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The Brewery Parking Structure

PERFORMANCE of an LED LIGHTING SYSTEM IN A PARKING APPLICATION

Final Report

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REPORT SUMMARY

This project characterizes the energy savings possible through the use of LED lighting in a parking application, with a connected load reduction of perhaps 60 percent compared to metal halide lighting, and a further energy savings in operation of 45 percent through the use of daylighting controls and motion sensors. The simple act of adjusting motion sensor timers to keep lighting at lower levels more of the time increased system energy savings to 52 percent. Lighting quality proved good, while fixture power factor appeared lower than desirable.

The project investigated the performance of an LED area lighting system in a Milwaukee, WI parking structure. The Brewery parking structure includes eight levels of parking over about 256,800 square feet. Area lighting includes 222 pendant fixtures, and four pole-mount fixtures on the exposed rooftop. Our study included illuminance measurements within the structure, short-term power and power factor measurement, and monitoring of lighting energy consumption over a two-year period.

About 38 percent of the lighting load is under daylight control, which disables fixtures when adequate daylight is sensed. Additionally, all the fixtures except those on the rooftop allow operation at full power or reduced power of about 50 percent of full power, with full-power operation triggered by motion sensors in each fixture. Adjustable delay timers control the period for which fixtures remain at full power, and adjustment of these timers from about 8 minutes to 30 seconds after the first year of monitoring provided an opportunity to evaluate the effects of timer setting on energy use.

The nominal connected power of the LED lighting system is about 12.0 kW. We estimate the connected power to be about 40 percent of that required for a conventional metal halide lighting system. Lighting power density is 0.051 W/sq ft for enclosed areas of the structure, and 0.018 W/sq ft for the exposed rooftop, and easily complies with even IECC 2012 model code values of 0.25 W/sq ft for enclosed parking and 0.13 W/sq ft for surface parking.

In almost every case, measured illuminance values meet current recommendations for minimum horizontal illuminance and vertical illuminance, and for maximum illuminance ratios applicable to parking facilities. The one exception was a deficit in some horizontal illuminance values on the rooftop. Measured illuminance appears to generally confirm an expected trend toward higher light output at lower ambient temperatures and may show early but not quantifiable evidence of a decrease in light output over time. Measured power consumption shows a clear trend of increasing power with reduced ambient temperature.

Short-term measurements yield circuit-level power factor values generally in the range of 0.55 to 0.85, with the exception of the rooftop lighting circuit, with a power factor uniformly about 0.95. The relatively low power factor for most circuits is believed to be primarily a consequence of using a power supply (driver) optimized for higher loads, while the rooftop fixtures operate near the optimal point. Power factor increases on each circuit as the total power increases (i.e. as a greater number of fixtures operate at full power under the control of motion sensors).

Using the nominal connected load of the LED fixtures and 8,760 hours of operation per year as a base value, daylighting controls reduced energy use by 50 percent for those fixtures subject to daylight control, or 19 percent for the overall system. Motion sensor controls in combination with daylighting controls reduced overall consumption to 55 percent of the base value during the first year of monitoring. In the

second year of monitoring, after adjustment of the motion sensor timers, overall energy use was 48 percent of the base value. This additional 13 percent reduction in measured energy use (7 percent of the base value) is a significant finding of the project.

The total electrical energy consumption by the lighting system in the second year of monitoring (after motion sensor timers were adjusted) was about 50,000 kWh. This translates to an average energy use of 0.20 kWh/sq ft, and an average power draw of 0.022 W/sq ft.

INTRODUCTION

BACKGROUND AND OBJECTIVES

This project is an investigation of the performance of a lighting system in The Brewery parking structure at 1213 N. 9th Street in Milwaukee, WI.[1] The lighting system for the parking and traffic areas throughout the structure uses light emitting diode (LED) technology, and includes daylight and occupancy controls. The system is representative of advanced lighting system design, and provides a case history that may have value to designers, energy providers, and program operators. The Energy Center of Wisconsin was asked to characterize the performance of this lighting system, under cooperative funding by Focus on Energy (Wisconsin's statewide public benefits energy efficiency program) and We Energies (the major investor-owned electric utility serving southeast Wisconsin).

The original objectives of the work included:

- Characterizing the electrical energy and demand of the LED lighting system
- Characterizing lighting levels provided by the lighting system, including degradation or changes in lighting levels over the term of the project
- Estimating the impact of LED lighting technology, occupancy sensors, and daylight controls on lighting energy use of this system as compared to a conventional system in the same structure

LED LIGHTING TECHNOLOGY

For use in outdoor area lighting, LED lighting competes primarily with high pressure sodium and metal halide technologies. Test methods for LED fixtures are evolving over time, but based on currently reported results, the basic luminaire (fixture) efficacy of LEDs is roughly equivalent or slightly better than that of the competing technologies. According to U.S. Department of Energy information available in 2010, typical comparative luminaire efficacy for LED products is around 67 lumens/watt, as compared to 61 for high pressure sodium, and 58 for metal halide.[2] LED technology also has significant advantages in terms of light distribution. While a typical high pressure sodium or metal halide fixture has a single light source, the equivalent LED fixture has many individual diodes (often 20 or more). These multiple sources can be arranged to provide light distribution that more precisely meets the intent of the fixture

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[1] The site is part of the former Pabst brewery property, which is undergoing redevelopment.
[2] www1.eere.energy.gov/buildings/ssl. The website information has been changed as of the time of our final report.

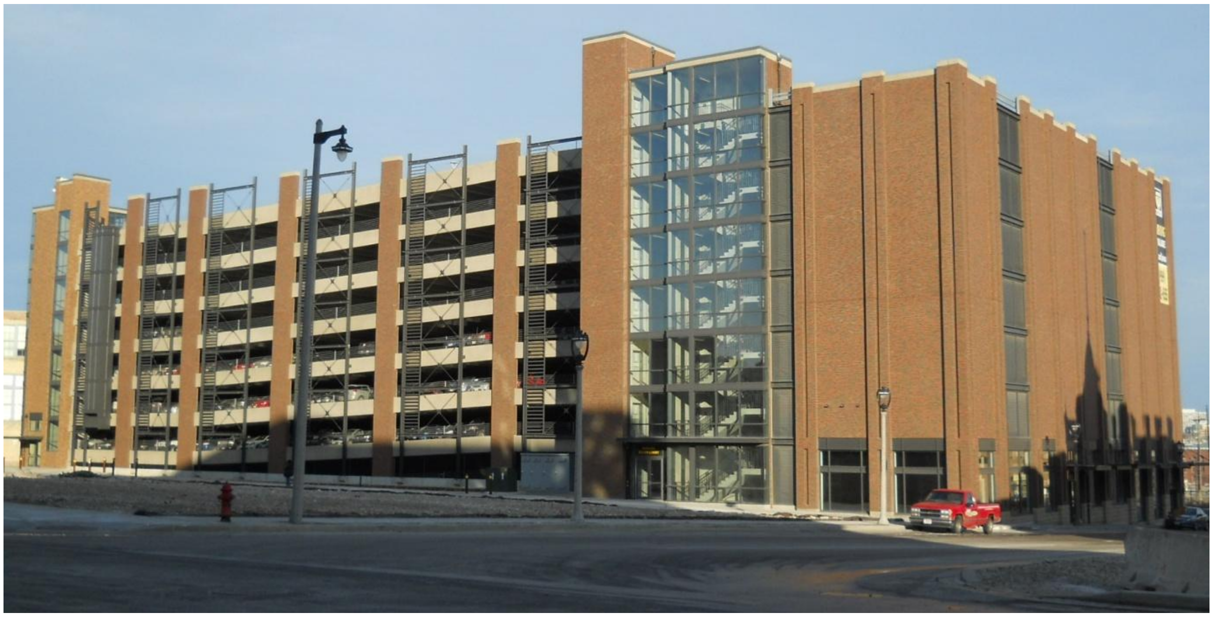
designer, including better uniformity over a given area. LED fixtures have an additional reliability advantage; because they typically use multiple parallel circuits, a failure of any single diode or circuit does not completely disable the fixture.

The efficacy of LED technology is temperature dependent, with lower lumen output at higher operating temperatures of the LED diode junction. For this and other reasons, the light output of LED fixtures under normal operating conditions may vary from manufacturers' specifications. The lumen depreciation (aging effect, or reduction in light output over time) of LED lamps can be significant, and is also dependent on operating temperature and thus on fixture heat removal design and operating environment. With well-designed heat removal, however, the lumen depreciation of LEDs appears to be less than that of typical metal halide fixtures.[3]

THE PROJECT

The Brewery parking structure is a reinforced concrete above-grade structure with 8 levels of parking and about 885 stalls (see Figure 1). The structure has an overall footprint size of about 292 x 122 feet, and includes some retail commercial space on lower levels in addition to parking. The surface area dedicated to parking spaces and driving lanes is about 256,800 square feet.

Figure 1. The Brewery parking structure



The structure was built in 2009, and the LED system we studied is the original lighting system. The lighting system for the parking areas in the structure includes 222 pendant (suspended) LED fixtures, used in the interior or enclosed areas of the structure where they are typically hung at about 8 feet above the surface, and 4 pole-mounted fixtures, used on the exposed top level or rooftop (see Figure 2 and Figure

[3] ibid

3).[4] The pendant fixtures have dual power supplies which allow operation at full power or at a reduced power of about 50 percent of full power (350 and 175mA drive current respectively). Nominal full-power ratings are 50 W for the two-row pendant fixtures used in most locations, 78 W for the three-row fixtures used at the entry to the facility, and 150 W for the pole-mount rooftop fixtures. All the LED fixtures are designed for 120 to 277 VAC operation and are wired at 277 VAC. The fixtures were manufactured by Beta LED (now part of Cree, Inc.).

