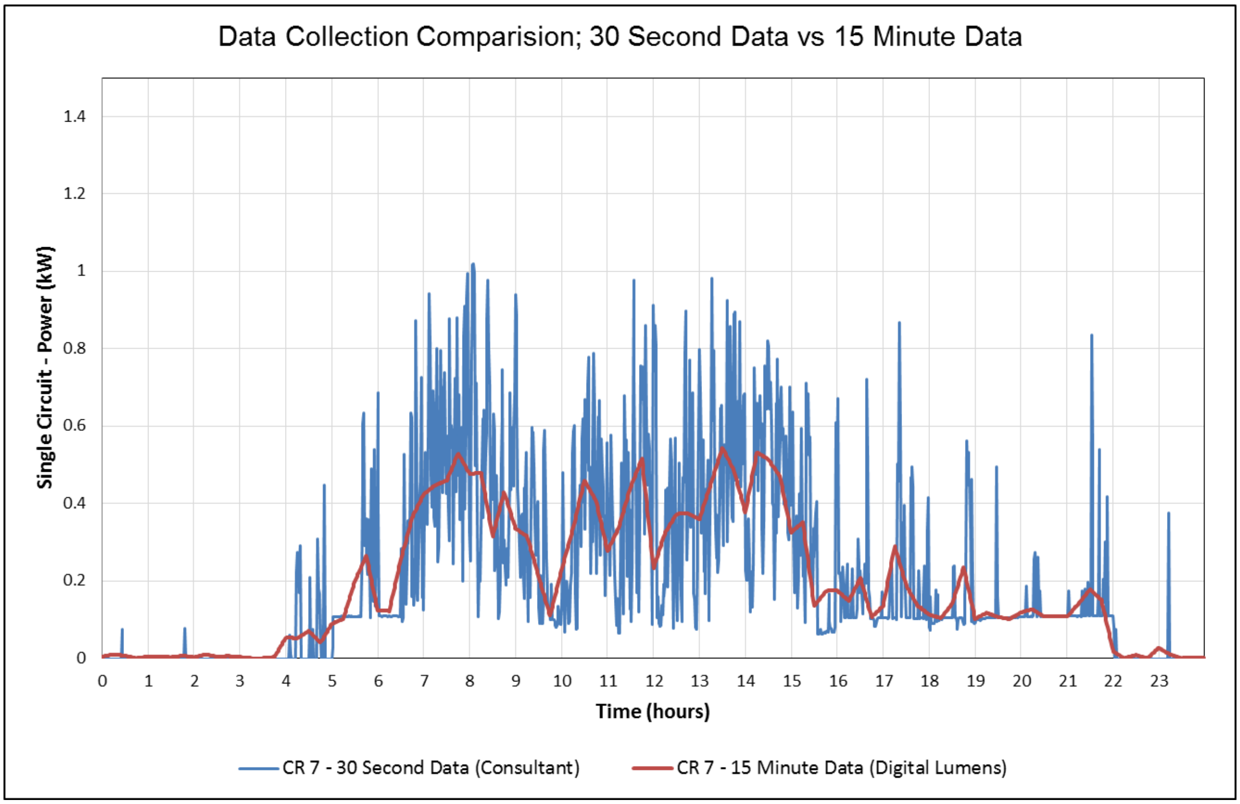


FIGURE 32. DATA COLLECTION COMPARISON; 30 SECOND DATA VS. 15 MINUTE DATA

Figure 33 below shows the difference in the results from the Dent DataLoggers and the Digital Lumens on-board software. The energy consumption from the DataLoggers is recording approximately 7.5% higher total for the day tested.

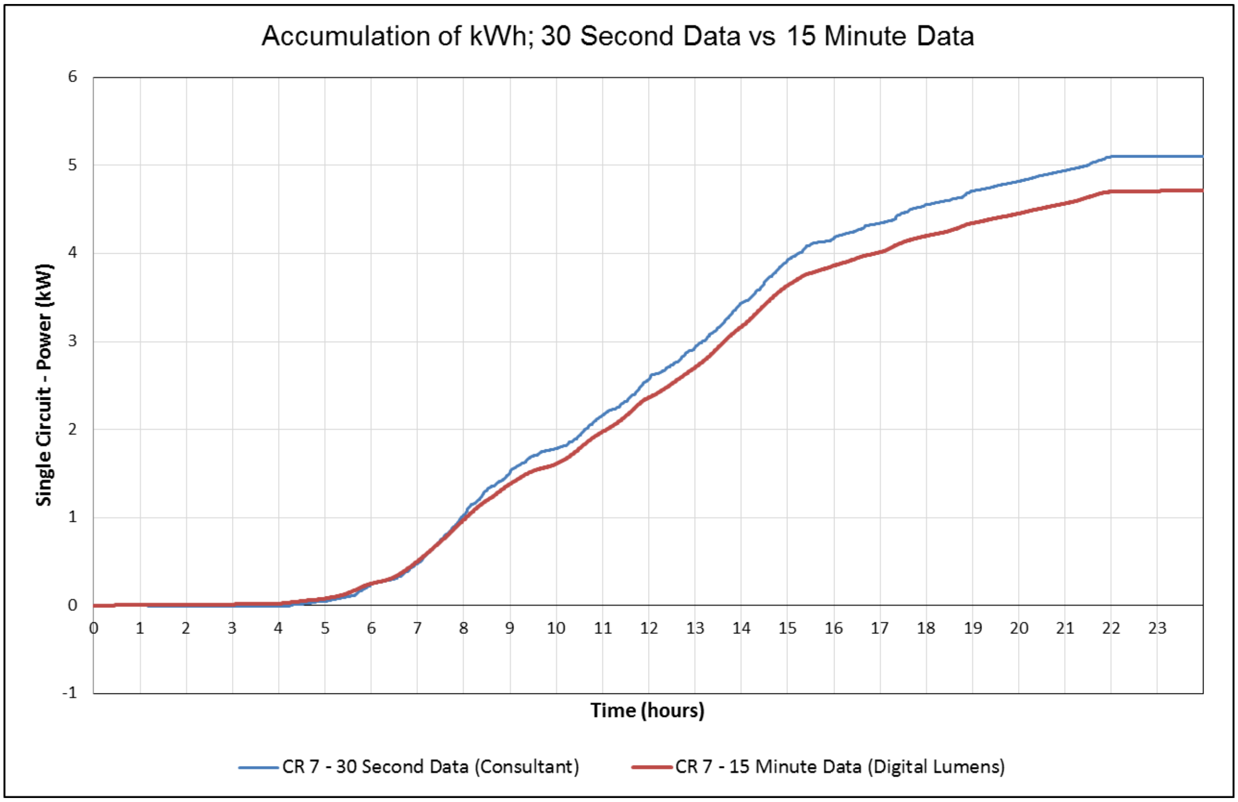


FIGURE 33. ACCUMULATION OF KWH; 30 SECOND DATA VS. 15 MINUTE DATA

Discussion with Digital Lumens has provided the most likely source of the difference in the readings. In the space, the luminaires are circuited in an "A-B" alternating arrangement, and this row is documented with circuit #7 having seven (7) luminaires connected to it, and the remainder connected to circuit #9. However, it is likely that either the documentation is incorrect, or when the retrofit was performed, one of the luminaires was switched from #9 to #7 inadvertently.

As a result, the full-connected load of this circuit now reflects eight (8) luminaires, not seven, and this is the source of the difference. Digital Lumens has reported that for the entire room (all circuits included), their energy consumption calculations for a day differs from those collected by the DataLoggers by only 0.7%, which indicates that this is a reliable method to verify performance after a retrofit with these luminaires and the use of the LightRules™ software.

RECOMMENDATIONS

The adoption of LED lighting is clearly at a point of maturity such that it can be easily adopted in a variety of lighting situations, including warehouse situations as represented by the circumstances in this project. What is less understood is the effects of the lighting controls on obtaining the deepest possible energy savings.

The controls are being effectively employed in this project, resulting in 44% energy savings beyond the 'no controls' post-retrofit conditions, so the impacts are very substantial.

This project has provided some information that suggests care is required to achieve the highest energy savings possible with controls. First, to ensure that the greatest possible savings is achieved, proper commissioning is critical. Further, incorporating a monitoring system, such as the LightRules system, can assist with commissioning to to ensure that the lighting controls are functioning as intended. In addition, a monitoring system can help to ensure that the lighting system does not drift in function with time.

The problems that were discovered during the post-retrofit testing were primarily noticed because of the close scrutiny of an emerging technology project of this nature. These problems may not have been observed without the assistance of the high density of data collected by the Dent DataLoggers, which was collecting circuit-level energy consumption information every 30 seconds.

However, the energy management software (LightRules™) built into the Digital Lumens luminaires reports information in 15-minute intervals; much too sparse to discover a problem with sensor noise in a particular luminaire. In that data, the night noise appeared as a slight increase in consumption, not nearly as apparent as the large amount of low-level noise that actually represents the operation of the problem luminaires in those circumstances.

The deepest energy savings are possible with the most aggressive controls strategies. These strategies also will require the highest level of monitoring to ensure that the lighting system is both meeting the visual task requirements for the space, and also operating at the lowest consumption possible within that task requirements.

The effort required to maintain a lighting system at the peak of efficiency is unknown. It is likely to be quite variable, with some projects or spaces functioning smoothly without much attention and other spaces requiring somewhat regular attention to ensure that a new performance artifact is not unnecessarily consuming energy.

Energy savings does function in cross-purpose with lighting performance at times, and the balance point for some customers may be different from other customers. In this project, the team chose to employ very aggressive controls strategies that use a short delay time on the occupancy sensors of 30 seconds. This appears to function well for the transient nature of the occupancy in the warehouse space because the occupants are either arriving and departing quite quickly, or they are actively moving through the space, so the sensor has little opportunity to lose them and 'time out' before their activity ensures in continuous awareness of their presence.

Several design decisions were made to ensure that the lighting system would gain high general acceptance from the occupants. These include:

1 Providing a baseline low level of illuminance that aims to provide lighting to meet the generally accepted definition of 'egress' lighting.

2 The lighting system will lower the light level below this level only if there is sufficient ambient lighting (daylighting) to replace this baseline level. Most of the warehouse space is not near enough to the skylights to fully reduce the lighting, but is substantially reduced for about fourteen (14) luminaires.

3 After normal work hours, this low level of light is reduced to approximate that of 'emergency egress' light. The occupancy sensors are still active, so an occupant will normally only experience the 'occupied' setting, which delivers about seventeen (17) footcandles in the space.

4 The occupancy sensors are fast enough and see down the aisles well enough to react to occupants so that they are not driving into darkness in the aisles.

As a result, the lighting system does not appear to be compromising the visual performance of the occupants, nor is there a perception that the lighting system is 'bothersome' or otherwise acting in an inappropriate manner. This can be considered the fundamental test of performance beyond the basic balance sheet on energy consumption. As long as the occupants feel the lighting is meeting their needs, the system is unlikely to be overridden.

This project demonstrates that deep energy savings can be achieved by the careful selection of appropriate lighting and controls equipment and an appropriate controls strategy that minimizes the opportunity for occupants to experience insufficient light levels or the lighting system in a less than optimal operation mode.

While the savings are quite deep, there may be considerable effort required to achieve the greatest possible energy savings without compromising the design intent of the lighting system. In this study the noise problems and other programming glitches were observed only through the careful attention of energy consumption monitoring by the project team. Had the close scrutiny not occurred, deep savings were still achievable, but the highest savings would not have occurred, with a reduction of possibly as much as 5-10% through a combination of the noise and programming issues.

