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Advanced Lighting Control System Performance: A Field Evaluation of Five Systems

May 2018

EE Richman
JA McIntosh

U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
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Executive Summary

This report describes a set of five field evaluations conducted by Pacific Northwest National Laboratory along with the DesignLights Consortium (DLC) for the U.S. Department of Energy between November 2015 and September 2017, to demonstrate the potential energy saving capability of a sampling of advanced lighting control systems in real world environments. The lighting control systems included task tuning (also known as high-end trim), occupancy sensors, and daylighting controls. These systems were installed, along with new LED fixtures and kits in five different commercial buildings: two different office buildings, a brewery, a grocery, and a medical office building. This evaluation project provides data and information that can help those responsible for energy use and savings at commercial facilities to determine the effectiveness of advanced control, LED-based lighting system retrofits. This study does not provide a direct comparison of system types and the amount and type of data reported cannot be used to significantly or statistically imply any direct comparisons.

The project evaluated five different advanced control LED lighting systems in five different buildings. The evaluation involved measuring the energy use of baseline conditions (pre-retrofit) as well as post retrofit energy savings.

Lighting energy use at each site was measured before and after the existing fluorescent lamps were replaced with new LED lamps and after each control was installed or activated so that energy savings could be identified separately for each significant capability of the new system. Table E.1 shows the energy savings at each site, for the initial fluorescent-to-LED replacement and for each control added; these savings are represented as percentages of the pre-retrofit energy use and the savings are combined in the last column for total percent savings at each site. As expected, savings vary by site because the sites differ in terms of size, occupant activity, and business schedules. Note specifically that occupancy control savings vary because some sites (Site 2-Office and Site 5-Office) already had basic versions of this control. Averages are shown in the last row of the table and provide a relative idea of savings that might be achievable in typical projects. The data indicate that occupancy sensor savings must be carefully considered because of their variability. Task tuning is also dependent on site conditions and can be significantly higher or lower than the 29% average found in two sites in this study.

Table E.1. Summary of Energy Savings across All Sites

Site	FL to LED Only	High-End Trim / Task Tuning	Occupancy Control	Daylighting Control	Total: LED with All Controls
1 – Brewery	50%	negligible	10%	6%	66%
2 – Office	64%	included in FL to LED	-2%	5%	67%
3 – Medical Office	29%	included in FL to LED	24%	9%	62%
4 – Retail/Grocery	30%	33%	3%	~	66%
5 – Office	43%	24%	-1%	4%	70%
Average – By Control		29%	7%	6%	
Average – Site	43%				66%

Note: Not all control savings could be separated at each site. Average savings provided at the controls level and the site level.

Light levels were measured before and after the retrofit to provide a characterization of the change in lighting conditions. Surveys were administered to the occupants before and after the retrofit to gauge acceptance and identify any issues. Separate surveys were also issued to the installers and the facility operators to capture ease of installation and operation of the new systems.

The results of the evaluation showed that these projects provided simple paybacks from 6.7 to 14.9 years and savings-to-investment (SIR) ratios of 1.3 to 3.0 with applicable utility rebates. The results show the greatest savings for advanced controls come from the implementation of task tuning. When implemented, this relatively new control strategy can provide significant savings by tuning light levels to the levels recommended by the Illuminating Engineering Society (IES) or to occupant preferences. The study also shows that savings will be limited for any control features, like occupancy sensors, that already existed at the site prior to the retrofit. Finally the study indicates that in some applications the "auto-on" functionality of some new advanced lighting systems with fixture-integrated occupancy sensors has the potential to slightly increase energy use relative to traditional occupancy controls with "manual-on" or "vacancy" functionality.

Occupant satisfaction was also determined through the use of pre- and post-retrofit surveys. The installation and operational experience provided by installers and facility operators through surveys also helped identify the capabilities of the new systems. These results can provide facility operators with some information useful in determining the cost effectiveness and occupant acceptance of these systems and the applicability of these controls in their own facilities.