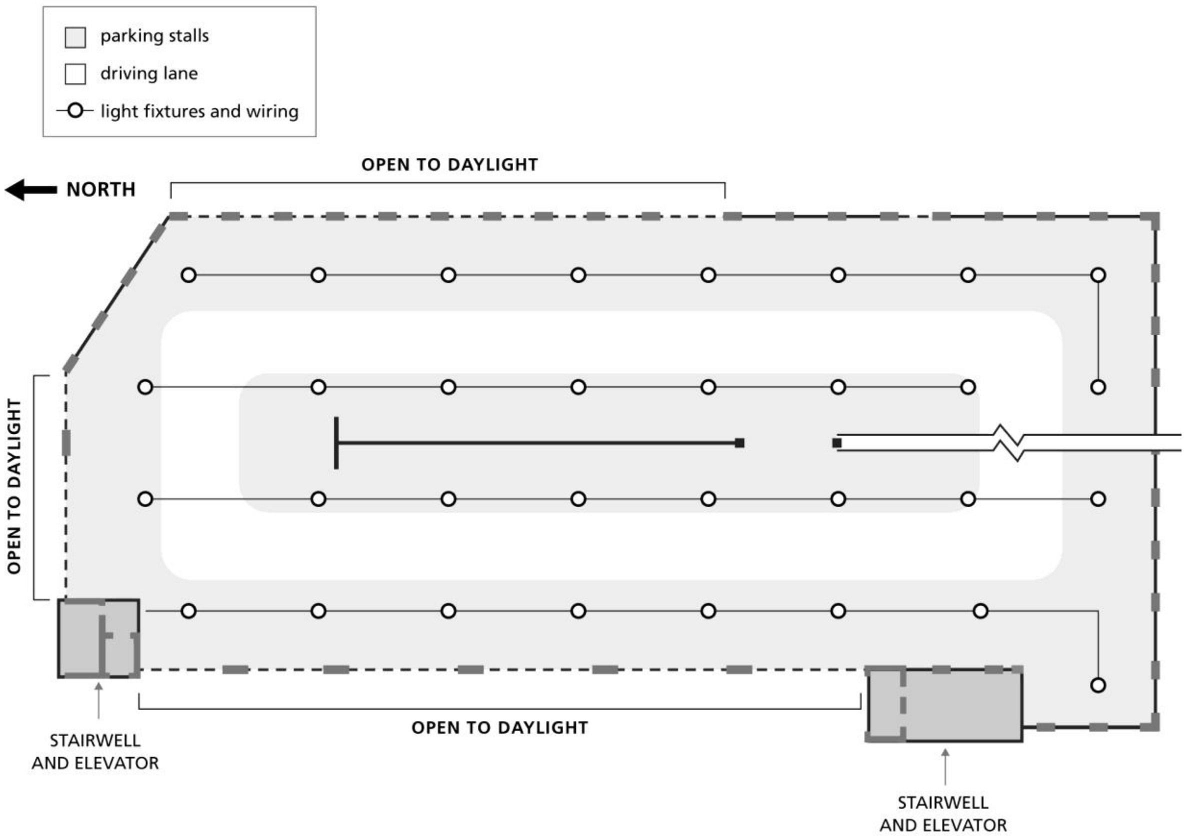
Figure 2. Pole-mount fixtures

Figure 3. Pendant fixture

The lighting system is controlled by a combination of a daylight sensing controllers and motion sensors. Fixtures on daylight control are disabled completely when adequate daylight is sensed. These fixtures are generally in rows along the outer perimeter of the structure and adjacent to openings that admit ambient light (see Figure 4). A single controller, with a sensor mounted high on the north wall of the structure, manages all daylight-controlled fixtures except the rooftop pole-mount fixtures.

[4] We use the terms "interior" or "enclosed" to mean all areas with a floor above, i.e. all areas except the exposed top level ("rooftop").

Figure 4. Typical upper level floor plan of The Brewery parking structure, showing light fixture arrangement and open sections along building perimeter.



Fixtures on the inner row (and away from exterior openings) are always powered. All fixtures except those on the rooftop operate at the lower power level until the motion sensor is activated. (Motion sensors are installed in and control each fixture individually.) When a car or person triggers a motion sensor, the fixture is switched to full power. A delay timer in each fixture controls the time spent at high output once no further motion is detected. These timers are adjustable from about 30 seconds to 30 minutes. The delay settings for the fixtures were initially set to at least 8 minutes in most cases, and to 15 minutes or longer in many cases. The facility owners reset all fixtures to their minimum delay setting on March 16, 2011. This change provides the basis for a before-and-after evaluation of the effects of timer delay on energy consumption.

The four rooftop fixtures are connected to a daylight control device that operates independently of other fixtures in the structure. The rooftop fixtures don't have motion sensors, and operate at full power or not at all.

Table 1 summarizes the nominal loads on the circuits comprising the parking area lighting system. Note that many circuits include a mix of fixtures in which only some are daylight-controlled. See Appendix A for more information on the lighting circuits and areas served by each circuit.

Table 1. Number of fixtures and nominal connected power of LED area lighting circuits monitored in this project.

Circuit identifier used in this report	Number of LED parking area lighting fixtures	Nominal connected power (kW)		
		Daylight controlled	Not daylight controlled	Other fixtures[a]
CIRC01	6	0.300	0.000	0.000
CIRC02	15	0.600	0.150	0.288
CIRC03	18	0.600	0.300	0.000
CIRC05	10	0.300	0.200	0.000
CIRC06	18	0.450	0.450	0.000
CIRC07	18	0.600	0.300	0.000
CIRC08	22	0.650	0.450	0.000
CIRC09	8	0.000	0.428	0.000
CIRC10	14	0.000	0.700	0.141
CIRC11	14	0.000	0.700	0.012
CIRC12	19	0.462	0.740	0.060
CIRC13	16	0.000	0.800	0.012
CIRC14	14	0.000	0.700	0.012
CIRC15	14	0.000	0.700	0.012
CIRC16[b]	4	0.600	0.000	0.000
CIRC17	16	0.000	0.800	0.015
Total	226	4.562	7.418	0.552

[a] "Other fixtures" refers to fixtures not part of the area lighting system.
[b] CIRC16 lighting consists of 4 pole-mount fixtures on the exposed rooftop level of the structure. All other LED parking area fixtures are pendant-mount.

The total nominal connected power of the relevant circuits is 12.53 kW, of which 11.98 kW represents LED area lighting for the parking area. The remaining 0.55 kW on these circuits is made up of other lighting loads that are not part of the LED area lighting system, including a number of exit fixtures and lighting in a circulation hallway, a storage closet, and at an exterior doorway. Using the manufacturer's ratings for the LED fixtures, the average lighting power density for the enclosed portions of the structure (i.e. not including the rooftop) is 0.051 W/sq. ft. For the open rooftop area (using pole-mount fixtures), the density is 0.018 W/sq. ft. These values easily comply with recent energy conservation standards (see Table 2). Starting with the 2009 edition, the International Energy Conservation Code defines four zones related to population density (rural to increasingly urban). We used Zone 4 (the most urban) for this comparison, based on the urban location of the parking structure, but the system as installed complies with even the more stringent requirements for other zones.

Table 2. Lighting power density of system as installed, based on nominal connected power. Recent energy standards requirements *(in shaded cells)* included for comparison.

Standard or system	**Parking Garages** Maximum allowed lighting power density, W/sq. ft.	**Surface Parking Areas** Maximum allowed lighting power density, W/sq. ft.
The Brewery parking area lighting system as installed	0.051	0.018
IECC 2006[5]	*0.30*	*0.15*
ASHRAE 90.1-2007[6]	*0.30*	*0.15*
IECC 2009[7]	*0.30*	*0.13*
IECC 2012[8]	*0.30*	*0.13*
ASHRAE 90.1-2010[9]	*0.25*	*0.13*

The project is not a retrofit, and direct measurement of a comparative system was not possible. Design comparisons of the connected load of alternative systems depend on a number of design inputs and performance factors (illuminance levels, uniformity ratios, lamp efficacy, fixture performance, lumen maintenance, etc.) and the connected power of a design will vary with the inputs used. Given this caveat, documentation submitted as part of an energy rebate application for The Brewery project estimated that the system as designed would reduce the connected load to about 34 percent of the load required for a pulse-start metal halide lighting alternative, i.e. a 66 percent savings.[10] In a recently documented retrofit project, replacement of metal halide fixtures with LED fixtures in a parking garage reduced connected load to 48 percent of the original value.[11] (The replacement of fixtures on a one-for-one basis, however, means the LED system was likely not optimized.) We believe that a reasonable estimate of the connected load reduction for the system considered here as compared to a metal halide-based alternative is 60 percent. Note that this value represents the reduction in connected load only, and that the fact that the operating power of LED lighting can be changed relatively rapidly and frequently means that additional savings through motion sensor controls are readily available in LED systems.

APPROACH

Our approach to meeting the project objectives included: a) making periodic, manual on-site measurements of lighting levels, b) monitoring the real electric energy consumption of the lighting system over time, and c) short-term on-site measurement of power and power factor. We also worked with the

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[5] *2006 International Energy Conservation Code* (Country Club Hills, IL: International Code Council, 2006).
[6] *ASHRAE 90.1-2007 Energy Standard for Building Except Low-Rise Residential Buildings* (Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2007.)
[7] IECC 2009
[8] IECC 2012
[9] *ASHRAE 90.1-2010 Energy Standard for Building Except Low-Rise Residential Buildings* (Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2010.)
[10] 2009 Focus on Energy incentive application
[11] Use of Occupancy Sensors in LED Parking Lot and Garage Applications: Early Experiences U.S. Department of Energy October 2012

managers of the parking facility to obtain records of traffic (entries and exits) at the facility, making possible a more complete evaluation of energy usage as it varies with traffic levels.

We monitored the energy consumed for lighting on 17 circuits in the facility using true power meters connected to a central data acquisition system, with a dedicated phone line for periodic transmission of data to Energy Center offices. Data was recorded at 15-minute intervals. Additional details concerning monitoring equipment used can be found in Appendix B.

We collected data from March 29, 2010 into June of 2012, and used data from April 1, 2010 through March 31, 2012 as the primary data set for our analysis. This provides very nearly one year of data before and one year after adjustment of the motion sensor timers in March, 2011, and thus captures seasonal effects for both years of the study.