If that level of lost opportunity is the approximate limit for a project with normal conditions, it may be a reasonable tradeoff for a project with little budget for ongoing commissioning beyond the basic level needed to produce a functional and initially programmed system.

There are several primary recommendations that the results of this project supports:

1. Promote the replacement of MH warehouse lighting systems with new LED-based lighting systems. Deep energy and demand savings of approximately 40 – 50 % are possible by the replacement of the MH luminaires with high quality LED luminaires. This retrofit strategy is cost effective, and will reliably produce energy and maintenance savings to the owner for many years to come beyond the payback period.

2. Promote the inclusion of occupancy and daylighting controls with warehouse lighting retrofit measures to reduce or eliminate lighting under certain occupancy and/or daylighting conditions. If done properly, this is will increase the energy savings considerably, up to approximately an additional 40-45%. Demand will be less affected, but will typically be reduced by 35-40%. Even in higher traffic warehouse spaces, the energy savings will likely be approximately half of that found in this project, in the 20-25% range, but demand savings will likely be reduced somewhat due to coincident activity within the space.

3. Promote the positive impact of establishing lighting controls settings (setbacks for unoccupied periods, delay times for setback, etc.) considerably more aggressive than that specifically mandated in Title 24-2013. That level of performance (requiring bi-

level occupancy controls at 50% for the low setting), are the minimum performance to meet the Standard in construction. The high energy and demand savings in this report are not possible when applying the minimum performance approach to the controls. Note that the 2013 version of the Standard has much more aggressive requirements for renovations and retrofit, so it is more likely that Title 24 will be relevant in a retrofit program.

4. A lighting retrofit in a warehouse will save considerable energy, but the Title 24 additions, alterations, and repairs (Section 141.0) mandates are already effectively responsible for a considerable portion of the savings; the 0.6 W/sq.ft. allowance in the code has not changed in the latest revision. This is a fairly low lighting power density (LPD), but a lower LPD can be achieved with an effective, efficient lighting system. In addition, it is easily possible to exceed the minimum Title 24 performance levels for controls, and this is particularly where the savings in a warehouse retrofit program can be achieved.

Further design guidance recommendations for programs to retrofit warehousing lighting:

1. Ensure that the schedule of operations is not just reported, but observed information.
2. Establish an unoccupied daytime light level or percentage that the lights will dim back to, but unless there is considerable daylighting, do not turn the lights fully OFF. Ensure the lighting is meeting all applicable egress requirements if necessary.
3. Establish a 30-second occupancy sensor delay time in most transient spaces. Longer (several minutes) for spaces with more permanent occupancy conditions.
4. If daylighting is sufficient, lights may be dimmed or turned OFF, but unless the lighting from the skylights is very uniform, set the photocell setpoint 20% or so higher than the target illuminance to avoid possible problems with photocell sensor coverage which may result in 'dark' areas.
5. At night (after normal operations), all lights may be turned OFF, but the occupancy sensors should remain active so that the system will accommodate a late shift or security guards. Ensure that the lighting is meeting all applicable emergency requirements if necessary.
6. Test the lighting system and ensure the occupants are satisfied with the results. Adjustments may be needed based on the customer's perceptions or sensitivity to light level changes. It is imperative that the conditions are perceived as positive and comfortable to ensure persistence.
7. Monitor for a period of time to work out any early programming or other functional bugs to maximize energy savings.

APPENDICES

LUMINAIRE CUTSHEETS

ILE-3-26
ILE-3-18

Intelligent LED Highbay Fixtures

DIGITAL LUMENS

THE MOST ENERGY-EFFICIENT INDUSTRIAL LIGHTING. PERIOD.

Whether you are upgrading industrial lighting in an existing facility or selecting a lighting solution for a new construction project, the most energy-efficient LED lighting choice is the Digital Lumens Intelligent Lighting System. With smart lights — wirelessly networked and centrally controlled — the Digital Lumens System delivers:

- Maximum Savings
- Maximum Flexibility
- Maximum Reliability

How? Integrated intelligence, system-wide. Built into every fixture. And centrally managed via the LightRules™ control system.

ILE-3-26

MAXIMUM SAVINGS

Up to 90% savings on lighting energy

- Integrated occupancy sensor delivers light when and where needed
- Integrated daylight harvesting drives up to 50% additional savings
  - Granular control yields more energy and dollar savings, and consistent light quality
  - No over-lit areas and wasted energy from circuit-wide implementations
  - Detailed LightRules reports provide occupancy feedback and detailed energy savings data
- Centralized management provides control over all lighting
- Rapid payback and best TCO (Total Cost of Ownership)

ILE-3-18

MAXIMUM FLEXIBILITY

Light when and where it is needed

- Suitable for a broad range of industrial environments: Warehouses, cold storage, manufacturing sites, production facilities requiring washdown
- Superior operation, flexibility and control
- Choice of optics for broad range of deployments: Narrow for aisles/ Wide for open spaces
- Appropriate for cold (-40°F), dry (122°F), and damp environments requiring IP65 fixtures
- Direct replacement for HID, HIF (T5, T8)

MAXIMUM RELIABILITY

- Rugged industrial design
- 5-year warranty

Preliminary

-40°F Min 122°F Max

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Intelligent LED Highbay Fixtures

ILE-3-26 / ILE-3-18

PERFORMANCE	ILE-3-26	ILE-3-18
Lumen Output	26,000 lm	18,000 lm
Power Consumption	350 W	230 W
Efficacy (lm/W)	74 lm/W	78 lm/W
Color Temperature*	5,000 K	
CRI	70 minimum	
Lumen Maintenance	L_{70} 50,000+ hours @ 77°F (25°C)	
Input Voltage	· 208 – 277 VAC, 50/60 Hz · 480 VAC, 60 Hz available (add-on transformer option)	
Power Factor	0.9 minimum	
Surge Protection	Per IEC 61547	
Wiring	· Sealed, integrated cable	

* *Nominal CCT, as defined by ANSI C78.377-2008.*

SENSING AND CONTROL	
Onboard Intelligence	· Built-in sensing with data logging · Energy and fault monitoring · Analog or digital input
Sensor Inputs	· Integrated occupancy sensor (PIR) · Integrated daylight sensor · Integrated temperature monitoring
Dimming Levels	· 0-100%, 16-bit digital resolution · High-Low dimming setpoints stored onboard in non-volatile memory
Wireless Networking	· ZigBee® Compliant Platform/802.15.4
Control Capabilities	· Scheduling via LightRules · kWh and occupancy logging · Daylight harvesting

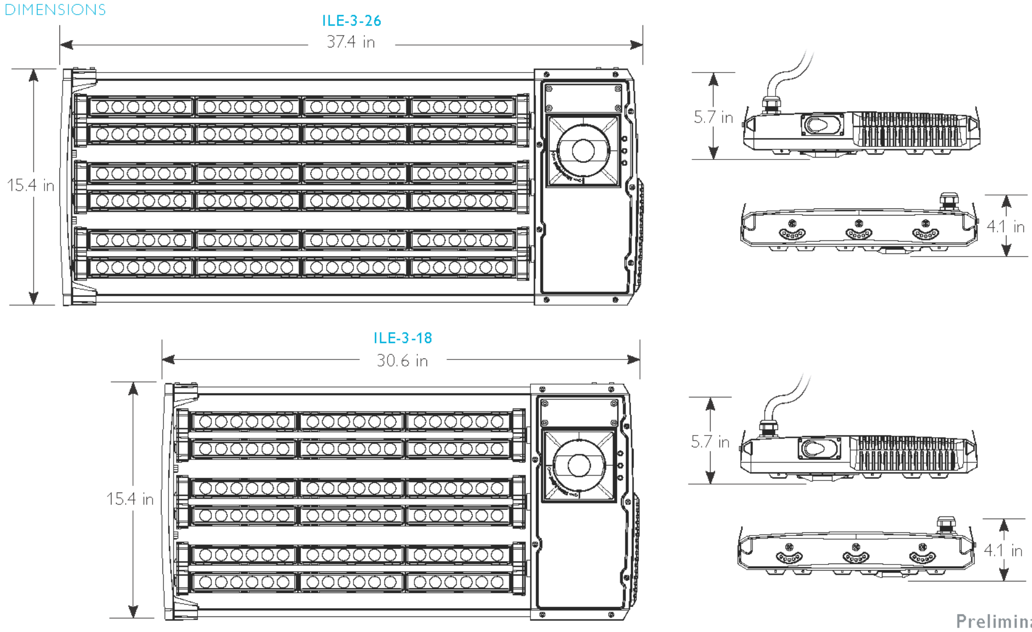
PHYSICAL		
Dimensions (H x W x D)	ILE-3-26	4.1 x 15.4 x 37.4 in (10.4 x 39.1 x 94.9 cm)
	ILE-3-18	4.1 x 15.4 x 30.6 in (10.4 x 39.1 x 77.7 cm)
Weight	ILE-3-26	22.0 lbs (9.9 kg)
	ILE-3-18	18.0 lbs (8.2 kg)
Mounting Options	· Aircraft cable suspension · Rigid Mount	
Frame	PC/ABS polymer and anodized aluminum	
Power Enclosure	PC/ABS polymer	

ENVIRONMENTAL	
IP Rating	IP65
Operating Temperature	-40° to 122° F (-40° to 50°C)

CERTIFICATION AND WARRANTY	
Pending Certifications	· UL 1598, cUL · UL-MX NOM · CE · DesignLights™ Consortium QPL
Warranty	5-year Limited Warranty

ORDERING INFORMATION	
26k with Narrow Optic	Item 21500
26k with Wide Optic	Item 22500
18k with Narrow Optic	Item 21400
18k with Wide Optic	Item 22400

DIMENSIONS



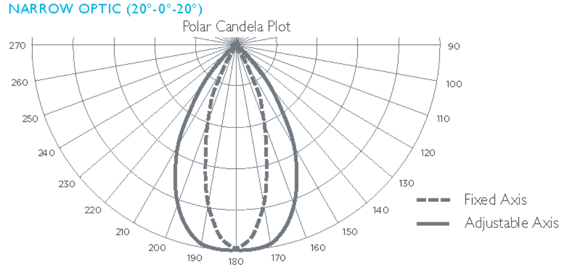
Preliminary

Intelligent LED Highbay Fixtures — ILE-3-26 / ILE-3-18

ILE-3-26 Photometrics

POLAR CANDELA DISTRIBUTION

NARROW OPTIC (20°-0°-20°)

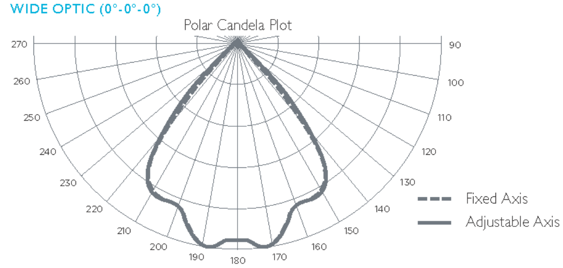


ILLUMINANCE AT DISTANCE

	Center Beam fc	Beam Width Fix	Beam Width Adj
5 ft	1110	3 ft	5 ft
10 ft	293	6 ft	10 ft
15 ft	130	9 ft	15 ft
20 ft	74	12 ft	20 ft
25 ft	47	15 ft	24 ft
30 ft	33	18 ft	30 ft
35 ft	24	20 ft	34 ft
40 ft	19	23 ft	38 ft

POLAR CANDELA DISTRIBUTION

WIDE OPTIC (0°-0°-0°)