Acknowledgments

The authors appreciate the willingness of those involved in the project to provide information and support these evaluation activities. This effort involved many different individuals and organizations who helped make the analysis and presentation of the data possible including The DesignLights Consortium, the U.S. Department of Energy, The Cadmus Group, Wendel Energy, Rise Engineering, OpTerra Energy Services (an ENGIE Company), Earthlight, Con-Serve Inc.

We would also like to thank our contacts at the field sites: Two Roads Brewery (Site 1), Avon Medical Offices (Site 2), Rhode Island Public Utility Commission (Site 3), Stop & Shop (Site 4), and Yale University (Site 5);

the lighting manufacturers and manufacturer representatives: Cree, Current by GE/Daintree, Digital Lumens, Enlighted, Langlais Group, and Signify (formerly Philips);

and the following utilities: Energize Connecticut, Eversource, National Grid, and United Illuminating.

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1.0 Intro0.15duction

Many new and existing advanced lighting control systems use LED technology to improve efficacy and because LED technology is easily controllable. This report describes a set of five field evaluations conducted by Pacific Northwest National Laboratory (PNNL) and DesignLights Consortium for U.S. Department of Energy, between November 2015 and September 2017, to demonstrate the potential energy-savings capability of advanced LED lighting control systems in real world environments. This report describes the sites and technologies as well as the data collection methods and analysis. The results include a summary of the typical capabilities of the systems, cost effectiveness, applications, and energy savings for the fluorescent-to-LED lighting retrofits and for each of the control measures added - task tuning (also known as high-end trim or institutional tuning), occupancy sensors, and daylight sensors.

For each site and control system, data were collected on energy use, economics, lighting characteristics, occupant satisfaction, and installer/operator experience. These data were analyzed to determine the potential for energy savings from these systems. This report provides details on the steps taken to collect and analyze the data as well as the results and recommendations on how to best consider these systems.

2.0 Sites

A search for appropriate test sites was conducted and five sites were identified (see Table 1). At each site the existing lighting, which consisted primarily fixtures with linear T8 fluorescent lamps, was replaced with LED based lighting.

Table 1. The Five Field Sites in the Lighting Evaluation

Site #	1	2	3	4	5
Building Type	Brewery	Office	Medical Office	Retail/Grocery	Office
Organization	Two Roads Brewing Company	Rhode Island Public Utilities Office	Multi-Tenant Medical Office Building	Stop & Shop	Yale Office Building
Location	Stratford, CT	Warwick, RI	Avon, CT	New Bedford, MA	New Haven, CT
Fixture Type	Troffers High Bays	Troffers	Troffers	Linear direct/indirect pendants	Troffers
Manufacturer	Digital Lumens	Philips Spacewise	Cree Smartcast	Current by GE & Daintree Control Scope	Enlighted
Site Size, sq. ft.	103,000	19,400	30,500	73,000	25,000
Occupancy Sensors	Added	Replaced	Added	Added	Replaced
Daylight Sensors	Added	Added	Added	None	Added
Task Tuning	None	Set at factory	Added	Added	Added
Other Features (Scheduling, battery backup emergency testing/management, Power/Energy monitoring, Data download/access, Occupant mapping) evaluated at ad hoc at certain sites.					

See Appendix B for detailed descriptions of each site.

3.0 Technologies

Lighting and control systems from five different manufacturers were selected and a different manufacturer's system was installed at each site. Although the same basic control capabilities were installed at each site, there were some optional capabilities that varied by site. The five manufacturers are listed in Table 1.

The basic control functions available with all of these systems are described in Table 2.