We experienced several failures in data collection. In two cases, the dedicated phone line we used for data transmission failed, and about two days of data was lost before repairs were made. In three other cases, wiring connections to our power meters in the electrical distribution panels failed partially or fully, resulting in data loss on specific circuits. Data not available for analysis includes:

- CIRC04 does not include any parking area lighting, and is excluded entirely.
- CIRC06 data is unavailable for the second year of the study. CIRC06 operation is assumed similar to an average of nearby circuits for purposes of estimating the total energy consumption of the lighting system in the second year.
- CIRC07 and 08 data is incomplete for the first year of the study. Data for these circuits is excluded from analysis of total energy use, but is included in bin analysis of energy under varying traffic conditions.
- CIRC06, 07, and 08 are excluded from comparison of average power draw between the two years of the study, since each is incomplete for one year of the study.

Our staff made at least seven visits to the project site during the course of the study. In addition to installation of the monitoring system, work performed during these visits included:

- Illuminance measurements
- “Mapping” to correlate each light fixture with a particular circuit and monitoring channel, and to identify all other loads connected through the monitored circuits
- Short-term measurement of power draw and power factor
- Measurement of the as-built dimensions of the structure

METHODS AND RESULTS

OBSERVED ILLUMINANCE LEVELS

We performed spot illuminance measurements six times during the course of the project. We established a grid in several areas of the parking structure, and marked each measurement location to allow repeated measurements at these locations (see Table 3). The grids on Level 1 and 7 included rows of measurement points under fixtures, halfway between adjacent fixtures, and on lines halfway between rows of fixtures.

Wherever a structural wall or screen at least 5 feet high existed at the end of a measurement row, we added a vertical-surface illuminance measurement at that point.

Table 3. Locations of illuminance measurements performed at The Brewery parking structure.

Level in structure	Description	LED fixture type	Number of horizontal surface measurement locations	Number of vertical surface measurement locations
8	Roof top, exposed to sky	Pole-mount	17	1
7	Uppermost covered level of parking	Pendant	15	5
1	Near-lowest level of parking; maximum traffic flow	Pendant	15	9

Illuminance measurements were made using an Extech light level meter provided by Focus on Energy. We intentionally triggered the motion sensors of nearby fixtures during each measurement, thus capturing illuminance at full power levels. (On one occasion, we used tape to disable the motion sensors and made readings at the lower lighting levels, but have not included this data in our reporting.) We believe caution is warranted in interpreting the results of our illuminance data because the measurement equipment used was not subject to calibration during the course of the project, and because the 0.1 footcandle resolution of the meter is a limitation, especially in measuring the lowest observed illuminance levels.

Illuminance measurements were made on the following dates:

3 June 2010
17 August 2010
21 December 2010
14 March 2011
11 April 2011
15 November 2012

Measured illuminance values as of the final measurement date are summarized in Table 4. The final date was selected as representing the worst case (the lowest overall average illuminance was observed on this date). The table reflects all measurements considered valid (individual measurements were judged invalid if clearly influenced by the presence of a parked car over or near the measurement point, or by snow cover around the measurement location). With only a couple of exceptions, both the average and minimum illuminance values measured on all other measurement dates were equal to or higher than those measured on this last date.

Table 4. Summary of measured illuminance values, based on final measurements made on 15 November 2012. IESNA recommended values included for comparison.

	Parking Level 1: covered parking, pendant fixtures (footcandles)	**Parking Level 7: covered parking, pendant fixtures (footcandles)**	**Parking Level 8: exposed rooftop, pole-mounted fixtures (footcandles)**
Average of all measured horizontal illuminance values	4.4	3.7	1.0
Minimum of all measured horizontal illuminance values	2.0	1.3	0.1[a]
Ratio of maximum to minimum measured horizontal value	3.1	4.5	10.7
IESNA recommended minimum horizontal illuminance[12]	*1.0*	*1.0*	*0.5*
IESNA recommended maximum horizontal uniformity ratio	*10*	*10*	*15*
Average of all measured vertical illuminance values	1.3	1.2	0.4
Minimum of all measured vertical illuminance values	0.8	0.6	0.3
IESNA recommended minimum vertical illuminance	*0.5*	*0.5*	*0.25*

[a] Only a single value was registered at 0.1 footcandle; values of less than the 0.5 footcandle design standard were observed on one or more measurement dates at 4 of 18 measurement locations on the rooftop.

Our illuminance measurements indicate substantial compliance with the relevant standards. A small number of observations fall below the minimum recommended horizontal illuminance values, and only in the case of lighting on the exposed upper level of the structure. The uniformity of illuminance easily complies with the recommended ratios.

Figure 5 presents the illuminance averaged across 44 locations at which we were able to obtain valid measurements on each of five dates.[13] These average values appear to show the expected inverse relationship between ambient temperature and light output[14] combined with a downward trend over the

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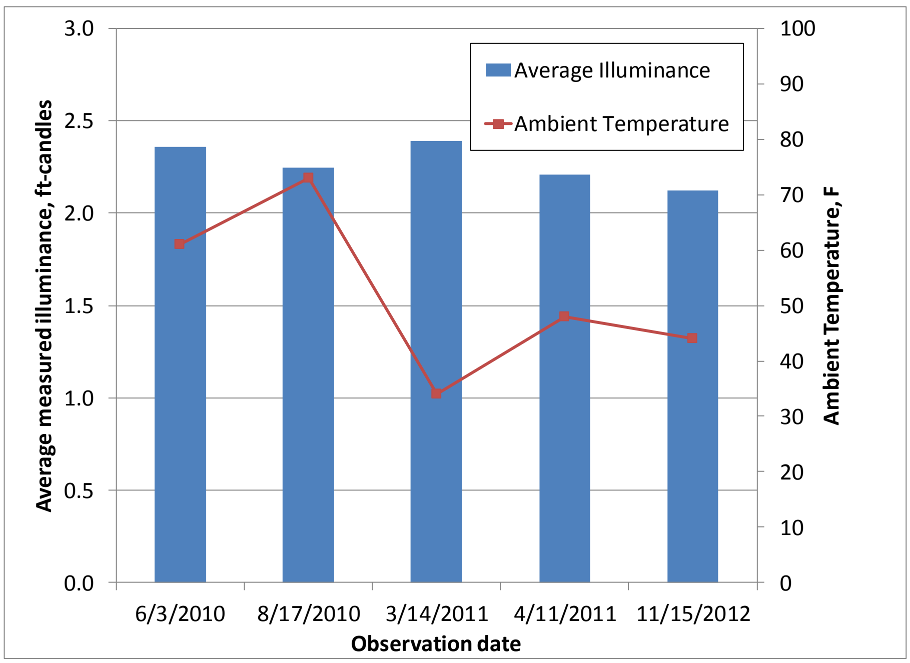
[12] *IESNA Lighting Handbook*, 9th edition, ed. M. Rea (New York: Illuminating Engineering Society of North America).

[13] One measurement date, December 21, 2010, is excluded from this analysis because snow cover affected a large number of measurement points

[14] According to the manufacturer, light output should increase 0.25% per degree C temperature drop. We calculated this ratio for each consecutive pair of measurements. The first three ratios are 0.40, 0.17, and 0.56% per degree C in the expected direction (illuminance increased as temperature decreased), roughly approximating the manufacturer's value. The last ratio is .95% with the opposite sign, suggesting that other phenomena are at work.

period of the study, suggesting reduced lumen output. Illuminance, however, can also be influenced by the accumulation of dirt (e.g. particulate matter from vehicle exhaust) on fixture lenses, and by aging of reflective surfaces in the lighting zone, both of which would reduce measured illuminance. Manufacturer's data suggests a maximum expected degradation of lumen output of about 3 percent, based on pro-rating values for lumen output under continuous full power operation and an average operating temperature of 50 F.[15] Since the fixtures in this structure operate at average power levels far below full power, we would expect the actual output degradation to be less that this value. Given the limitations of our measurement methods, and other factors that may influence illuminance, we are not attempting to quantify lumen depreciation.

Figure 5. Average illuminance and ambient temperature on five measurement dates. These values appear to show the expected inverse relationship of temperature with light output, as well as a decrease in measured illuminance over the period of the measurements.



OBSERVED POWER AND POWER FACTOR

The maximum recorded hourly average power, represented as a fraction of nominal connected load, is shown for each monitored circuit in Table 5.[16] The table also shows the date and time at which this maximum occurred, and the temperature in the structure at that time. Not surprisingly, the times of maximum power consumption for most circuits, and for the system as a whole, fall within morning or evening peak traffic periods, or later in the evening when event traffic is likely at a peak. All maxima also fall in winter months. This is probably due in part to the fact that more fixtures are likely to be operating

[15] Cree Lighting Report TR-13, Recommended Cree Outdoor Luminaire Lumen Maintenance Factors.

[16] For these measured-to-connected load ratios, we included non-LED loads on each circuit based on an evaluation of whether they typically operate at the time of the peak loads.

during peak traffic hours during the winter (when daylight hours are shorter), and possibly in part due to higher typical traffic levels in the facility in winter months.

Ambient temperature is also a likely factor in the timing of maximum power, as well as helping explain the observation that the maximum power exceeds rated power for most circuits. Using data for the rooftop fixture circuit (since that circuit provides data consistently at full-power operation), we estimate the relationship of power with temperature to be -.083%/F, or a .083% increase in power per degree F reduction in temperature from a 77 F base. Applying this slope to nominal rated power, the expected power draw at 15 F is 5 percent higher than at 77 F. We suspect the remaining difference between nominal rated power and maximum observed power is related to variance in actual fixture performance compared to rated values, and perhaps the effects of power quality. We found the minimum power observed on each circuit to be consistent with the expected minimum load.

Table 5. Maximum observed hourly average power observed during two-year monitoring period, by circuit. Power draw is represented as a ratio to nominal connected load for each circuit.