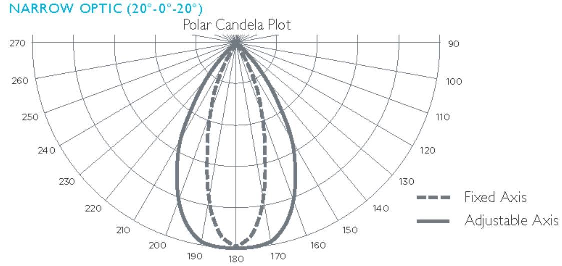
ILLUMINANCE AT DISTANCE

	Center Beam fc	Beam Width Fix	Beam Width Adj
5 ft	650	6 ft	6 ft
10 ft	165	13 ft	13 ft
15 ft	73	19 ft	19 ft
20 ft	41	26 ft	26 ft
25 ft	26	32 ft	31 ft
30 ft	18	38 ft	38 ft
35 ft	14	43 ft	42 ft
40 ft	10	51 ft	50 ft

ILE-3-18 Photometrics

POLAR CANDELA DISTRIBUTION

NARROW OPTIC (20°-0°-20°)

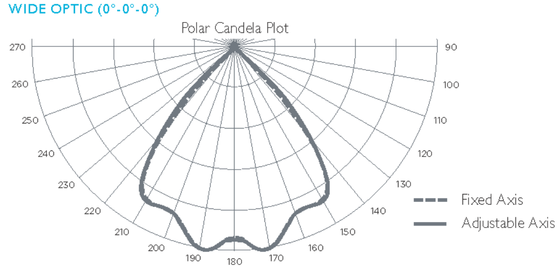


ILLUMINANCE AT DISTANCE

	Center Beam fc	Beam Width Fix	Beam Width Adj
5 ft	789	3 ft	5 ft
10 ft	203	6 ft	10 ft
15 ft	91	8 ft	14 ft
20 ft	51	12 ft	19 ft
25 ft	33	14 ft	24 ft
30 ft	23	16 ft	27 ft
35 ft	17	20 ft	33 ft
40 ft	13	20 ft	35 ft

POLAR CANDELA DISTRIBUTION

WIDE OPTIC (0°-0°-0°)



ILLUMINANCE AT DISTANCE

	Center Beam fc	Beam Width Fix	Beam Width Adj
5 ft	431	6 ft	6 ft
10 ft	107	14 ft	14 ft
15 ft	47	21 ft	21 ft
20 ft	27	27 ft	27 ft
25 ft	17	34 ft	34 ft
30 ft	12	41 ft	41 ft
35 ft	9	47 ft	47 ft
40 ft	7	53 ft	53 ft

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Preliminary

OCCUPANT SURVEY AND RESULTS

Bldg ID: Ace Distribution **Room ID:** Aerosol Rm. **Survey ID:** ______

OCCUPANT SURVEY – Is this room visually comfortable?

1. Today's date ______day______month______year 2. Time of day: ________Hour __am/pm

3. Your age:
❑ 18-25 ❑ 26-33 ❑ 34-41 ❑ 42-49 ❑ 50-57 ❑ 57-64 ❑ 65+

Please choose the closest correct answer

4. How long have you been regularly entering the Aerosol room?
❑ less than a month ❑ 2-4 months ❑ 5-11 months ❑ 1 year ❑ 2-4 years ❑ 5+ years

5. How many times per work period do you enter the Aerosol room?
❑ 1-3 ❑ 4-6 ❑ 7-9 ❑ 10-12 ❑ 13+

6. When you come here, approximately how long is each visit?
❑ less than 30 seconds ❑ 30 seconds ❑ 1 minute ❑ 1-2 minutes ❑ 2-4 minutes ❑ 4+ minutes

Please consider your experience of this room based on conditions right now as you fill out this form:	Worse << >> Better											
7. Temperature in the space is comfortable	Strongly Disagree	1 ☐	2 ☐	3 ☐	4 ☐	5 ☐	6 ☐	7 ☐	8 ☐	9 ☐	Strongly Agree	n/a ☐
8. The lighting conditions are comfortable	Strongly Disagree	1 ☐	2 ☐	3 ☐	4 ☐	5 ☐	6 ☐	7 ☐	8 ☐	9 ☐	Strongly Agree	n/a ☐
9. I am satisfied with the amount of light in the space	Strongly Disagree	1 ☐	2 ☐	3 ☐	4 ☐	5 ☐	6 ☐	7 ☐	8 ☐	9 ☐	Strongly Agree	n/a ☐
10. I can/could work happily in this room with SOME of the electric lights turned off	Strongly Disagree	1 ☐	2 ☐	3 ☐	4 ☐	5 ☐	6 ☐	7 ☐	8 ☐	9 ☐	Strongly Agree	n/a ☐
11. The daylight in this room is sufficient	Strongly Disagree	1 ☐	2 ☐	3 ☐	4 ☐	5 ☐	6 ☐	7 ☐	8 ☐	9 ☐	Strongly Agree	n/a ☐
12. The daylight in this room is not too bright (i.e. not causing glare or discomfort)	Strongly Disagree	1 ☐	2 ☐	3 ☐	4 ☐	5 ☐	6 ☐	7 ☐	8 ☐	9 ☐	Strongly Agree	n/a ☐
13. I am able to do my work here without any problems from glare or troubling reflections	Strongly Disagree	1 ☐	2 ☐	3 ☐	4 ☐	5 ☐	6 ☐	7 ☐	8 ☐	9 ☐	Strongly Agree	n/a ☐
14. I can comfortably read labels on packages and racking in this room	Strongly Disagree	1 ☐	2 ☐	3 ☐	4 ☐	5 ☐	6 ☐	7 ☐	8 ☐	9 ☐	Strongly Agree	n/a ☐
15. I do not find the changing light level conditions to be distracting	Strongly Disagree	1 ☐	2 ☐	3 ☐	4 ☐	5 ☐	6 ☐	7 ☐	8 ☐	9 ☐	Strongly Agree	n/a ☐
16. I am satisfied with the lighting control systems in this space	Strongly Disagree	1 ☐	2 ☐	3 ☐	4 ☐	5 ☐	6 ☐	7 ☐	8 ☐	9 ☐	Strongly Agree	n/a ☐

This survey is part of a study funded by Pacific Gas & Electric Co. (PG&E). The results of this survey will be used to guide the development of better buildings. Your responses will remain anonymous. If you have any questions about the survey, please contact Stephanie Berkland at Heschong Mahone Group. (916) 962-7001 or berkland@h-m-g.com.

	Ace PRE results									
	Temp.	Ltg Cond.		Elec. Ltg	Daylight		Glare		Ctrl	
	Question 7	Question 8	Question 9	Question 10	Question 11	Question 12	Question 13	Question 14	Question 15	Question 16
Strongly Disagree										
2					1					
3				1						
4		2	2	1						2
Neutral	1	1	1		1			2	1	1
6					1	1	1	1		
7										
8	1					1	1			
Strongly Agree	1			1		1	1			
n/a									2	

	Ace POST Results									
	Temp.	Ltg Cond.		Elec. Ltg	Daylight		Glare		Ctrl	
	Question 7	Question 8	Question 9	Question 10	Question 11	Question 12	Question 13	Question 14	Question 15	Question 16
Strongly Disagree	3				1					
2				1						
3					2					
4	1				1					
Neutral			1	2		1			1	
6		2	1			1	1		1	1
7			1	1	1			1	1	
8	1	1		1		1	2	1	1	
Strongly Agree		2	2			2	3	3	1	4
n/a										

		Ace Results Comparison									
		Temp.	Ltg Cond.		Elec. Ltg	Daylight		Glare		Ctrl	
Pre	Average	3	7.6	7.2	5.4	3.6	7.4	8.2	8.4	7	8.4
Post	0	7.3	4.3	4.3	5.3	4.3	7.7	7.7	5.3	5	4.3
	Delta	-4.3	3.3	2.9	0.1	-0.7	-0.3	0.5	3.1	2	4.1