Table 2. Control Strategies Employed in Field Evaluations

	**Task Tuning** – Also referred to as "High-End Trim" this strategy makes uses of the dimming feature inherent in most LED products to adjust the light levels to match task needs or occupant preferences. In retrofits, this often results in energy savings as the original lighting design may have over light the space. "Institutional tuning" is tuning that typically occurs during the initial commissioning process when the lighting is installed in a new or retrofit situation. It applies to whole zones, floors, or buildings where lighting levels are set to a target, such as the Illuminating Engineering Society-recommended (IES) task levels, and the high end is capped, resulting in permanent energy savings. In contrast, personal tuning is where occupants in an individual space can separately control the output level of the lighting in their own space, using either wall switches or wireless remotes or handheld tablets or smart phones.
	**Occupancy-based controls** – Occupancy sensors automatically turn on the lighting when motion is detected and automatically reduce or turn off the lighting when no occupancy is detected. Vacancy sensors are manually switched on and automatically turn off when no motion is detected.
	**Daylight harvesting** controls – These are sensors that detect ambient light levels and reduce or turn off electric lighting when sufficient daylight is available.

4.0 Evaluation Plan

For each site and system, PNNL evaluated five characteristics of the lighting systems: 1. energy savings; 2. lighting characterization; 3. cost-effectiveness; 4. occupant satisfaction; and 5. installer/operator experience.

Energy usage metering was provided by The Cadmus Group (Cadmus) through a subcontract with PNNL. PNNL completed the light level measurements and developed the survey instruments. Site representatives administered the surveys and provided utility rate, rebate, and installation cost values.

4.1 Energy Savings

Cadmus installed Watt-Node energy monitoring devices on each measured electric lighting circuit and used cellular modems to collect energy data and to check for consistency. Pre-retrofit and post-retrofit data were typically gathered for a minimum of 2 weeks and up to 2 months for each project retrofit stage, depending on site type and usage. This ensured consistency in the data so that PNNL could extrapolate the evaluation period to a full year of use. Some sites operated under a routine schedule (e.g., 9am-5pm) with very specific on and off times for lighting loads while others had inconsistent daily operational hours. Cadmus also installed daylight photo-sensors in selected locations to capture the amount of daylight entering the space during measurement periods to help in daylight savings analysis.

Cadmus applied a method to consistently extrapolate the effect of controls between pre-retrofit and post-retrofit measurements. This method uses Hours of Use (HOU) from the pre-retrofit time and from the post-retrofit time to determine the effective occupant use.

Once data were collected for a reasonable time frame the data were used to extrapolate out to a complete year. Holiday hours were removed from the pre-and post-retrofit data Annual hours were then multiplied by the average energy use per hour over the data collection time frame. Pre- and post-retrofit data were then compared for an overall energy savings value. This method was used to determine energy savings for the initial replacement of the fluorescent lighting with the LED technology and for each of the control capabilities:

- Task tuning of the system
- Occupancy sensor control and
- Daylight sensor control (where applicable).

Each site was metered continuously before and after the retrofit to capture the following:

1. Baseline energy. Appropriate lighting circuits were measured for a minimum of 2 weeks prior to any retrofit.
2. Replacement of lighting technology. Energy use was captured after installation and before tuning. In most cases, fluorescent fixtures were replaced one for one with LED lighting systems. For example, a 2’ x 4’ or a 2’ x 2’ fluorescent fixture would be replaced with an LED fixture of the same size. Linear light fixtures and downlights were commonly replaced in a similar fashion. Once the lighting systems were changed out, the LED system was energized at full output for 24 hours to calibrate the energy meters for post-LED, but pre-control load values.
3. Task tuning. Light levels were adjusted (typically reduced) to meet occupant or programmatic needs. In most cases this resulted in light levels near IES recommendations. Energy meters captured energy use at tuned lighting levels for a minimum of 24 hours prior to any other control activation to established post-LED tuned (but no active control) load values.
4. Occupancy controls. After the occupancy controls were activated, the energy meters were used to collected energy usage data associated with these occupancy sensors before daylighting controls were activated. At some sites, the controls were set to turn off the lights based on a timer set to the building’s operating hours in addition to being based on detecting a lack of motion.
5. Daylighting controls. Energy usage was metered after the daylight controls were activated. In addition the amount of daylight coming through the windows was also measured; the measured daylight was compared to published weather data to correlate daylight energy savings and available daylight. The

measured energy savings from daylight controls was then extrapolated for the entire year. To properly extrapolate the number of hours of annual daylighting control, Typical Meteorological Year (TMY)[1] data were used. These data give an approximated annual hours of solar data averaged over the past 30 years. The TMY data were then used to extrapolate the measured daylight-driven energy savings to a typical annual savings value.