Circuit	Ratio of maximum observed 1-hour average power draw to nominal connected power	Date & time of maximum observed power draw	Ambient temperature at time of maximum observed power draw
CIRC01	1.11	2/9/2011 17:00	16
CIRC02	1.02	12/6/2010 21:00	24
CIRC03	1.06	2/9/2011 18:00	15
CIRC05	1.10	2/8/2011 17:00	17
CIRC06	1.13	1/7/2011 17:00	21
CIRC07	1.03	[a]	
CIRC08	1.07	[a]	
CIRC09	1.11	1/21/2011 8:00	4
CIRC10	0.96	1/20/2011 22:00	13
CIRC11	1.13	2/9/2011 9:00	10
CIRC12	1.11	2/1/2011 17:00	24
CIRC13	1.15	2/9/2011 7:00	10
CIRC14	1.11	2/9/2011 12:00	13
CIRC15	1.15	2/9/2011 18:00	15
CIRC16	0.99	1/21/2011 6:00	4
CIRC17	1.12	2/9/2011 17:00	16
Overall system	0.99 [b]	12/6/2010 19:00	24

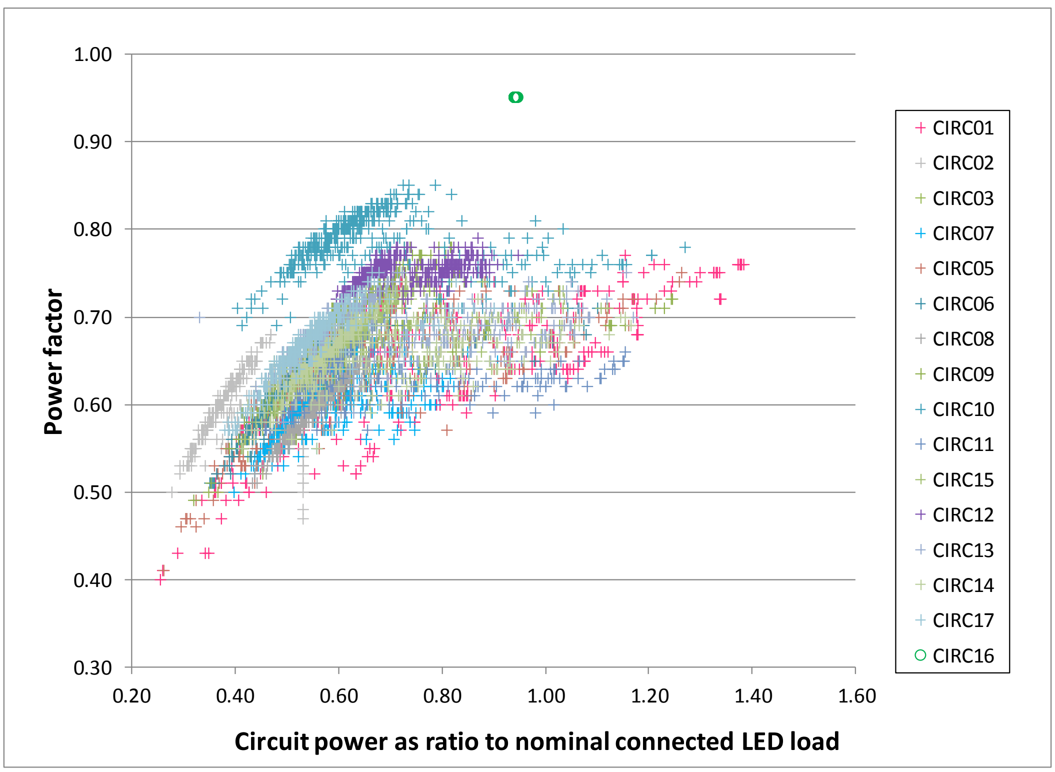
[a] These circuits experienced significant data loss during the first year of monitoring, and the date and time of the maximum observations may not represent true peak times and are excluded. The value of the peak loads may also be biased low for the same reason.
[b] This ratio excludes Circuits 7 and 8; data for these circuits was missing at the time of the peak observation.

In addition to long-term monitoring of lighting energy consumption, we performed short-term monitoring of each circuit during site visits. These measurements included power consumption and power factor made using a Dent ElitePRO power metering system, and using Continental Controls "AccuCT" current transformers. While monitoring on November 15 2012, we drove and walked near the fixtures on circuits being measured, to assure that we would collect power factor data with a significant number of fixtures operating at their full power level.

With the exception of the rooftop lighting circuit, power factor measured in this testing typically ranges between 0.55 and 0.75 (see Figure 6), and are consistent with manufacturer's test results for similar fixtures.[17] The visible relationship between power and power factor at the circuit level confirms that the high power (high output) operating mode for individual fixtures corresponds to a higher power factor.

The relatively low observed power factor is a consequence of using power supplies in these fixtures that operate below an optimal output power. The rooftop lighting circuit (CIRC 16), in contrast, exhibits stable power consumption (since they don't use motion sensors) and a power factor of about 0.95. In this case, the same power supply is being used at more optimal conditions.

Figure 6. Measured power factor for individual circuits, as related to fraction of nominal connected load. Based on 3-second data collected Nov 15, 2012. Higher power on any circuit is a function of the number of fixtures triggered by the motion sensor to operate at full power. CIRC16, the rooftop lighting (shown with a circular symbol), is unique in operating at a consistently high power factor.



[17] Personal communication, Eric Haugaard, Director of Product Technology, Cree Lighting Power factor values of similar fixtures operating at 277 VAC were reported to be .65 at high power, .60 at low power.

The relatively low observed power factor values mean that, as compared to operation at a high power factor, the average current on the conductors serving the lighting circuits is somewhat increased. We haven't attempted to estimate distribution wiring energy losses due to this effect, but such losses are inherently included in our monitored energy consumption data. Power factor may also interact with performance of distribution transformers at the site, but any analysis of these effects is beyond our current scope. According to the lighting fixture manufacturer, a different power supply that should provide improved power factor under most conditions is used in newer fixtures of this type.[18]

LIGHTING ENERGY USE

The energy use data collected over the course of the study provides a clear picture of energy consumption as a function of time. Figure 7 shows the average power draw by hour of day for each of 15 monitored circuits over the second year of data collection (after adjustment of motion detector delay timers).[19] The effects of daylight control are clear as a drop in average power during daytime hours on many circuits. The effects of higher traffic flow, which triggers higher output and power consumption through the operation of motion sensors, are visible as bumps around the time of morning and afternoon peak periods (e.g. see circuits 9, 10, and 13).

[18] Personal communication, Eric Haugaard, Director of Product Technology, Cree Lighting

[19] Excludes CIRC06 due to missing data in second year of monitoring. We judge the second year of data as more representative of the expected long-term performance of the lighting system, both because usage of the facility was initially low and growing through at least the first year, and because the revised setting of motion sensor timers at the start of the 2nd year is likely to remain in effect permanently.

Figure 7. Average power by circuit, by hour of day for second year of monitoring. Vertical bars represent 1st through 99th percentile of observed power, and dashed horizontal line is the nominal total connected power for the circuit.

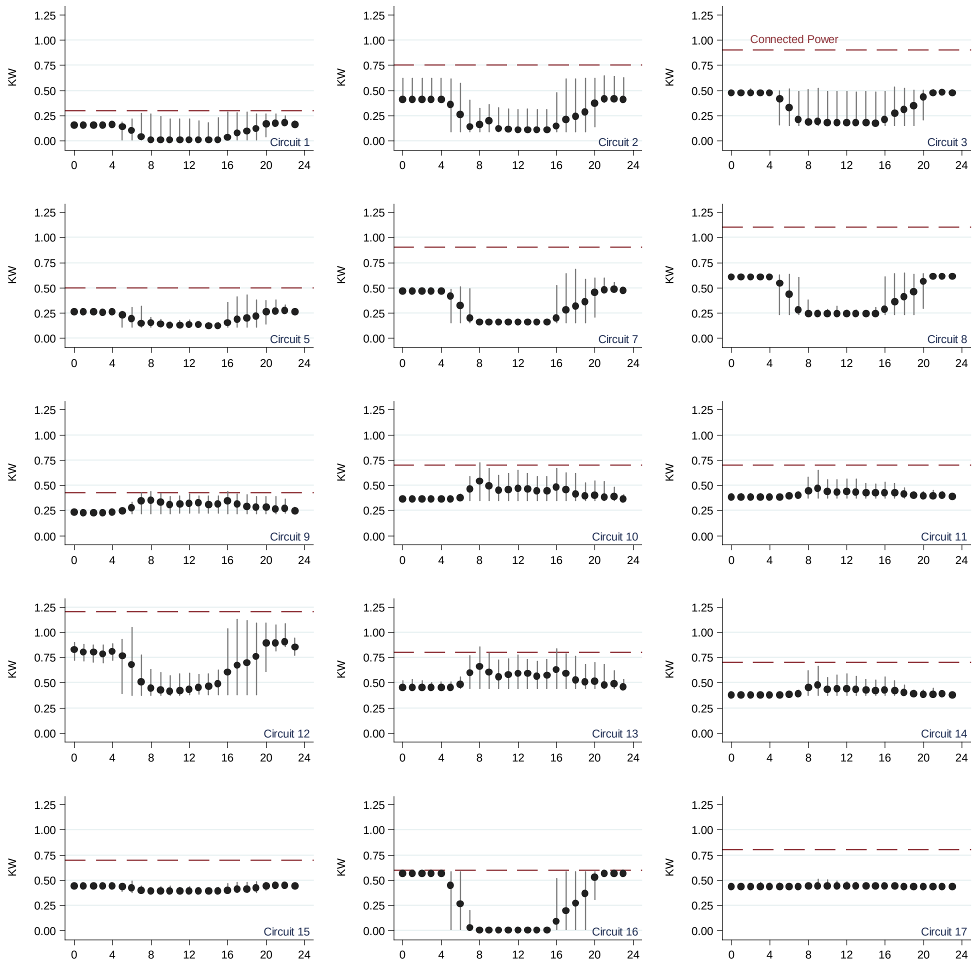
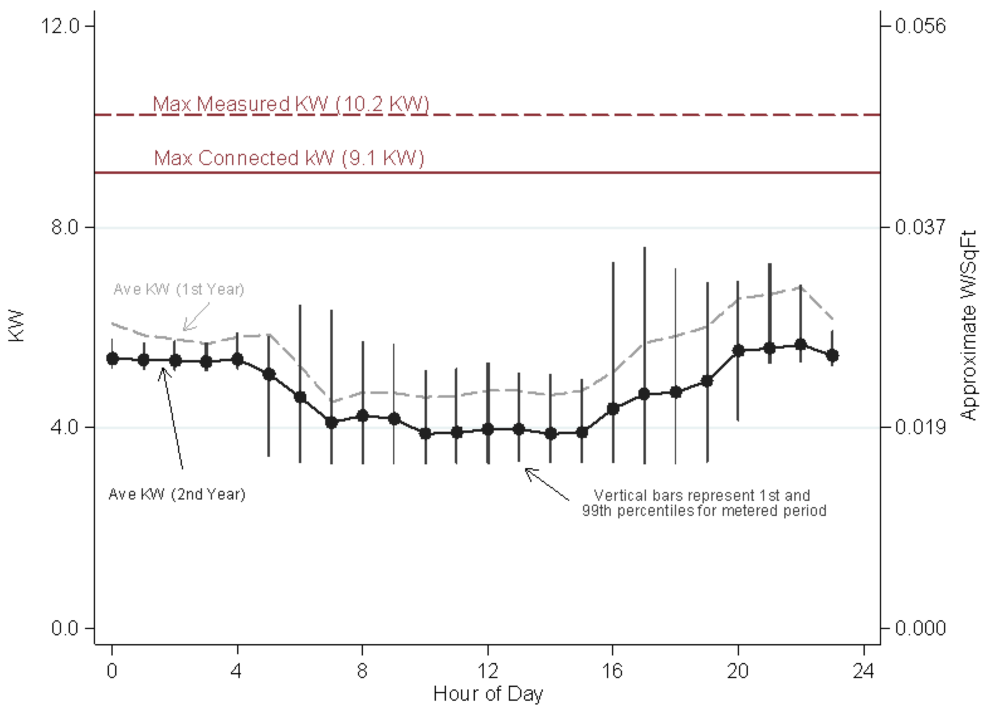