ADDITIONAL GRAPHS

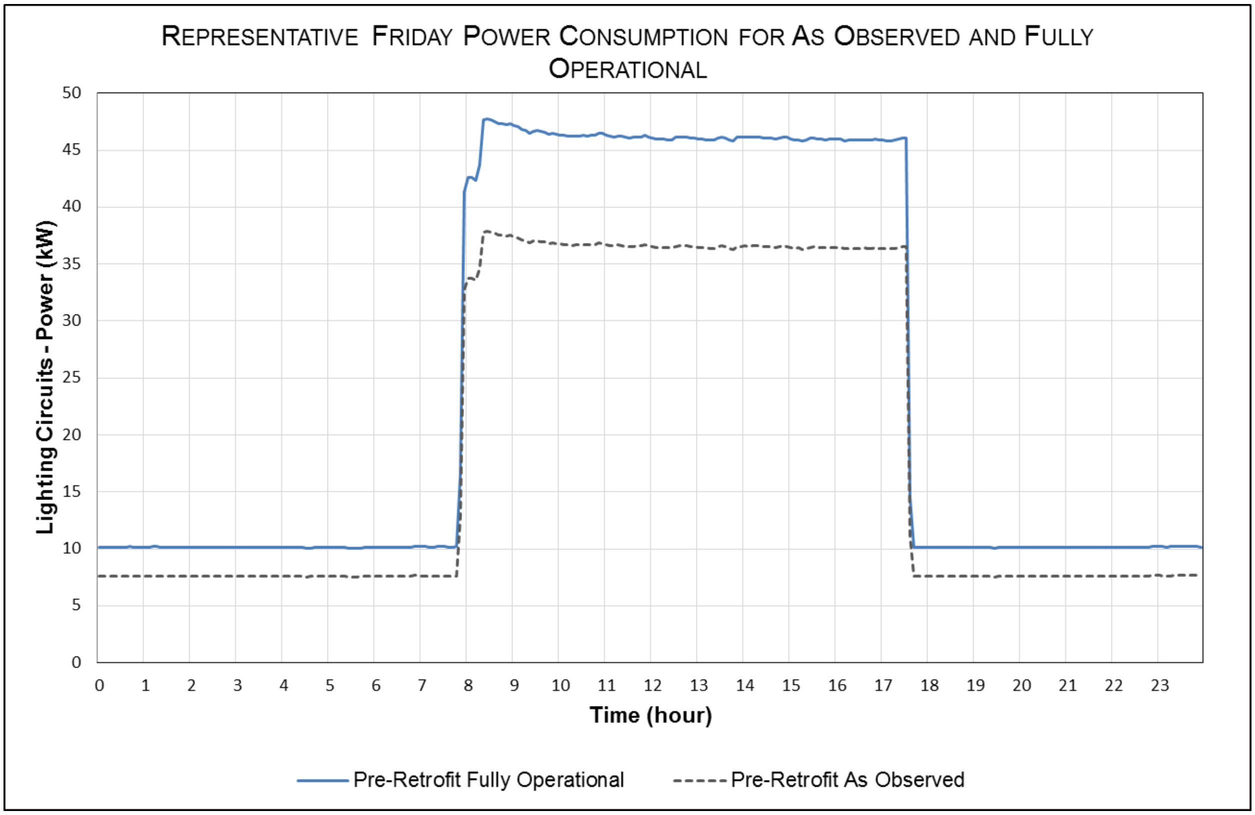

FIGURE 34. REPRESENTATIVE FRIDAY POWER CONSUMPTION FOR AS OBSERVED AND FULLY OPERATIONAL

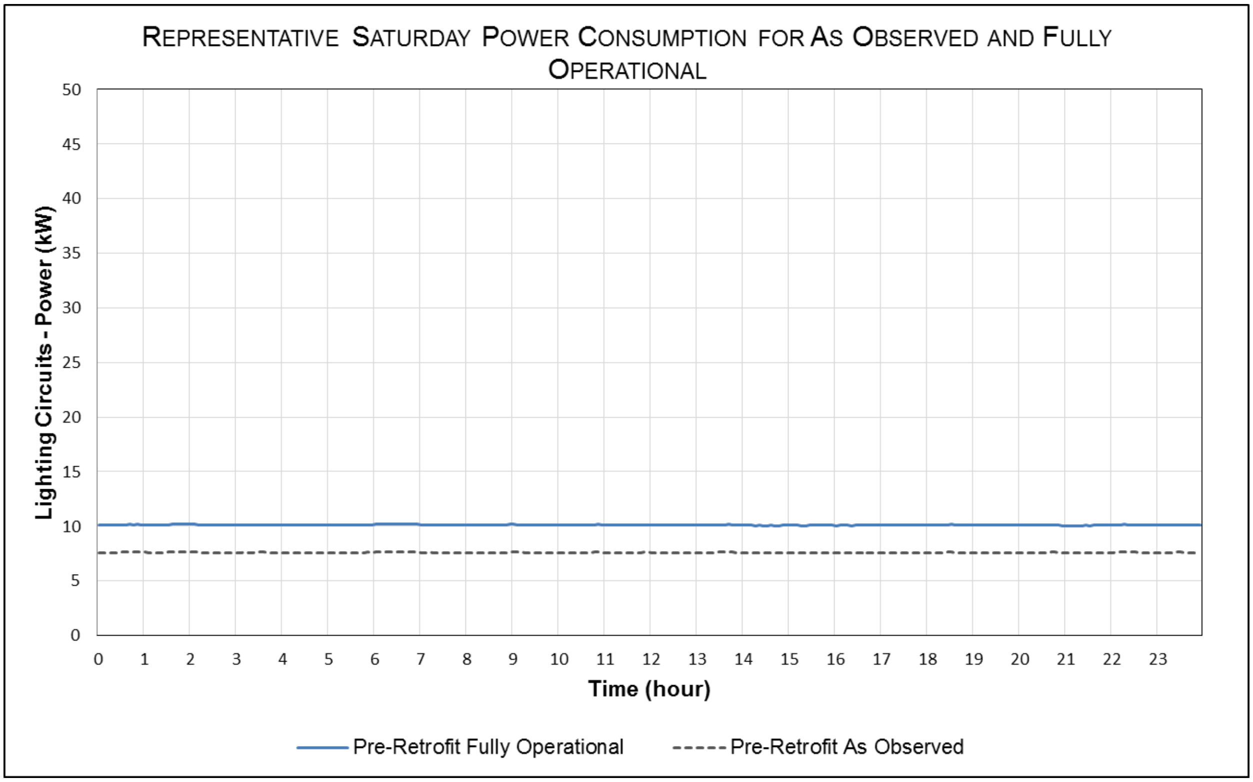

Figure 35. Representative Saturday Power Consumption for As Observed and Fully Operational

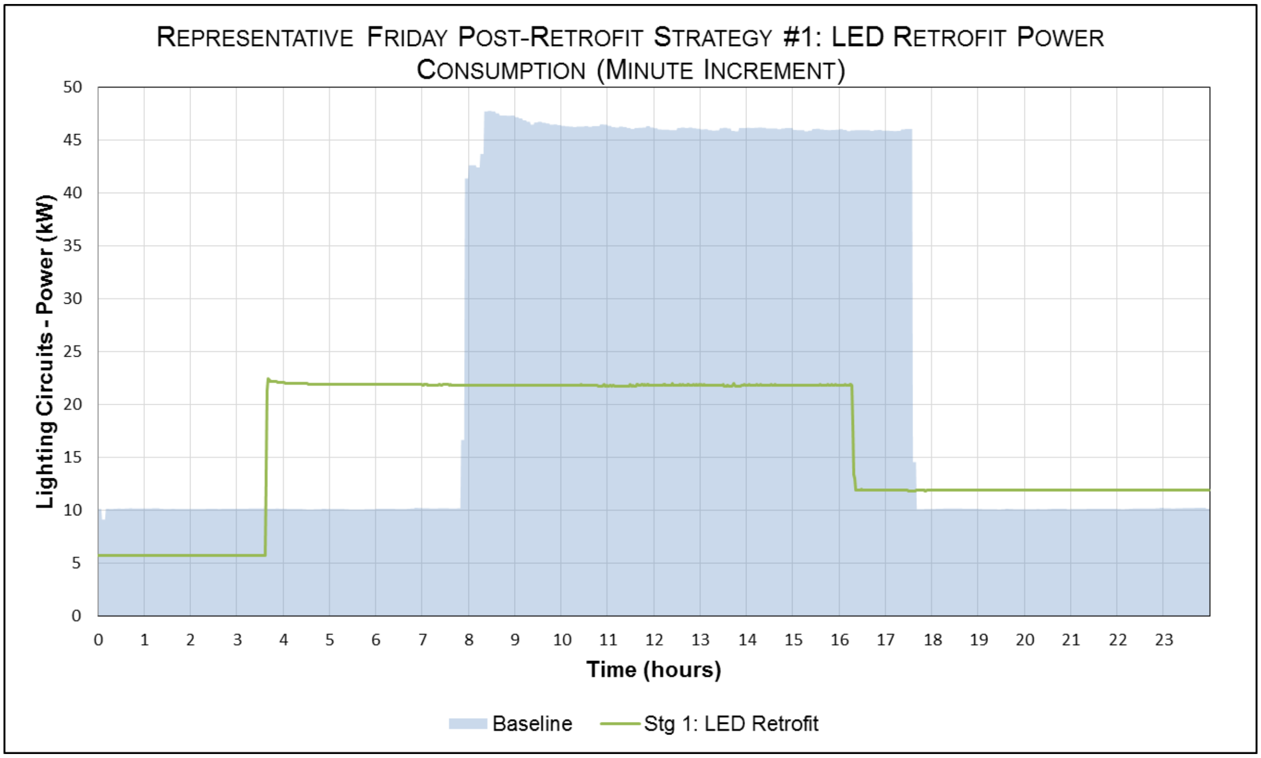

FIGURE 36. REPRESENTATIVE FRIDAY POST-RETROFIT STRATEGY #1: LED RETROFIT POWER CONSUMPTION (MINUTE INCREMENT)

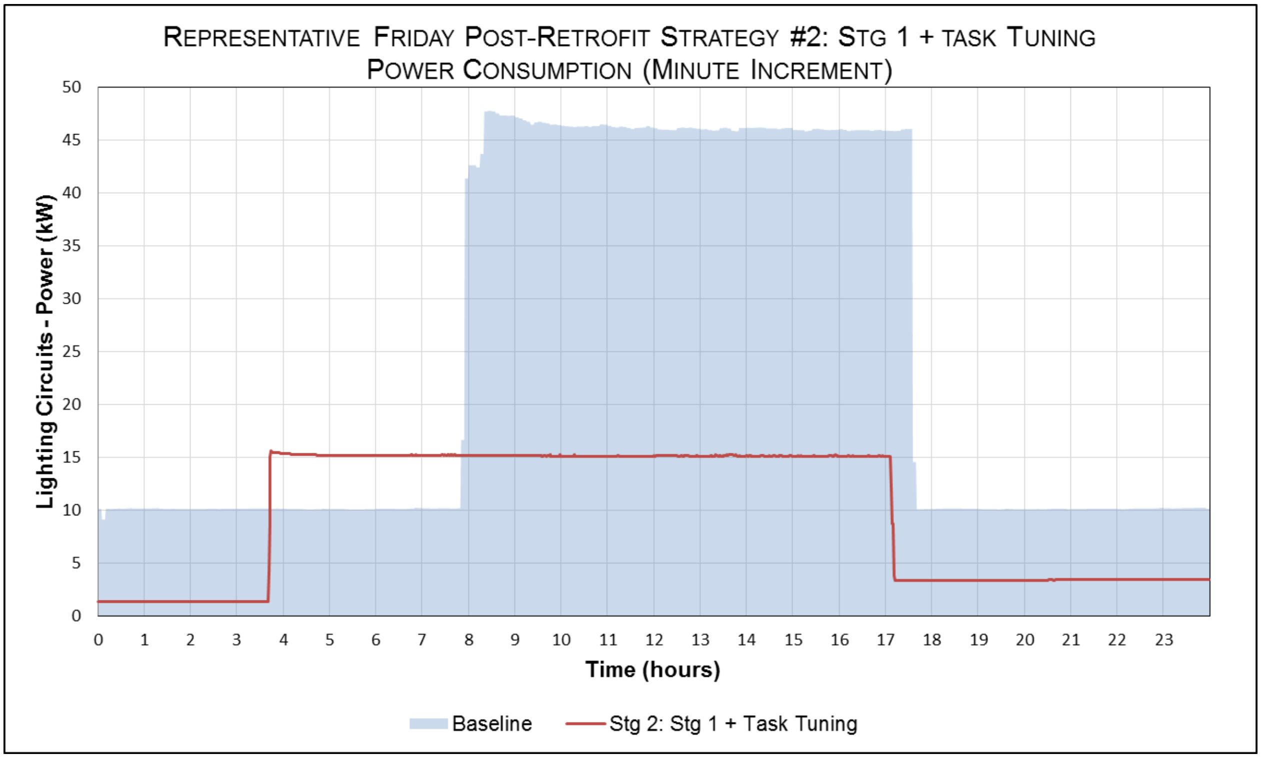

Figure 37. Representative Friday Post-Retrofit Strategy #2: Stg 1 + Task Tuning Power Consumption (Minute Increment)

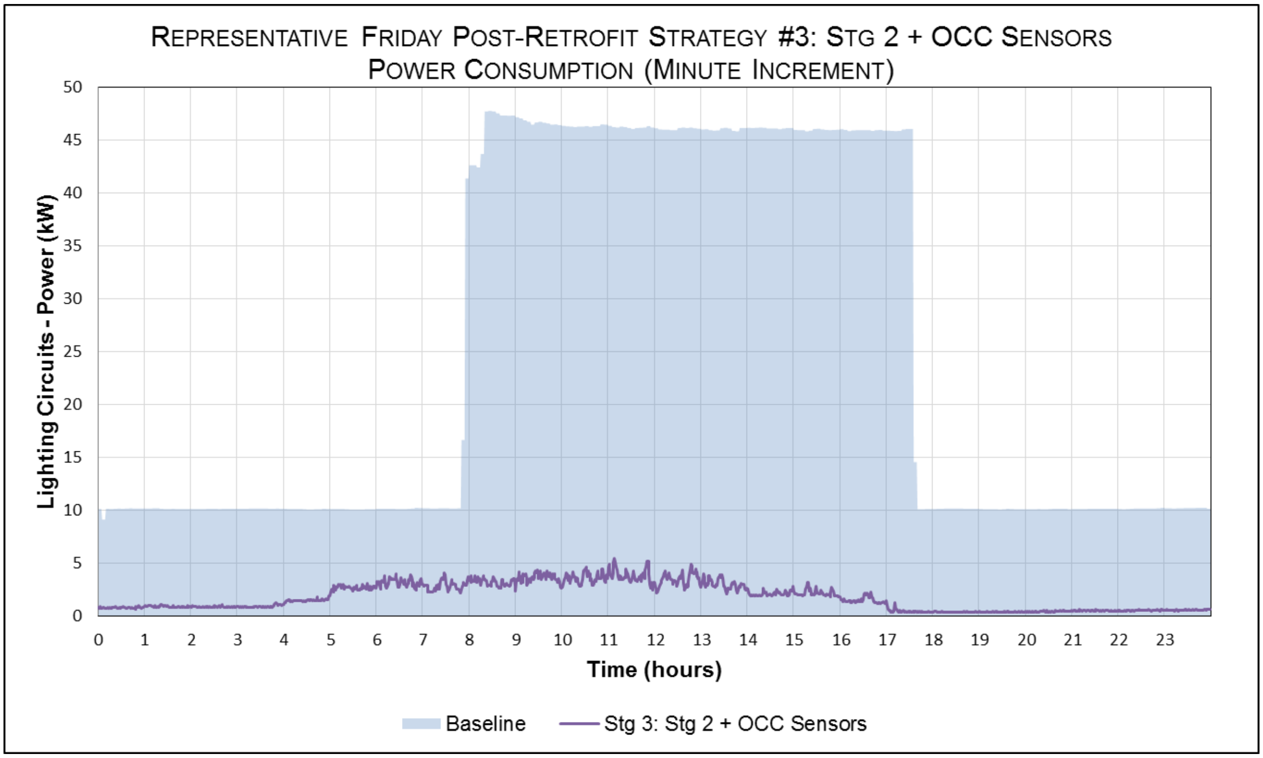

FIGURE 38. REPRESENTATIVE FRIDAY POST-RETROFIT STRATEGY #3: STG 2 + OCC SENSORS POWER CONSUMPTION (MINUTE INCREMENT)