4.2 Lighting Characterization

The characterization of lighting before and after a lighting retrofit is useful in helping to understand how changes to light levels can affect energy savings and occupant satisfaction. For these evaluations, light levels were measured on horizontal work surfaces or the floor, both before and after the retrofit. Measurements were taken using handheld Minolta light meters on typical grid formations with measurements typically 2 feet apart where practical and in the same locations before and after the retrofits. Post-retrofit levels were taken after full commissioning was completed. This ensures that the occupants have settled into the space and are comfortable with the levels so that representative measurements will result. Both sets of measurements were taken after hours when no daylight was present to ensure that the measurement captured just the electric lighting.

4.3 Cost Effectiveness

Cost effectiveness was evaluated using actual installation costs and energy costs. This also included utility rebates that were provided for each product. System installation costs were provided by the technology provider. Energy rates and rebate values were provided by the appropriate local utility. Cost-effectiveness was evaluated using Simple Payback (SPB) and Savings-to-Investment Ratio (SIR) metrics.

4.4 Occupant Satisfaction

To measure satisfaction among occupants, PNNL developed an occupant survey that was administered by site staff to occupants in the facility. The surveys were designed to solicit anonymous responses to ensure the most candid input possible. The surveys were distributed both before and after the retrofit. The "after" survey was distributed with a 2-week delay that allowed occupants to have time to get used to the new lighting and to avoid the instant reactions that might not be representative of overall acceptance or rejection.

Staff turnover within the various departments within the buildings was relatively low and therefore the responses received are generally from the same pool of occupants both before and after the retrofits. See Appendix C for copies of the occupant satisfaction survey, installer survey, and facilities or building manager lighting system operation survey.

Survey results were then analyzed to identify trends in occupant satisfaction or issues across the site. The survey asked specific questions related to overall satisfaction as well as glare, level of brightness, and the effectiveness of the controls.

[1] http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/tmy3/

4.5 Installer Experience

A separate survey was administered by project staff to the individuals performing the physical retrofitting of the lighting and connections shortly after the work was completed. Questions on this survey were specifically aimed at identifying any issues with installing the controls technology that might be different, easier, or more troublesome compared to installing more typical fluorescent or standard LED technology. A copy of a typical installer survey used in this evaluation is in Appendix C.

4.6 Operator Experience

The responsible facilities operations staff also received a survey with specific questions. These questions were designed to evaluate the operation of the new system as compared to the previous system. The survey also inquired about the operator's opinion regarding the effectiveness of the new system for meeting facility needs. A copy of a typical operator survey used in this evaluation can be found in Appendix C.

5.0 Evaluation Results

5.1 Energy Savings

Energy savings from these evaluations are presented in this section. The majority of energy savings were provided by 1) the reduction in energy usage from the basic replacement of the previous lighting to the new LED lighting (separate from any control savings) and 2) implementation of tasking tuning lighting control strategies. For sites 4 and 5, the task tuning control strategy saved more energy than occupancy sensing and daylight harvesting combined. As older lighting systems are replaced with new LEDs and control technologies, the task tuning strategy provides a significant opportunity for additional energy savings. Savings opportunities are greatest where the pre-existing lighting levels are more than is needed or where LED replacements may be conservatively oversized in their lumen output.

Table 3 shows the energy savings for each site. Additional details and descriptions of the savings measured at each site can be found on the DesignLights Consortium website.