Figure 8 shows the average power by hour of day for the overall lighting system for the second year of monitoring. The effects of daylight control are again visible, and the variation due to traffic is visible in the 1st to 99th percentile bars, which are largest during morning and afternoon peak traffic periods, and smallest at night. For comparison of the first and second year of monitoring, the graph includes the first year average power (without the percentile bars). The average power is clearly lower for all hours of the day in the second year as compared to the first year of monitoring, a result of motion sensor timer re-set at the start of the second year.

Figure 8. Combined average hourly power (KW), by hour of day, for overall LED lighting system, excluding circuits 6, 7, and 8. The darker line with symbols shows the average hourly lighting load during the second year of monitoring, after the timer delay settings were adjusted, and the vertical bars show the 1st through 99th percentiles of observed power. The lighter dashed line represents the average hourly lighting load for the same circuits during the first year. Approximate W/sq ft represents average power use, not connected load, and is adjusted to approximately represent the building area served by circuits excluding 6, 7, and 8.



The average power draw for each circuit, for the first year and second year of monitoring, is shown in Table 6. Because of missing data, values for one monitoring year for circuits 6, 7, and 8 are based on estimates.[20] The table includes the average fraction of the nominal connected load drawn by each circuit in each year of monitoring. These average fractions, and the fraction of total connected load for the entire lighting system, provide an initial look at the reduction in energy use provided by daylight control plus motions sensors: in the second year of monitoring, the system as a whole drew an average of 47.8 percent of connected load, meaning the daylight and motion sensor systems together reduced energy consumption by about 52 percent as compared to expected use under continuous full power.[21]

[20] Specifically, we estimated the energy consumption for circuit 7 in the first year from a blend of circuits 2, 3, 5, and 6, for circuit 8 in the first year from a blend of circuits 3 and 6, and circuit 6 in the second year from a blend of circuits 5 and 7. These circuit selections reflect location in the structure and similarity in daylight control.

[21] We compare average power consumed to nominal connected power as the basis for estimating energy savings throughout this report. This may introduce a bias that understates savings, since the maximum recorded power draw on most circuits exceeds nominal ratings.

Table 6. Average power consumption and average fraction of total connected load for lighting circuits, for first and second year of monitoring (before and after resetting of motion sensor controls). Loads that are not part of the LED area lighting system are excluded.

Circuit	Average power, 1st year (kW)	Average power, 2nd year (kW)	Average fraction of nominal connected load, 1st year	Average fraction of nominal connected load, 2nd year
CIRC01	0.111	0.087	0.370	0.291
CIRC02	0.286	0.263	0.382	0.351
CIRC03	0.348	0.324	0.387	0.360
CIRC05	0.238	0.199	0.476	0.397
CIRC06	0.395	0.258 [a]	0.439	0.375 [a]
CIRC07	0.317 [a]	0.317	0.420 [a]	0.352
CIRC08	0.372 [a]	0.424	0.413 [a]	0.385
CIRC09	0.383	0.288	0.895	0.672
CIRC10	0.515	0.420	0.735	0.600
CIRC11	0.454	0.410	0.649	0.586
CIRC12	0.808	0.658	0.672	0.547
CIRC13	0.659	0.529	0.824	0.662
CIRC14	0.461	0.407	0.658	0.582
CIRC15	0.441	0.418	0.630	0.597
CIRC16	0.279	0.279	0.465	0.465
CIRC17	0.481	0.439	0.601	0.548
Overall LED lighting system	6.548	5.721	0.547	0.478

[a] Data for circuits 6, 7, and 8 is incomplete; these values are estimates.

The overall lighting energy consumption of the parking structure, based on the second year of monitoring data, is summarized in Table 7. Except for circuit 6, all values are based directly on average power data, extrapolated to 8,760 hours to represent one year. We estimated the average power for circuit 6 based on data for two other circuits with similar characteristics.

Table 7. Predicted annual lighting energy consumption for The Brewery parking structure area lighting, based on 2nd year of monitoring data. These values include LED area lighting only, not unrelated load on monitored circuits.

	Enclosed areas	Exposed rooftop	Overall structure
Average power (kW)	5.442	0.279	5.721
Estimated annual kWh	47,670	2,446	50,116
Area, sq ft	222,580	34,258	256,838
Average W per sq ft	0.0244	0.0082	0.0223
Estimated annual kWh per sq ft	0.214	0.071	0.195
Average power as fraction of connected load	0.478	0.465	0.478

The energy use projected for The Brewery system in the Focus on Energy submission was 41,365 kWh annually. This estimate was based on an estimated connected load of 13.1 kW, and an assumed average power consumption of 36 percent of the connected load (i.e. an average reduction of 64 percent of full load by daylight and/or motion sensor controls). We identified a somewhat lower connected load on the lighting circuits, and a higher average power as a fraction of the connected load.

A recently published report on work sponsored under the DOE GATEWAY Solid-State Lighting Technology Demonstration Program offers some values that can be compared to our results (see Table 8).[22] All the comparison projects use LED lighting in parking garages, and the main focus of the work was exploration of the energy impacts of motion sensors. As at The Brewery, all the sites used motion sensors controlling individual lighting fixtures. Site A fixtures operate 24 hours a day (it's an underground facility), and use a low-power level of just 10 percent of full power. Motion sensor time delay was tested at 10 min and 2.5 min. Site B is an above-ground parking structure, with fixtures near the perimeter subject to daylighting control (B1), and those in the interior always operating (B2). This is similar to the daylighting control scheme at The Brewery. The low-power level is 66 percent of full power. Motion sensor time delay was tested at an initial mix of settings (typically about 20 min) and at settings of approximately 3.5 min. The study did not explicitly report the area of each parking facility, so our normalization of values to a "per square foot" basis relies on estimating area indirectly from fixture placement dimensions or other information.

[22] Use of Occupancy Sensors in LED Parking Lot and Garage Applications: Early Experiences U.S. Department of Energy, October 2012.

Table 8. Comparison of overall energy performance of LED lighting systems at The Brewery and two other parking garage applications.

	The Brewery system, enclosed areas only	Site A Underground parking garage	Site B1 Above-ground parking structure, interior	Site B2 Above-ground parking structure, exterior
Description	Some fixtures on daylight control. Time delay settings 8 min, 30 sec.	Lights always operate, low level is 10% of full power. Time delay settings 10 min, 2.5 min.	Lights always operate, low level is 66% of full power. Time delay settings 20 min, about 3.5 min.	Lights operate 12 hrs/day, low level is 66% of full power. Time delay settings 20 min, about 3.5 min.
Lighting power density (W/sq ft)	0.051	.056	.063	.063
Average power as fraction of connected load	0.478	0.539 to 0.247	0.827 to 0.800	0.385 to 0.361
Estimated annual kWh per sq ft	0.214	0.265 to 0.121	0.455 to 0.440	0.212 to 0.199

Results from the GATEWAY study sites appear to be consistent with our results from The Brewery. The low-power setting for the fixtures at Site A is effective in generating large savings even without daylighting, and the savings increase substantially when the timer delay is reduced to 2.5 min. This reduced low-power setting offers the dual benefit of further reducing energy consumption and prolonging fixture life, assuming lighting levels are acceptable to users of the facility. We believe reduced low-power settings could be used in most parking applications, and include it as a recommendation for consideration by designers.