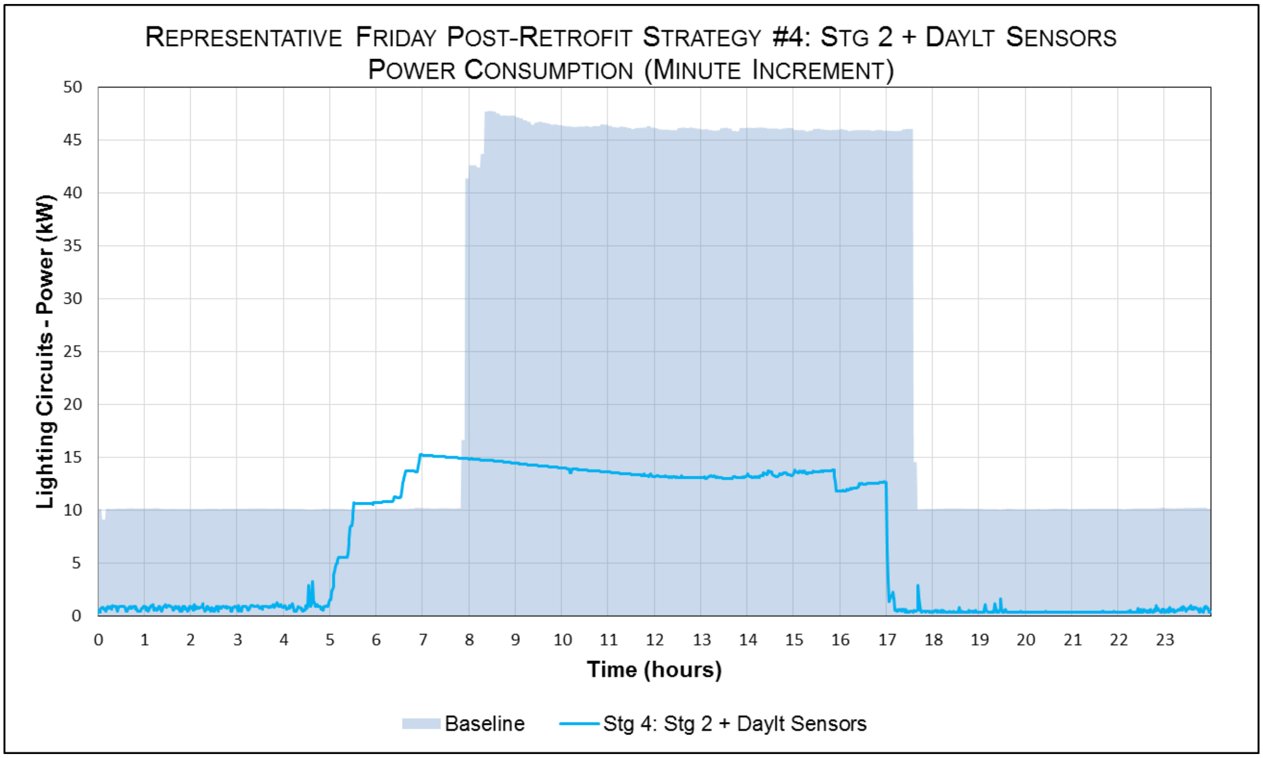

FIGURE 39. REPRESENTATIVE FRIDAY POST-RETROFIT STRATEGY #4: STG 2 + DAYLT SENSORS POWER CONSUMPTION (MINUTE INCREMENT)

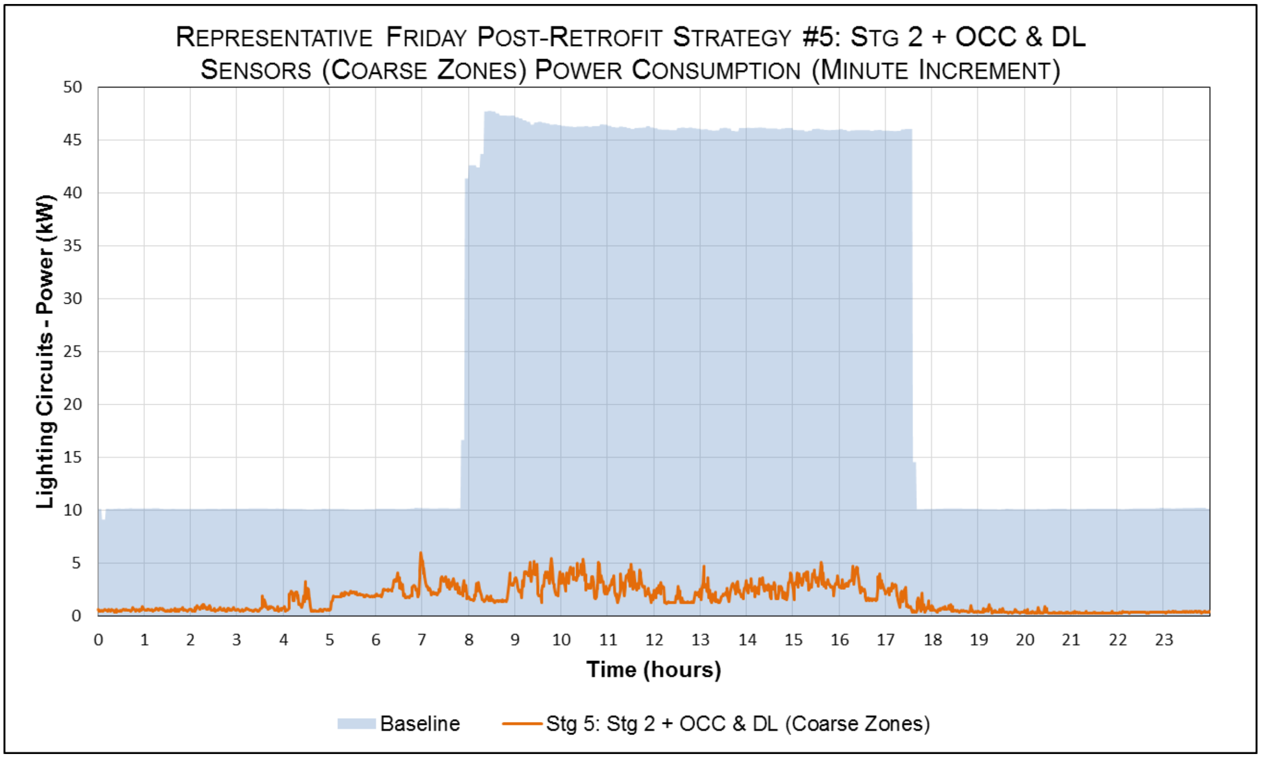

Figure 40. Representative Friday Post-Retrofit Strategy #5: Stg 2 + OCC & DL Sensors (Coarse Zones) Power Consumption (Minute Increment)

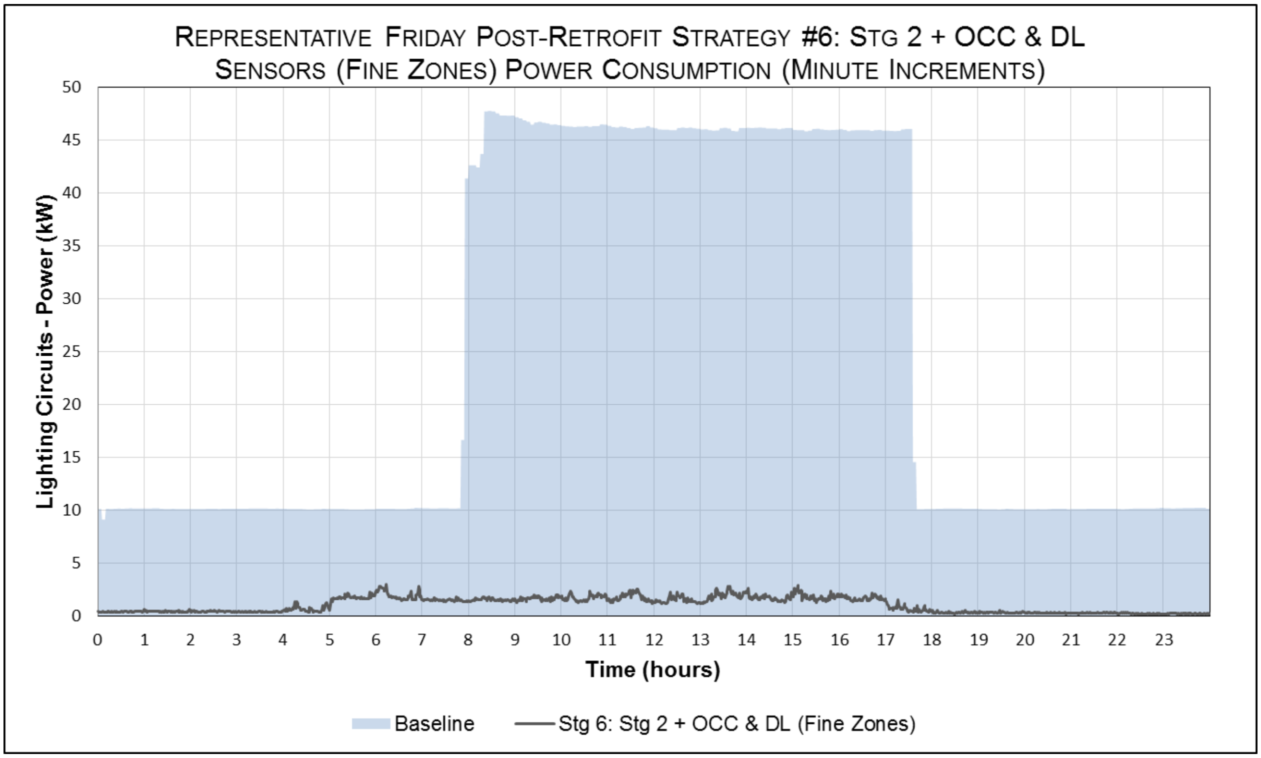

FIGURE 41. REPRESENTATIVE FRIDAY POST-RETROFIT STRATEGY #6: STG 2 + OCC & DL SENSORS (FINE ZONES) POWER CONSUMPTION (MINUTE INCREMENT)