The FL-to-LED fixture change savings reported in 3 show that, for most sites, this initial change to LED fixtures provided a very significant portion of overall savings. Occupancy control savings vary greatly, and two of the sites show very small negative occupancy sensor savings from the new advanced controls. These are sites where occupancy sensors already existed in many areas of the facility before the retrofit. Although these sensors were replaced with new occupancy sensors, the new occupancy controls did about the same job of saving energy as the previous occupancy controls. The fact that the relative savings in these examples are slightly negative may be because of certain performance characteristics of advanced occupancy controls. Some advanced control systems are incorporated into luminaires that have integrated sensors that turn-on automatically and dim rather than turning off completely when not sensing motion, as opposed to a simple manual on/off occupancy control. Although this creates a more pleasing and less distracting adjustment, it may use slightly more energy than traditional occupancy control methods. The limited occupancy-based savings in site 4 is expected since this is a grocery story with steady activity. Also, although retail environments have become comfortable with display case lighting dimming in response to lack of aisle occupancy, few retail stores have embraced dimming aisle lighting when the aisles are not occupied. In retail facility types, there may be few periods with no occupancy. There is also a desire to keep the lights on during operating hours regardless of occupancy; therefore, the controls are commonly commissioned for higher ambient levels across large areas even with limited occupancy.

Daylight control savings were found to be more consistent across these test sites; the smaller numbers indicate the limited daylight availability in the sites evaluated. Site 1 savings came primarily from manufacturing areas. Site 2 (an office building) had a significant amount of space with limited window access. Site 3 (the medical office) had significant perimeter spaces, and site 5 (the other office building) was configured with a hallway next to the windows thus limiting the ability of daylight to reach the office areas.

Savings vary because of variations in pre-retrofit fluorescent lighting products, pre-retrofit lighting levels, and post-retrofit lighting levels (to meet occupant needs). The most significant variability is found in the FL-to-LED replacement savings. Occupancy control savings also vary greatly but this is commonly a result of the differences in occupant activity. Note that although all sites have a similar total savings between 60% and 70%, it should not be assumed that this level of savings can be expected for most other sites. See the second set of savings comparisons in Table 4 for more widely applicable savings potential.

Table 3. Summary of Energy Savings – All Site Applications

Site	FL to LED Only	Task Tuning	Occupancy Control	Daylighting Control	Total: LED with All Controls	Notes
1 – Brewery	50%	(a)	10%	6%	66%	
2 – Office	64%	(b)	-2%	5%	67%	Pre-retrofit occupancy sensors
3 – Medical Office	29%	(c)	24%	9%	62%	
4 – Retail/Grocery	30%	33%	3%	~	66%	
5 – Office	43%	24%	-1%	4%	70%	Pre-retrofit occupancy sensors

Tuning at this site was negligible as it only applied to a very few fixtures in one area.

Task tuning was not separately done at this site. Fixtures were shipped to the site with 88% output effectively applying a 12% tuning.

Task tuning was done at two different steps at this site in direct coordination with both FL to LED replacement and Daylighting Control savings and therefore not separately captured.

The savings shown in Table 4 are calculated as the percentage of savings that a system of advanced controls could save by themselves, not counting the fluorescent-to-LED savings; i.e., the new LED equipment is the baseline here. These savings represent the percentage savings possible with advanced controls irrespective of changes in lighting technology. This is most typically known as the “Control Factor” and is often used by utilities in their energy savings calculations.

Task tuning shows significant potential for savings and is typically a unique capability of advanced control systems. These savings are, however, commonly driven by the existing conditions at the site (higher light levels than needed or wanted).

Savings for occupancy-based advanced controls show a wide variation from a high of 34% to essentially no savings where sensors already existed or occupancy control is not an option, such as retail.