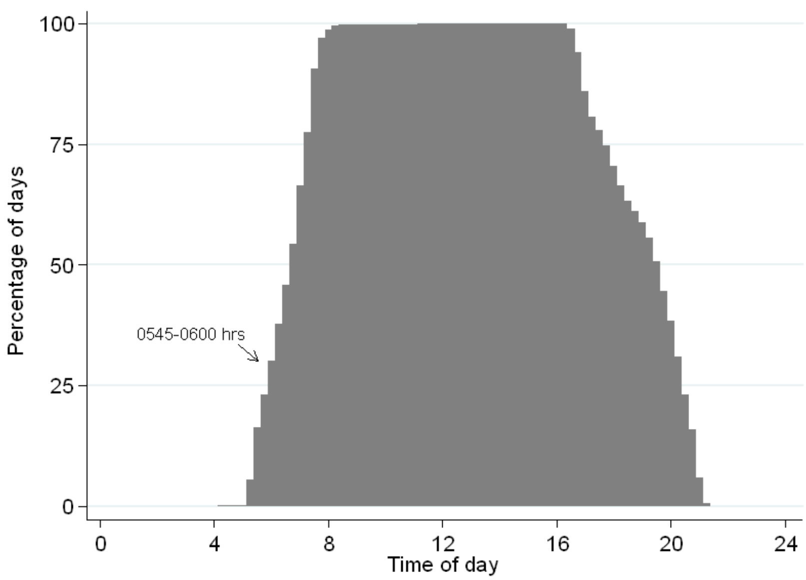
Site B2 shows the effect of daylighting control as compared to B1 with no daylighting control. The savings due to motion sensors appear to be much more modest at site B, consistent with the less aggressive low-power setting of 66 percent of full power.

Daylighting Control

Daylighting control is applied to fixtures in locations where ambient light is most available, including many of the fixtures in the outer row and closest to openings that allow outside ambient light to enter. The daylighting controls fully disable these fixtures when an adequate level of ambient light is sensed. A single sensor (located at the 7th level on the north wall of the structure) and controller manages all daylight-controlled fixtures except the four rooftop fixtures, which use a second sensor and controller.

Figure 9 illustrates the time of day that daylighting controls were active. The daylighting controls were generally activated between 0800hrs and 1600 hours local time on all days. Activation was seasonally dependent between the hours of 0500-0800 and 1600-2100 (i.e. the amount of daylighting during these time periods fluctuated with the changing length of days). The asymmetry in the graph is an artifact of daylight savings time; the wider time span of daylight in the summer is shifted away from early morning and toward late evening when daylight savings is in effect.

Figure 9. Percentage of days with daylighting control active, by quarter hour (e.g. about 30% of days had some amount of daylighting control between 0545 and 0600 hours).



Analysis of monitoring data establishes that the overall annual fraction of time during which the daylighting controls are active is almost exactly 50 percent. Although observation and video taping of the lighting system shows that the daylighting controls for the rooftop and for the interior lighting do not switch at the same time, the average fraction is nearly identical for the two control systems.

Since the daylighting controls disable fixtures completely, we can use the 50 percent time fraction to estimate overall savings that can be attributed to these controls, ignoring for now any additional reduction related to motion sensors. The fixtures subject to daylighting control comprise 38.1 percent of the LED area lighting total power. Applying 50 percent savings to this fraction, the gross savings attributable to daylighting control in this system is 19 percent.

Motion Sensor Control

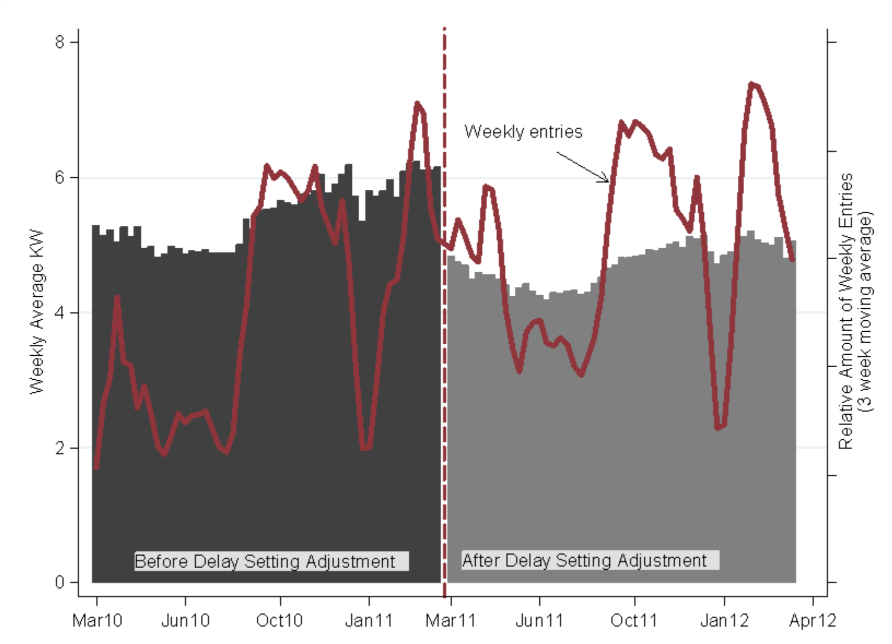
All the area lighting fixtures in the parking structure, with the exception of the four rooftop pole-mount fixtures, include motion sensors. The energy savings effects of motion sensor controls is made clear from the average power values; even circuits in which there is no daylighting control show average power values well below full connected power (see Figure 7).

When a motion sensor is triggered by a car or pedestrian, fixture power is switched from the low-power setting of about 50 percent to the full-power setting. After being tripped, a time delay function is initiated; if no further motion is detected before the delay period expires, the fixture returns to low power. The time delay in these fixtures is adjustable from about 30 seconds to 30 minutes, and an adjustment performed during the study allows comparison of system performance under two conditions.

During a site visit in early 2011, we measured the typical time delay on a sample of fixtures at about 8 minutes, with maximum values of at least 15 minutes. As a result of discussion with the facility managers, the timers on all fixtures were re-set to the minimum delay on March 16, 2011. Our observation of a sample of fixtures indicates the typical delay after re-setting to be about 30 seconds, consistent with the manufacturer's specifications.

The effects of the delay adjustment can be seen as an obvious drop in average power consumption after the timer adjustment in March, 2011 (see Figure 10). Also visible in this plot are the effects of daylight controls (as somewhat lower typical power consumption during the summer) and an expected relationship between average power and traffic in the facility. Since the average traffic in the facility clearly increased from the first year to the second year of monitoring, and this growth affects energy consumption, isolating the effect of the timer adjustment requires us to further understand the effects of traffic.

Figure 10. Weekly average kW power for lighting over two years of monitoring, excluding circuits 6, 7, and 8. Moving average of relative traffic flow in facility also shown.

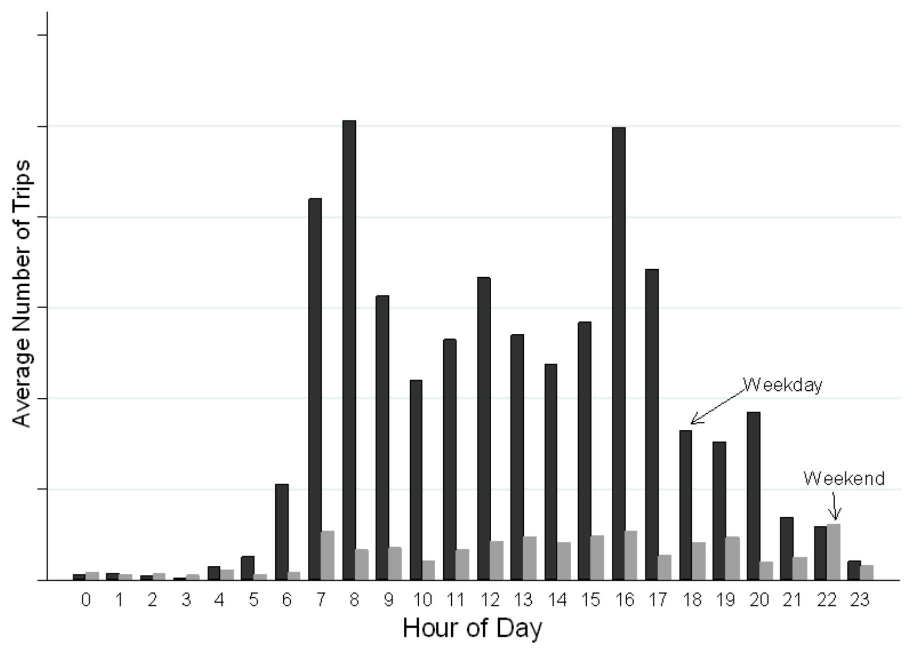


Traffic and Occupancy in the Parking Structure

Lighting power consumption is likely affected by traffic volume and the occupancy of the parking structure in two ways: 1) a larger volume of traffic necessarily activates the motion sensors installed on the LED lighting fixtures more frequently, increasing the amount of time fixtures operate at high power and 2) as the occupancy of the facility (number of cars parked at a given time) increases, drivers travel farther to find an open parking space, thus passing and activating a greater number of motion sensors. We used vehicle entry and exit data recorded by the parking facility operator during the monitoring period to characterize the effects of traffic on lighting energy use.[23] We considered both traffic and occupancy in evaluating the effects of motion sensor controls.

We counted either an entry into or an exit out of the facility as an individual "trip." Figure 11 compares the average number of trips recorded in the parking structure for each hour of the day, for weekdays (dark bars) and weekends (light bars). In this and other cases, we present traffic data as relative values to obscure proprietary data contributed by the parking operator.

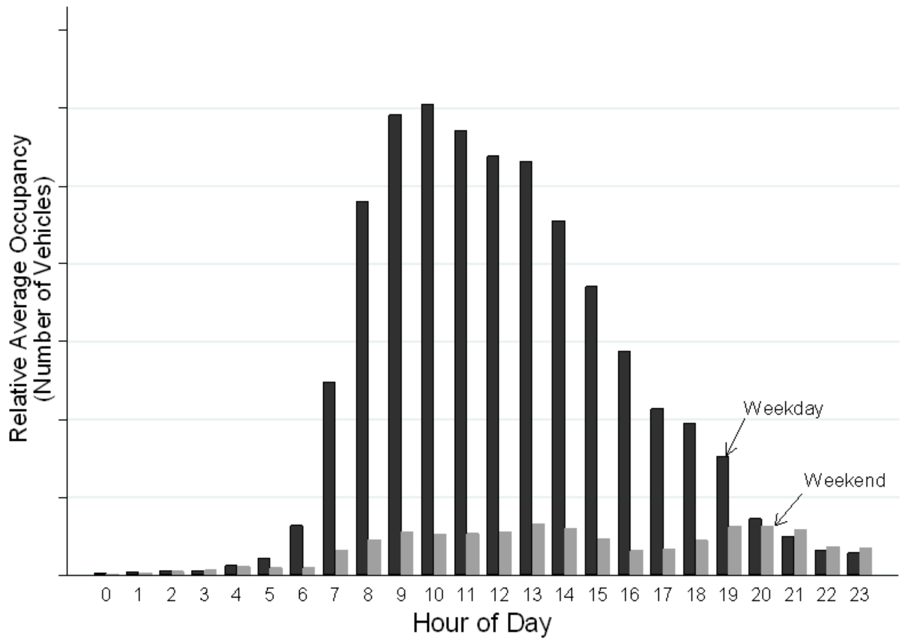
Figure 11. Average number of trips, by hour of day over the two year monitoring period. Darker bars represent hourly averages on weekdays.