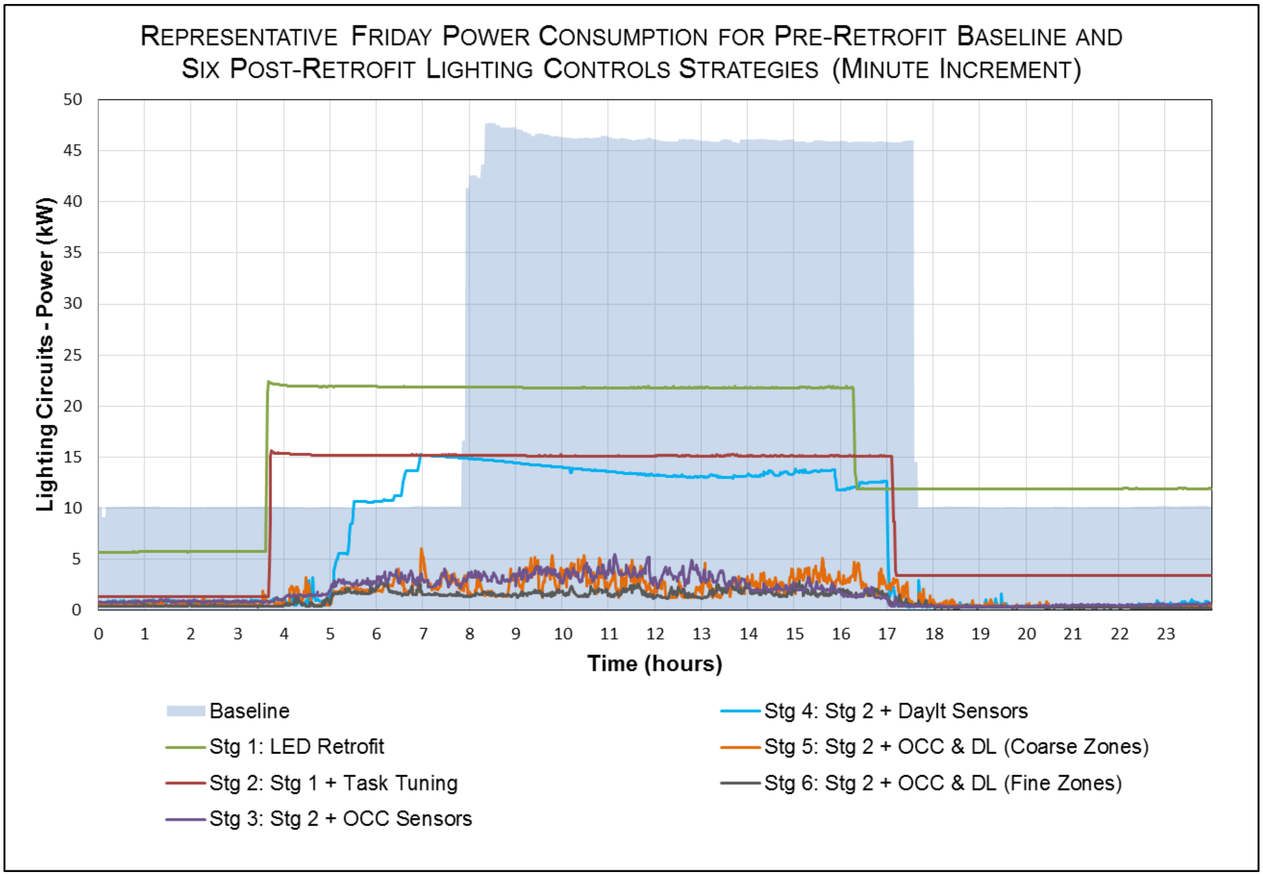

FIGURE 42. REPRESENTATIVE FRIDAY POWER CONSUMPTION FOR PRE-RETROFIT BASELINE AND SIX POST-RETROFIT LIGHTING CONTROLS STRATEGIES (MINUTE INCREMENT)

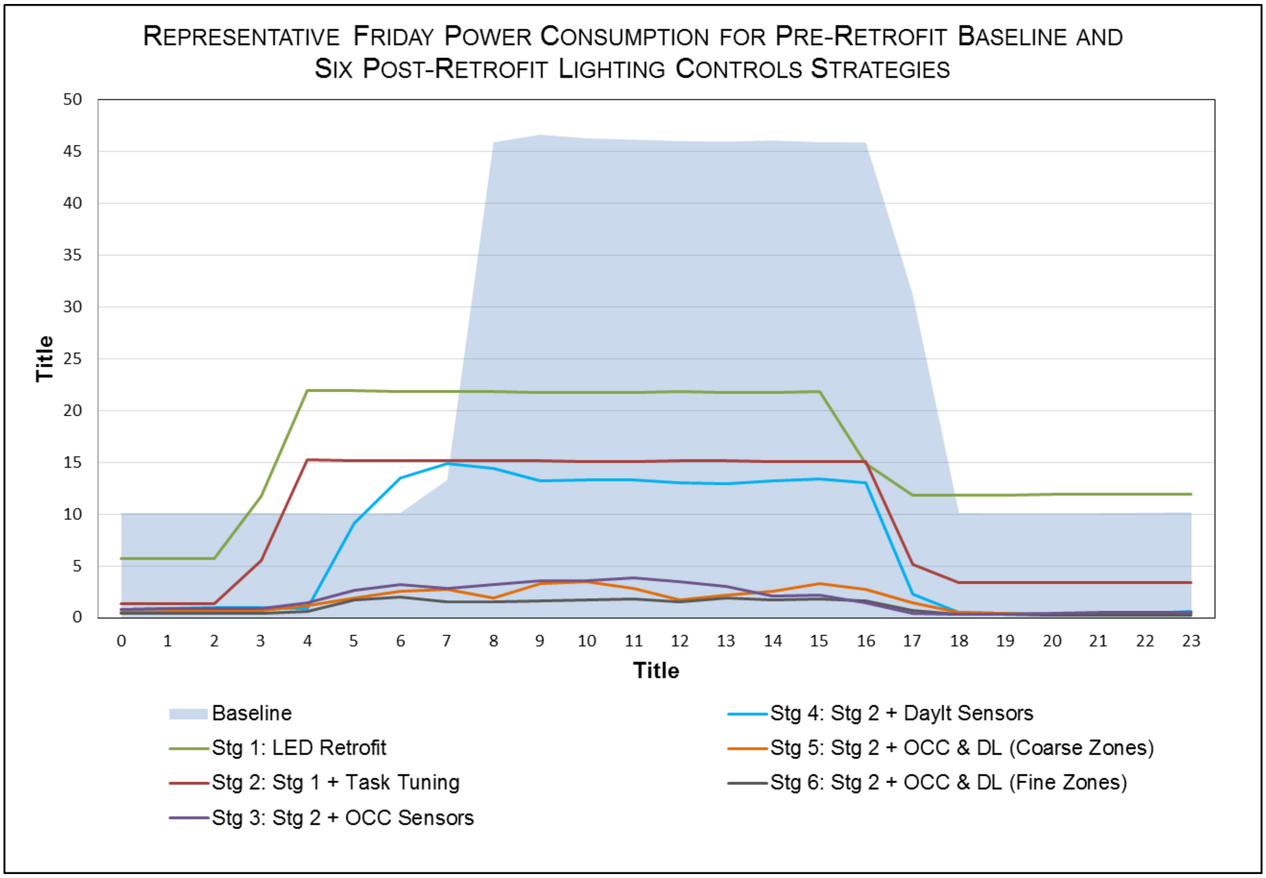

Figure 43. Representative Friday Power Consumption for Pre-Retrofit Baseline and Six Post-Retrofit Lighting Controls Strategies

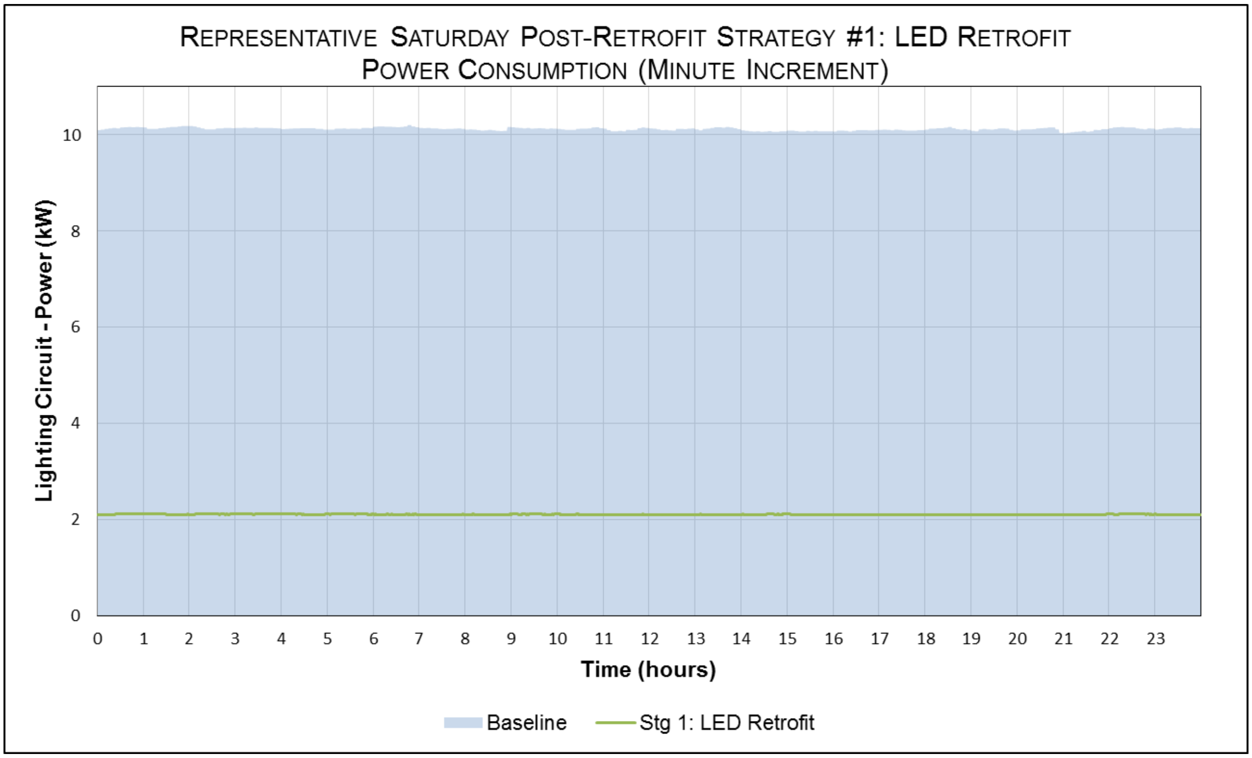

FIGURE 44. REPRESENTATIVE SATURDAY POST-RETROFIT STRATEGY #1: LED RETROFIT POWER CONSUMPTION (MINUTE INCREMENT)