Table 4. Summary of Control Energy Savings – Projected for Typical Application (Control Factors)

Site	Task Tuning	Occupancy Control	Daylight Control	Total[a]
1 – Brewery	~[b]	19%	13%	32%
2 – Office	12%[b]	-5%[c]	16%	23%[c]
3 – Medical Office	8%[b]	28%	10%	46%
4 – Retail/Grocery	47%	4%[d]	~[d]	51%[d]
5 – Office	43%	-2%[c]	7%	48%[c]
Average[e]	28%	9%	12%	40%[e]

(a) Because of rounding, not all values will laterally sum to the value in the total column

(b) These values are estimated. Site 1 had no significant tuning performed. Site 2 had fixtures shipped to the site with 12% output reduction. Site 3 had tuning completed at two different times, one of which was after the monitoring of this site, Therefore the 8% estimate for site 3 is not directly comparable to other collected data for this site.

(c) These sites had standard occupancy sensor controls in most spaces prior to the retrofit.

(d) This site is a retail grocery that has little opportunity for occupancy sensor savings and daylighting.

(e) Average is for the vertical column and is no additive laterally.

5.2 Illuminance

Illuminance values were taken at selected locations in each facility that were expected to represent typical lighting conditions. Table 5 presents these values in footcandles (fc) for all five evaluation sites. The values show that lighting levels both pre- and post-retrofit varied between sites as expected based on differences in initial site conditions and post-retrofit occupant and task needs.

Table 5. Light Levels Pre- and Post-Retrofit

	Pre-Retrofit (fc)	Post-Retrofit (fc)	Change
Site 1 (Brewery)			
Waiting Lounge	35	56	59%
Exterior Covered Storage	36	21	-41%
Front Lower Mezzanine	9	53	496%
Lunchroom	42	54	31%
Outer Office	51	55	7%
Rear Lower Mezzanine	38	55	45%
High Bay Production	13	37	188%
Site 2 (Office)			
Open Hallway	47	38	-18%
Elevator Lobby	36	30	-18%
Open Hallway	38	32	-16%
Enclosed Hallway	11	26	147%
Lobby	19	36	85%
Site 3 (Medical Office)			
Suite 304	63	25	-61%
Hallway	56	15	-74%

	Pre-Retrofit (fc)	Post-Retrofit (fc)	Change
Suite 204	49	29	-40%
Site 4 (Retail/Grocery)			
Conference/Lunchroom	23	18	-23%
Floral Shop	64	33	-49%
Central Storage	18	15	-15%
Cracker/Juice Aisle	46	39	-15%
Juice Shelves (vertical)	38	41	7%
Site 5 (Office)			
Open Office	32	44	38%
Meeting Room	62	45	-27%

5.3 Cost Effectiveness

Cost savings and associated effectiveness is presented in this study as Simple Payback (SPB) and Savings-to-Investment Ratio (SIR). Total project costs were provided by the installation contractors. It should be noted that at the time of these projects that these were new technologies. The installation contractors were less familiar with these (or some aspects) of these technologies and the contractors included additional installation labor time into their pricing to address unfamiliarity with certain aspects of the technology. Further the projects were not competitively bid; therefore, the costs presented may not be typical for projects of this type that are competitively bid. Table 6 provides installed costs of the fixtures and controls at each site, without and with the available rebates included in the costs for each project.

Table 6. Site Installation Costs and Rebates

			Installed Cost without Rebate		Installed Cost with Rebate	
Site	Fixture Type	Floor Area, Sq. Ft	Total	Per Sq. Ft	Total	Per Sq. Ft
1 – Brewery	High bays and troffers	103,000	$158,489	$1.54	$95,093	$0.92
2 – Office	Troffers	19,400	$110,900	$5.72	$69,900	$3.60
3 – Medical Office	Troffers	30,500	$92,500	$3.03	$54,550	$1.79
4 – Retail/Grocery	Linear direct/ indirect pendants	73,000	$583,061	$7.99	$490,808	$6.72
5 – Office	Troffers	25,000	$116,600	$4.66	$67,600	$2.70

Table 7 shows that, with the rebates in place, in all cases, the SIR is at least 1.0, indicating the project should pay for itself over the estimated life of the system (assumed to be 20 years).