To estimate occupancy, we summed the total number of entries and subtracted the number of exits, starting at midnight each day. This calculation yields a value that is often greater than zero at the end of a 24-hour period, and is reset to zero at midnight each day. Figure 12 shows the average occupancy for each hour of the day during weekends and on weekdays. Average occupancy is highest during daylight hours between 0900 hrs and 1400 hrs.

[23] Our thanks to the staff of Interstate Parking for their cooperation in releasing parking data for this study.

Figure 12. Average occupancy for the parking structure during the two-year monitoring period by hour of day, both on weekdays and weekends.



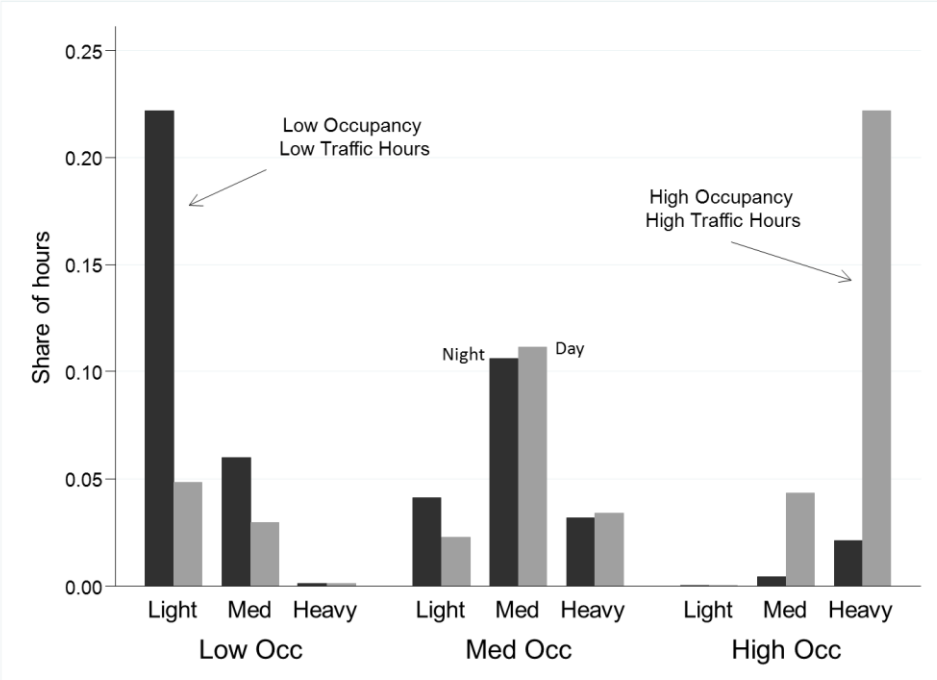
Exploration of the data revealed irregular relationships between vehicle traffic, occupancy and the timer settings. Linear regression did not appear to be an appropriate tool for analysis, and we rely instead on binning of data to allow comparison of power consumption under similar traffic conditions before and after the timer re-set. We assigned each hour of the monitored periods into one of nine bins described by three levels of occupancy and three levels of traffic. The cut-off values used to identify these bins are listed below in Table 9, and are selected to distribute hours evenly between the three bins during the second year (after timer adjustment).

Table 9. Traffic and occupancy ranges used in bin analysis

Level	Occupancy	Traffic (trips/hr)
Low/Light	<8 cars	<4 trips
Medium	8-100 cars	4-40 trips
High/Heavy	100+ cars	40+ trips

Figure 13 displays how hours were distributed across each combination of traffic and occupancy bins, as well as during daylight and non-daylight time periods. Most low occupancy and/or light traffic hours occurred during non-daylight hours, and most high-occupancy and/or heavy traffic periods occurred during daylight hours. Medium occupancy and/or medium traffic hours are split fairly evenly across time periods with and without daylight.

Figure 13. Distribution of hours by occupancy and traffic bin during two year monitoring period.



Vehicle occupancy and traffic in the parking garage gradually increased over the two-year monitoring period. The average number of trips was about 25 percent higher in the year after the motion sensor adjustment. Table 10 compares relative vehicle traffic and occupancy during the pre- and post-adjustment periods.

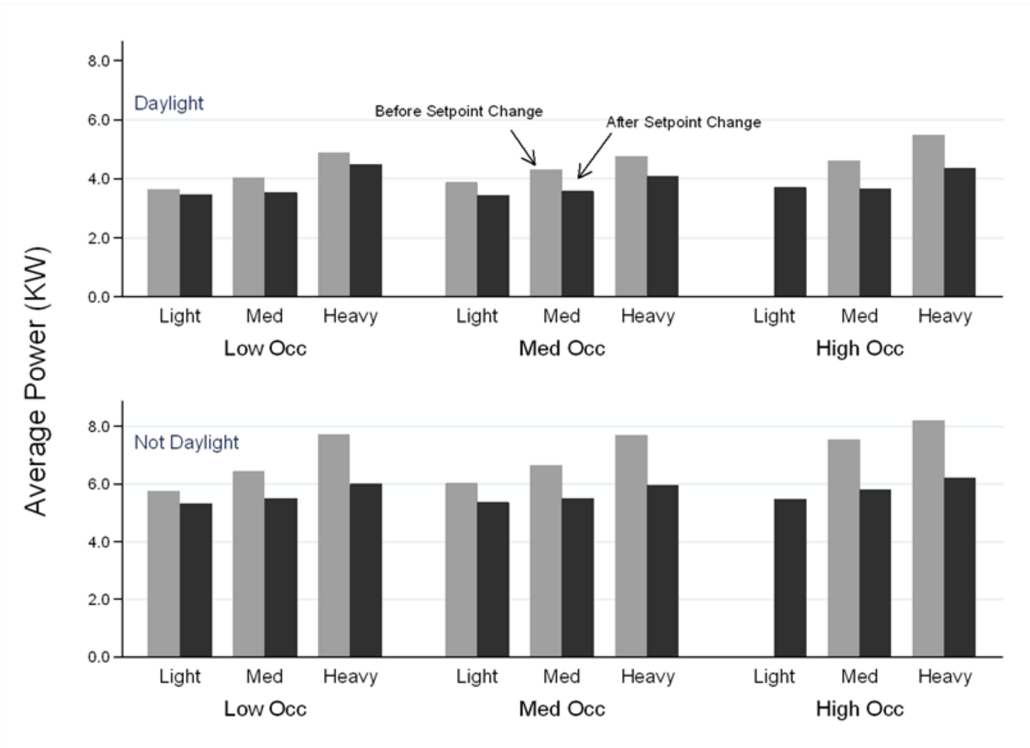
Table 10. Traffic and occupancy metrics for the parking garage during both the pre- and post-monitoring period.

Monitoring Period	Relative Number of Trips/Day	Relative Average of Daily Peak Occupancy
Pre-Adjustment	100	100
Post-Adjustment	124	144

.

Figure 14 illustrates the effect of adjusting motion sensor time delay on average power consumption within each bin of occupancy and traffic effects on power draw for the parking structure, both before and after the occupancy were reset. Not surprisingly, the most noticeable reductions in power draws were during high occupancy and/or heavy traffic periods, but there is a noticeable reduction in average power in every bin.

Figure 14. Comparison of average lighting power before and after adjustment of motion detector timers, for each bin of occupancy and traffic, and by periods with and without active daylighting control. Includes all circuits except 6, 7, and 8. Light, Medium and Heavy refer to traffic bins. The darker bars in the figure below represent the time period after the time-delay of occupancy sensors were adjusted.



To estimate the effects of changing traffic and occupancy patterns on energy use, we estimated the expected energy use that would have occurred during the first year of monitoring if the number of hours in each bin of traffic and occupancy had been equal to that during the second year. The results indicate a very modest change of about one percent in overall energy consumption, and we have not applied a correction for traffic levels to our final analysis of energy use and savings.

SUMMARY OF ENERGY SAVINGS

A summary of predicted annual energy use and percent energy savings for the enclosed areas of the structure, the rooftop, and the overall system appear in Table 11, Table 12 and Table 13. The base case or starting point for this analysis is the predicted annual energy consumption of the lighting system as installed, but under the scenario of no daylighting or motion sensor controls in place. (Note the system is not compared to an alternative design, such as a metal halide lighting.) The expected base case consumption is calculated using nominal rated connected power for the lighting fixtures; while this may introduce a bias in savings estimates due to differences between actual and rated power consumption, it provides a consistent, defined baseline. Such a bias appears in the case of the rooftop fixtures, and we have changed the fractional energy use under daylighting control in Table 12 from the 50 percent value derived from data to 0.465 to adjust for this bias. Any bias occurring in other circuits is obscured by power levels that vary under control of motion sensors.

The estimated usage and savings under conditions of daylighting control and the two conditions of motion sensor control are derived from measured data. The values in the tables are not adjusted for traffic growth over time. Correcting for the lower usage of the facility during the first year of monitoring would change only the values for energy use and savings with the original motion sensor timer setting (i.e. row C) in the tables), and would change those values by less than 2 percent.

Table 11. Predicted annual energy use and savings, area lighting system at The Brewery, enclosed areas of structure using pendant fixtures.