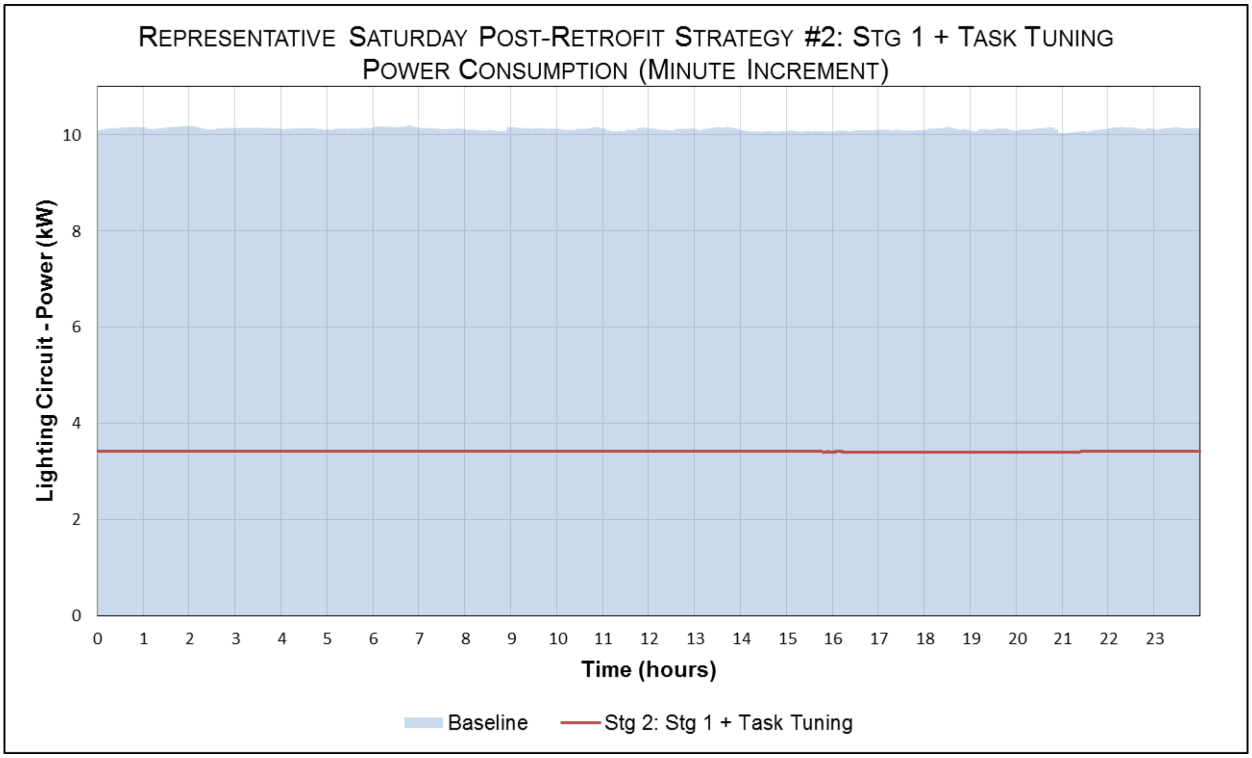

FIGURE 45. REPRESENTATIVE SATURDAY POST-RETROFIT STRATEGY #2: STG 1 + TASK TUNING POWER CONSUMPTION (MINUTE INCREMENT)

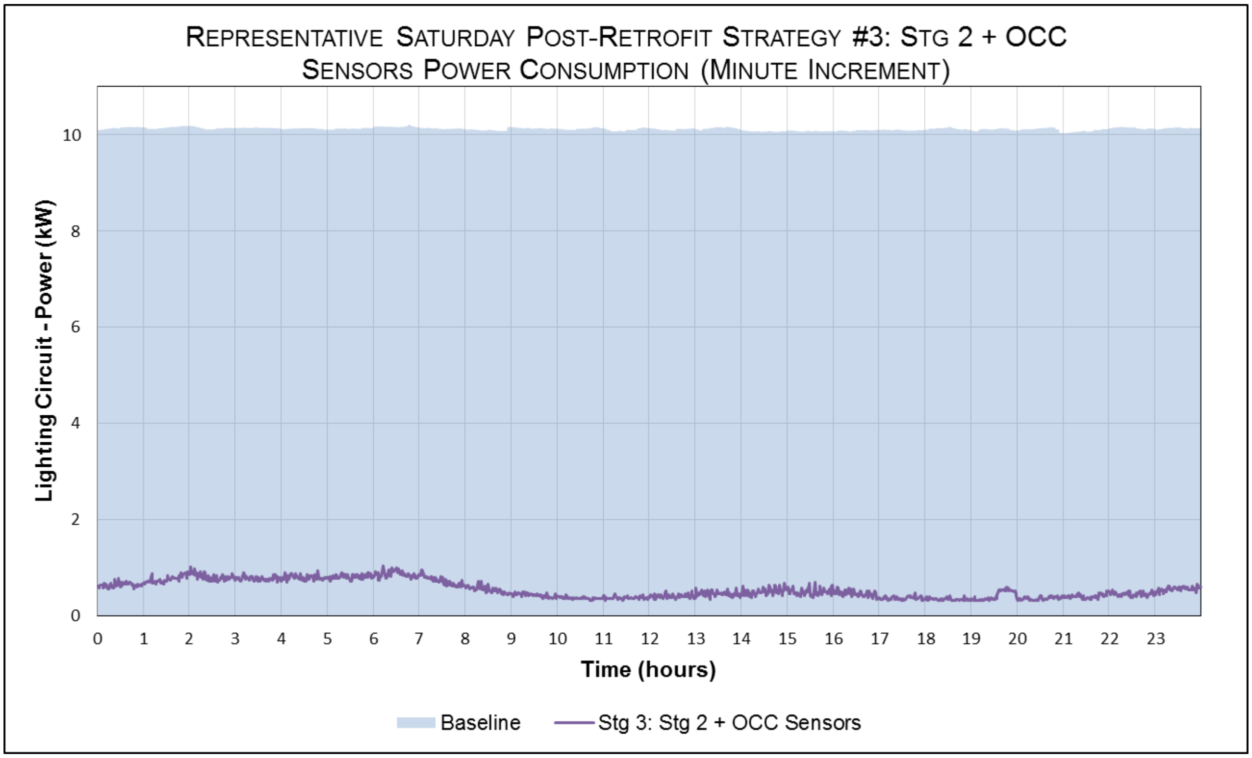

Figure 46. Representative Saturday Post-Retrofit Strategy #3: Stg 2 + OCC Sensors Power Consumption (Minute Increment)

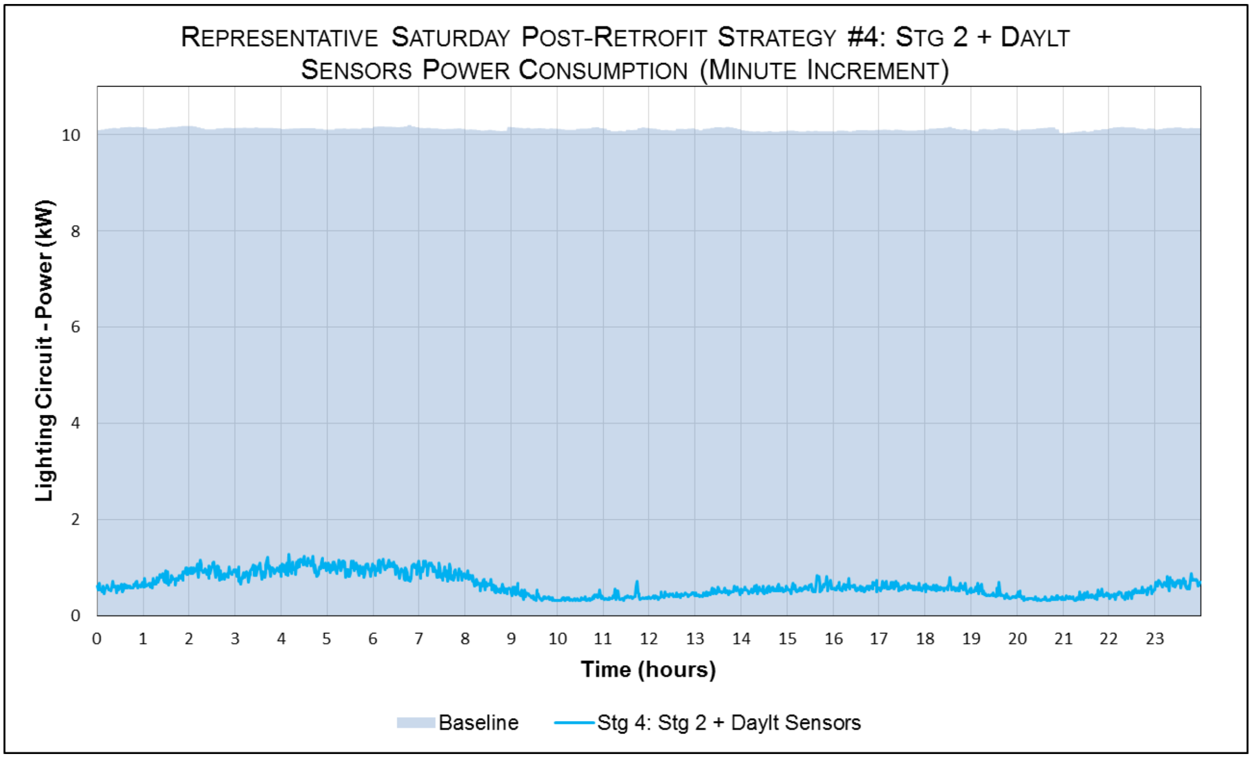

FIGURE 47. REPRESENTATIVE SATURDAY POST-RETROFIT STRATEGY #4: STG 2 + DAYLT SENSORS POWER CONSUMPTION (MINUTE INCREMENT)

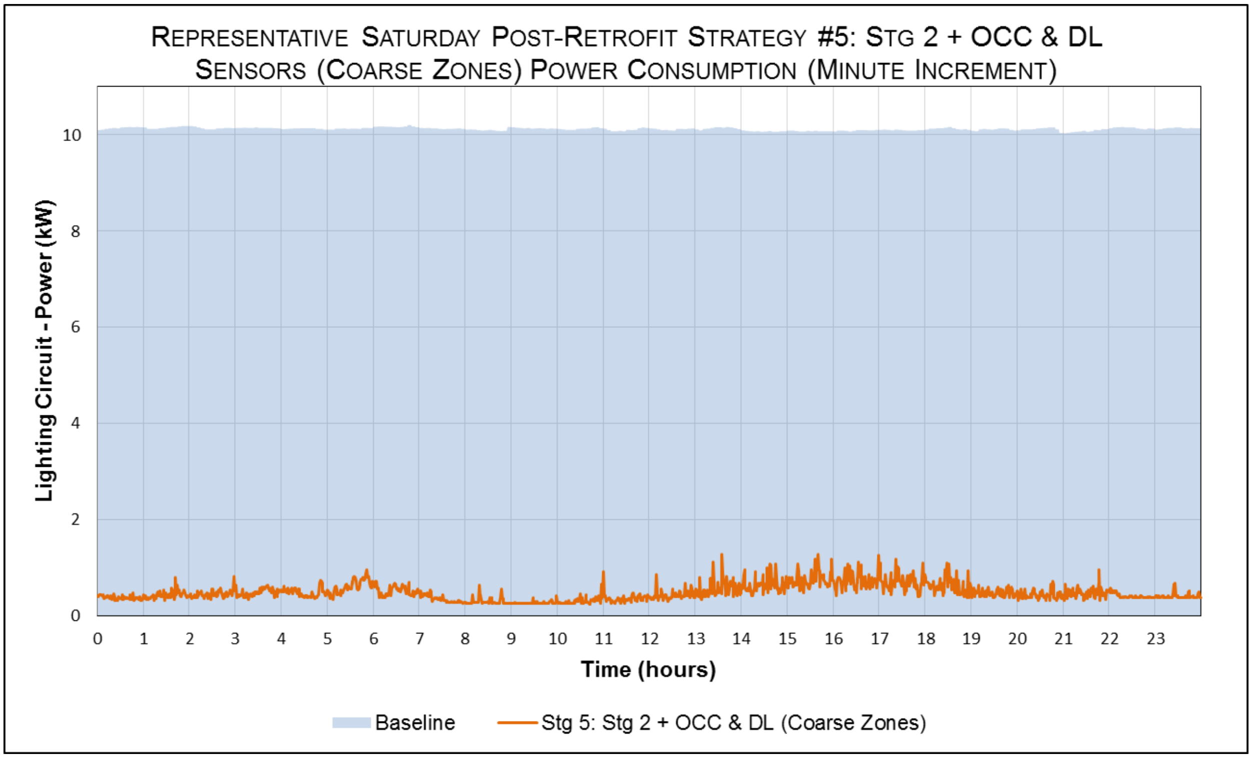

Figure 48. Representative Saturday Post-Retrofit Strategy #5: Stg 2 + OCC & DL Sensors (Coarse Zones) Power Consumption (Minute Increment)