Table 7. Site Cost Effectiveness – Savings, Simple Payback, and Savings-to-Investment Ratio

Site	Annual Energy Savings	Product Life	SPB/SIR without Rebate	SPB/SIR with Rebate

	(kWh)	$	Years	SPB (years)	SIR	SPB (years)	SIR
1 - Brewery	95,000	$13,800	20.0	11.5	1.74	6.9	2.90
2 – Office	39,500	$4,700	20.0	23.6	0.85	14.9	1.34
3- Medical Office	69,000	$8,200	20.0	11.3	1.77	6.7	3.01
4 – Retail/Grocery	439,300	$65,985	20.0	8.8	2.26	7.4	2.69
5 - Office	34,600	$5,190	20.0	22.5	0.89	13.0	1.54

Without the rebates, the payback period is longer, as expected, and the SIR for two of the three projects dips below 1.0. It is important to keep in mind that the costs and benefits for each project are different and the results shown will not necessarily apply elsewhere.

5.4 Occupant Satisfaction

For these evaluations, occupancy surveys were developed by PNNL and administered by each site to as many building occupants as possible. Survey responses ranged from 21 to 38 completed pre-retrofit surveys and 9 to 28 post-retrofit surveys. Three of the sites were able to collect both pre-retrofit and post-retrofit data. One site was only able to provide post-retrofit survey responses, and one site was unable to provide survey data.

Response rates are considered too low to be used to provide any comparative ratings (i.e., one system has a specific better satisfaction rating than another). The generally lower response rates after the retrofit (35% to 67% of the initial response rates) are considered typical and also have some effect on the statistical significance of the differences between pre- and post-retrofit responses. However, where large differences in average responses are found, they can be instructive in identifying potential trends in occupant acceptance. The analysis of survey responses for this evaluation project focuses on the general overall trends across the sites. Table 8 provides a summary of the time-of-day lighting responses on lighting conditions both before and after the retrofits.

Table 8**. Occupant Survey Time-of-Day Lighting Response Summary**

Site		Morning lighting is too bright or too dim at times.	Afternoon lighting is too bright or too dim at times.	Nighttime lighting is too bright or too dim at times.
1 – Brewery	Before	26%	15%	28%
	After	0%	0%	11%
2 – Office	Before	26%	23%	---
	After	22%	17%	---
3 – Medical Office	Before	---	---	---
	After	21%	21%	---
4 – Retail/Grocery	Before	---	---	---
	After	---	---	---

5 – Office	Before	24%	29%	---
	After	38%	21%	---
Weighted (by response)	Before	26%	22%	28%
Average	After	22%	18%	11%

Significant findings related to occupant satisfaction with time-of-day lighting levels include the following:

- Compared to other parts of the day, lighting during the morning yielded the highest responses of the lighting being either too bright or too dim for either the fluorescent (26%) or LED (22%) lighting systems.
- In general, lighting during the afternoon was neither too bright nor too dim for either lighting system evaluated.
- Only Site 1 had evening and overnight shift work. Survey responses indicate that the nighttime lighting at this site was neither too bright nor too dim.

Questions about the lighting systems were asked about lighting conditions as well and not just time of day conditions. Table 9 provides a summary of the lighting conditions responses on lighting conditions both before and after the retrofits.