	Predicted annual energy consumption (kWh)	Predicted annual consumption (kWh/sq ft)	Energy use as fraction of base case	Reduction in energy use from base case
A) Base case: Continuous full-power operation, no daylight controls or motion sensors	99,689	0.448	1.00	0
B) With daylight controls	82,335	0.370	0.826	17.4%
C) With daylight controls and motion sensors (using original timer settings)	54,914	0.247	0.551	44.9%
D) With daylight controls and motion sensors (using adjusted timer settings)	47,670	0.214	0.478	52.2%

Table 12. Predicted annual energy use and savings, area lighting system at The Brewery, rooftop pole-mount fixtures

	Predicted annual energy consumption (kWh)	Predicted annual consumption (kWh/sq ft)	Energy use as fraction of base case	Reduction in energy use from base case
A) Base case: Continuous full-power operation, no daylight controls or motion sensors	5,256	0.153	1.00	0
B) With daylight controls	2,445	0.071	0.465	53.5%
C) With daylight controls and motion sensors (using original timer settings)	2,445	0.071	0.465	53.5%
D) With daylight controls and motion sensors (using adjusted timer settings)	2,445	0.071	0.465	53.5%

Table 13. Predicted annual energy use and savings, area lighting system at The Brewery, overall structure including enclosed areas and rooftop.

	Predicted annual energy consumption (kWh)	Predicted annual consumption (kWh/sq ft)	Energy use as fraction of base case	Reduction in energy use from base case
A) Base case: Continuous full-power operation, no daylight controls or motion sensors	104,945	0.409	1.00	0
B) With daylight controls	84,963	0.331	0.810	19.0%
C) With daylight controls and motion sensors (using original timer settings)	57,359	0.223	0.547	45.3%
D) With daylight controls and motion sensors (using adjusted timer settings)	50,116	0.195	0.478	52.2%

CONCLUSIONS

Based on observation and monitoring of the LED area lighting system at The Brewery parking structure in Milwaukee, we offer the following conclusions. While based on one specific system and research project, we believe most can be generalized to other outdoor LED area lighting systems.

- Lighting power density achieved by the LED system installed is excellent, at about 20 percent or less of the most aggressive current code requirements.
- Illuminance provided by the system is generally good, meeting current standards for parking garages (and for open parking lots in the case of the rooftop) in all cases except some horizontal surface measurements on the rooftop. The equipment used for illuminance measurements, however, was not calibrated and had relatively low resolution in the range of our measurements.
- Measured illuminance shows the expected effects of ambient temperature (illuminance tends to increase as ambient temperature decreases). Illuminance appears to decrease over the period of the project, but we cannot quantify the effect. Both declining light output from fixtures and dirt accumulation could contribute to an apparent decrease.
- Maximum recorded power draw exceeded the rated connected load for individual circuits by around 10 percent in many cases. About half of this increase is easily explained by temperature effects: the fixtures draw about 5 percent more power at 15 F than at 77 F, and all the maximum readings occurred during cold weather. Variability among fixtures and power quality may also be factors.
- The fixtures used here (with the exception of the rooftop fixtures) exhibited low power factor values, typically 0.55 to 0.75. Low power factor could be a source of concern in terms of power quality in the facility where fixtures are used. Different power supplies are used in newer fixtures from the same manufacturer. We recommend reviewing expected power quality and power factor during fixture selection.
- Overall energy use of the system is about 50,000 kWh annually, or about 0.223 kWh per square foot. This is similar to the performance of LED lighting systems in other parking garages.
- The combined daylight and motion sensor controls reduce the energy consumption of this system by about 52 percent compared to the same system operated continuously at full power. Daylighting controls reduce consumption by 19 percent, and motion sensors an additional 33 percent in their final setting.
- The savings attributable to motion sensors increased from 26 percent to 33 percent of full power when sensor time delay was changed from 8 min to 30 sec.
- As compared to a metal halide lighting system for the same facility using daylighting control for a similar proportion of fixtures, but no motion sensors, we believe the system as installed reduces energy consumption by about 76 percent. As compared to a metal halide system operated continuously at full power, we believe the system as installed reduces energy consumption by about 80 percent.

In summary, LED area lighting appears to offer an excellent option for parking areas, where tailored light distribution allows low overall power density, and both daylighting and motion sensor controls can reduce energy consumption significantly compared to "always on" operation. (This project did not evaluate economics of lighting system options.) Parking garages, with the need for lighting during daytime as well as nighttime periods, offer perhaps an ideal application for LED technology.

Designers and owners considering LED lighting for parking applications in future projects should consider the following guidelines drawn from experience on this project:

- The time delay setting used with motion sensors, i.e. the time from the last motion detected to switching to a low-power mode, should be variable, and the setting should be specified by the designer. In parking applications, values of 30 seconds to 3 minutes may be adequate. Designers and installers should understand how to set the time delay.
- The reduced power level, used when motion sensors are not triggered, can be less than 50 percent of full power, and possibly as low as 10 percent.
- Designers should understand the power factor of the fixtures selected at the operating voltage to be used, and high- and low-power settings, and should consider any implications of power factor for the facility as a whole.
- Both dirt accumulation and declining lumen output can affect illuminance levels over the life of a project. Consider modifications to design illuminance to accommodate these factors.

Future lighting energy monitoring projects would benefit from the use of advanced electric metering which allows collection of detailed continuous data on both power and power factor and would permit better time resolution in data collection. Additional field research topics that would add to our understanding of the performance and optimal use of advanced lighting systems include:

- Customer response research on lighting levels, frequency of switching, and responsiveness of motion sensors
- Measured power as compared to rated power, across typical temperature ranges
- Lumen maintenance, or the decrease in light output over time, as it relates to operating power and temperature
- The effects of dirt accumulation on illuminance levels
- The operating temperature of fixtures in typical installed configurations (in closed structures, open structures, and when fully exposed)

APPENDIX A

MONITORED CIRCUITS AT THE BREWERY

Circuit identifier used in this report	Levels, areas of structure	Number and type of LED parking area lighting fixtures	Nominal connected power (kW)		
			Daylight controlled	Not daylight controlled	Other fixtures
CIRC01	1 W Outer	6 2-row	0.300	0.000	0.000
CIRC02	3 W End, 4 & 5 W Outer	15 2-row	0.600	0.150	0.288
CIRC03	4 & 5 W End, 6 & 7 W Outer	18 2-row	0.600	0.300	0.000
CIRC05	2 & 3 E Outer	10 2-row	0.300	0.200	0.000
CIRC06	4 & 5 E Outer	18 2-row	0.450	0.450	0.000
CIRC07	2 & 3 W Outer, 6 & 7 W End	18 2-row	0.600	0.300	0.000
CIRC08	6, 7 & 8 E Outer	22 2-row	0.650	0.450	0.000
CIRC09	1 W Inner	8 2-row	0.000	0.428	0.000
CIRC10	2 & 3 W Inner	14 2-row	0.000	0.700	0.141
CIRC11	4 & 5 W Inner	14 2-row	0.000	0.700	0.012
CIRC12	1 E Inner, 1 E Outer, & Entry Area	19 2-row	0.462	0.740	0.060
CIRC13	2 & 3 E Inner	16 2-row	0.000	0.800	0.012
CIRC14	4 & 5 E Inner	14 2-row	0.000	0.700	0.012
CIRC15	6 & 7 W Inner	14 2-row	0.000	0.700	0.012
CIRC16	Rooftop	4 pole-mount	0.600	0.000	0.000
CIRC17	6, 7 & 8 E Inner	16 2-row	0.000	0.800	0.015
Overall system		226	4.562	7.418	0.552

Fixture descriptions:

2-row

Pendant LED fixture with 2 dual rows of diodes, 50 W nominal
Model BETA BLD-PKG-T5-PD-034-LED-B-UL-SV-TL*350/175

3-row

Pendant LED fixture with 3 dual rows of diodes, 78 W nominal
Model BETA BLD-PKG-T5-PD-051-LED-B-UL-SV-TL*350/175

Pole-mount

Pole mounted LED fixture, 150 W nominal
Model BETA BLD-ARR-T5-R3-102-LED-B-UL-BZ-P

Level and area designations:

W refers to West of the building centerline
E refers to East of the building centerline
Outer means fixtures in the outer row, nearest openings in the structure, most commonly subject to daylight control
Inner means fixtures are in the inner row, away from building openings, and generally not subject to daylight control
End means fixtures in the South end of the building, with few openings, and less frequently subject to daylight control

APPENDIX B

MONITORING EQUIPMENT

We installed equipment on site to allow automated collection of electrical energy consumption data over time. This monitoring system was set up to gather data independently on 17 circuits that include all the parking area LED light fixtures. This system provides continuous monitoring of real electric power (i.e. true energy use, not the apparent power as influenced by voltage and current phase relationship), which is integrated over 15-minute data recording intervals. Ambient air temperature within the structure is also recorded. Key components of the monitoring system are listed in the table below.

Primary components of lighting energy consumption monitoring system.

Description	Qty	Component	Notes
Power monitors, pulse output	6	Continental Controls Watt Node model WNB-3Y-480-P Opt P3	Each device includes 3 independent input channels.
Current transformers	18	Continental Controls model CTT-0300-005	Matched to Watt Node WNB-3Y-480
Data logger	1	Campbell Scientific CR-10	Standard data logger compatible with analog inputs or pulse inputs via extension modules.
Pulse input modules	3	Campbell Scientific SDM-SW8A	Allow monitoring up to 24 separate pulse input channels on one CR-10 data logger.
Modem	1	Campbell Scientific COM-220	Modem for communications via standard telephone line.

Expected errors in the measurement system include errors in the power metering devices and the current transformers. We estimate the overall accuracy of the monitoring system to be +/- 2.0% of full range values, or about +/- 5.0% of data values across the range of measurements.

The monitoring system counts pulses from the watt-hour meters, and as such is subject to a counting error (Poisson error) related to variation in the number of counts falling in any arbitrary measurement interval. Given the 15-minute data collection interval, however, and the typical rate of pulses produced, this error is very small and does not contribute to the overall estimated measurement error.

Short-term power factor measurements were made during site visits, using a Dent Elite Pro power meter and Continental Controls AccuCT current transformers, with results downloaded to a laptop on site. The averaging interval was set to the minimum of 3 seconds.