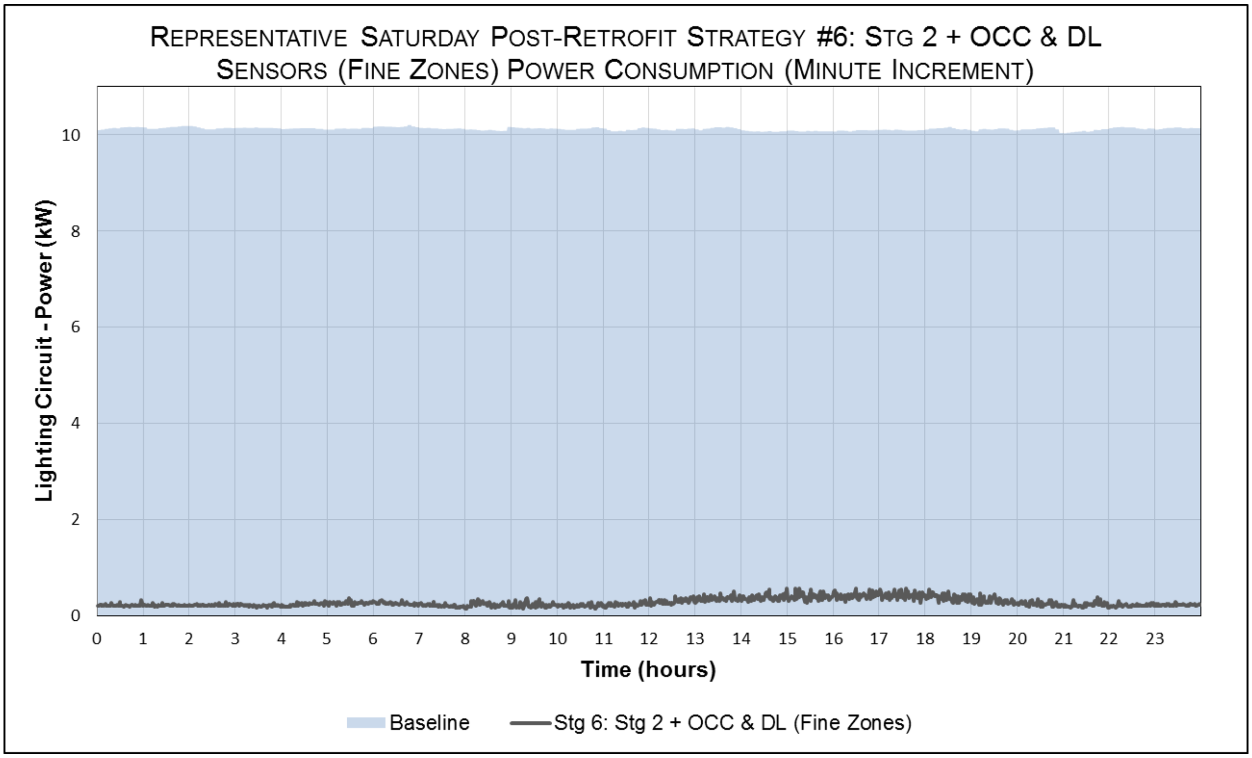

FIGURE 49. REPRESENTATIVE SATURDAY POST-RETROFIT STRATEGY #6: STG 2 + OCC & DL SENSORS (FINE ZONES) POWER CONSUMPTION (MINUTE INCREMENT)

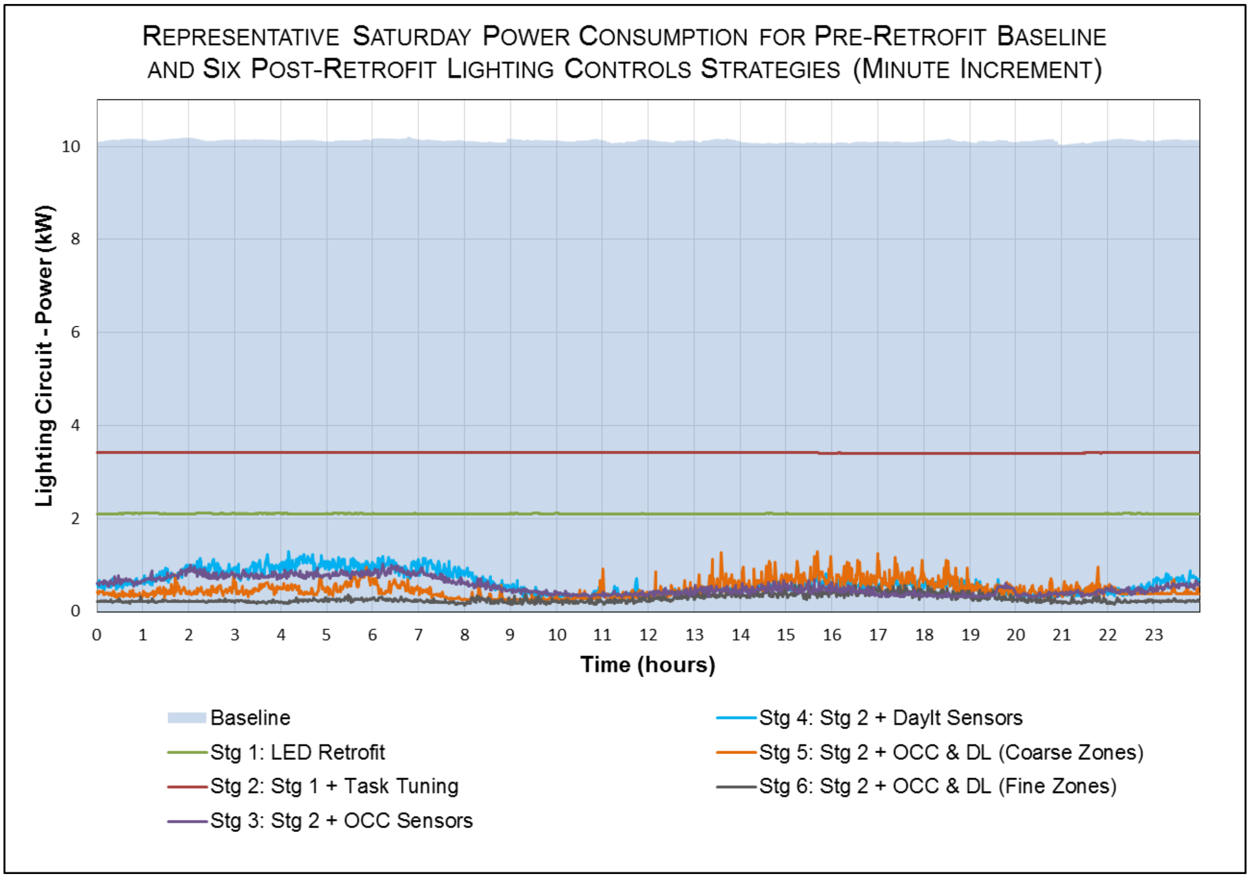

FIGURE 50. REPRESENTATIVE SATURDAY POWER CONSUMPTION FOR PRE-RETROFIT BASELINE AND SIX POST-RETROFIT LIGHTING CONTROLS STRATEGIES (MINUTE INCREMENT)

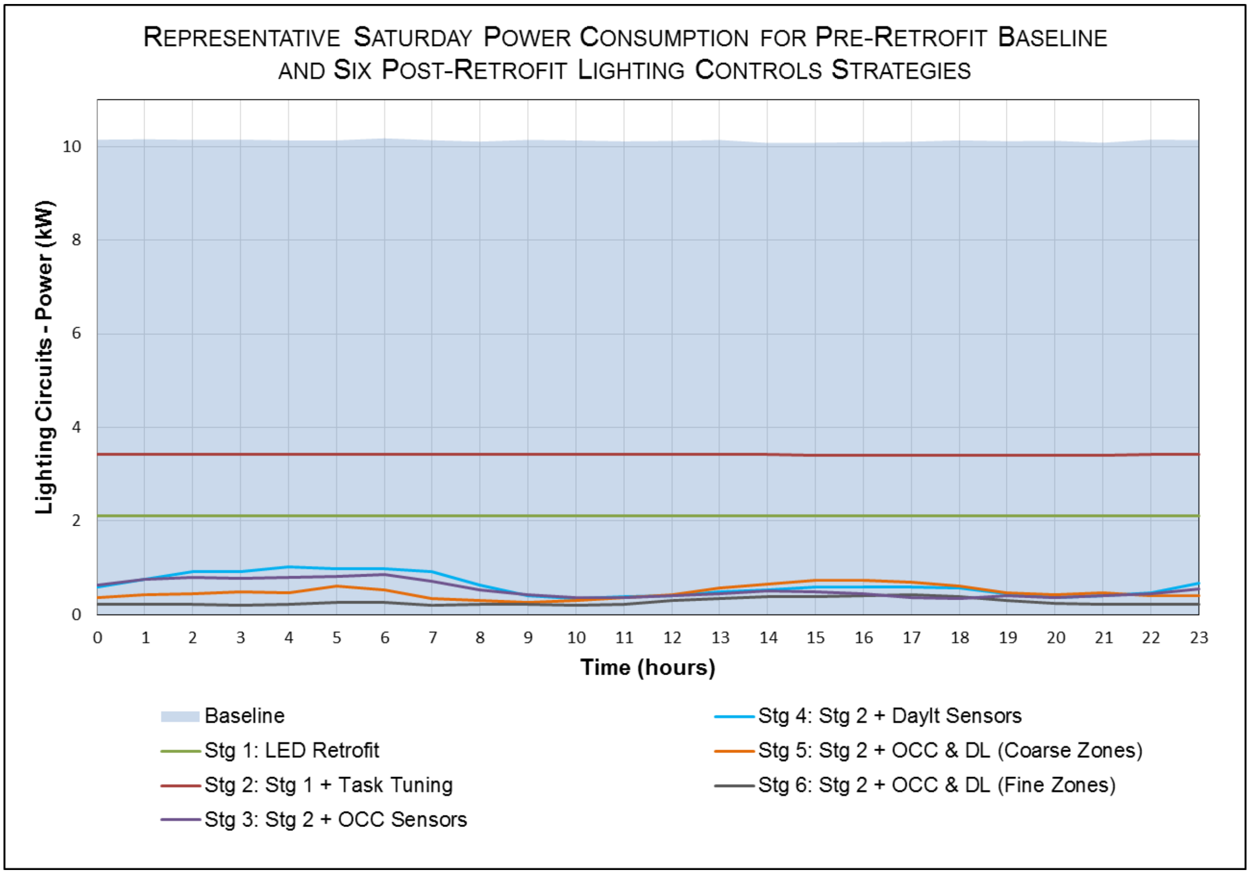

Figure 51. Representative Saturday Power Consumption for Pre-Retrofit Baseline and Six Post-Retrofit Lighting Controls Strategies