Table 9. **Occupant Survey Lighting Conditions Response Summary**

Site		Neutral or very satisfied with brightness of lighting.	Neutral or very satisfied with automatic control of lighting.	Neutral or very satisfied with overall lighting conditions.
1 – Brewery	Before	81%	81%	85%
	After	89%	89%	100%
2 – Office	Before	78%	59%	89%
	After	100%	87%	96%
3 – Medical Office	Before	---	---	---
	After	89%	86%	86%
4 – Retail/Grocery	Before	---	---	---
	After	---	---	---
5 – Office	Before	89%	85%	100%
	After	79%	71%	85%
Weighted (by response)	Before	82%	72%	90%
Average	After	91%	84%	90%

Significant findings related to occupant satisfaction with lighting conditions include the following:

- In response to a general question on brightness, the occupant responses were mixed but show a weighted average increase in satisfaction of the brightness of the lighting with the new advanced system going from 82% (fluorescent) to 91% (LED) satisfaction.
- The occupants were overall more satisfied with the function of the automatic controls installed with the new system showing satisfaction rates going from an average of 72% to 84%.
- The responses to a separate generic question about overall satisfaction with the lighting shows that occupants had approximately the same level of satisfaction with both systems (approximately 90% before and after).

5.5 Installer/Operator Experience

Installers (5 respondents) and facility operators (5 respondents) provided an estimate of the time needed for commissioning the system, which in some cases was completed by the lighting system manufacturer and in other cases by the installation contractor with support from the lighting system manufacturer. The reported estimates varied from 10 minutes to a few hours to 2 days per fixture. This large variance may be driven by different site lighting needs, which can increase commissioning time. In some sites, there were no specific light level requirements and the system was installed and commissioned to standard settings. In other cases, light levels were customized to meet overall facility and/or individual occupant needs. For those sites noted below where initial control issues were found and corrected, additional commissioning time would typically be required. Although some noted that some additional time was needed to meet specific occupant needs, the adjustment for this was easy.

Several specific notable observations were made by the installers and facility operators:

- Initially there were issues with loss of control/program settings and shutoffs at Site 2 (office) and Site 3 (medical office site), which resulted in the replacement of LED drivers.

- Most sites also noted that the software system for the new LED lighting had a learning curve but the control function was more user-friendly than the previous stand-alone occupancy sensor controls.

6.0 Findings and Recommendations

This set of field evaluations does not seek to compare advanced control systems. However, the results provide information on the viability of various advanced control capabilities as applied to site types and points to consider when evaluating options.

The following are conclusions and recommendations for the use of advanced lighting control systems based on these five site evaluations:

- Task Tuning can provide a large opportunity for energy savings, often greater than occupancy and daylight harvesting. The tuning (dimming) capability of most advanced lighting control systems can take advantage of high pre-retrofit light levels, oversizing of LED replacement luminaires/lamps, and individual occupant preferences to provide maximum savings from initial and ongoing light level adjustments. This study shows the potential for energy savings of 30% or more from tuning when high pre-retrofit light levels exist. It is highly recommended that potential energy savings from the reduction of lighting levels (new fixtures and tuning) be calculated as part of any justification of project cost-effectiveness. Site-specific light level needs (proposed design illuminance) should be determined and existing light levels should be measured to support these calculations.
- The potential for savings based on occupancy controls is limited if the site has existing basic occupancy sensor technology already installed. Advanced control systems can provide a more uniform and smoother transition from occupied to unoccupied lighting levels and back again, promoting better quality lighting for work environments along with granular sensing and automatic-on features. However, the data from these evaluations found that in many cases this more advanced occupancy sensor control methodology can slightly increase energy use compared to more typical pre-existing occupancy sensors. This is attributable primarily to two reasons:
  - The sometimes distracting on-off control of traditional occupancy sensors is replaced with more gradual tuning up and down with advanced systems, which can mean slightly more energy usage in some cases.
  - Fully automatic advanced controls typically replace any manual-on occupancy sensor function, which can also slightly increase energy use in some applications.

  It is recommended that if occupancy sensor or daylighting controls already exist in areas being retrofitted at the site, then any savings associated with this part of the advanced system should not be used to justify project cost-effectiveness for those areas. Further, to ensure the same or better performance with new advanced occupancy sensors, it is important to ensure that the new occupancy control is correctly commissioned with the lowest timeout settings possible and implemented with manual-on “vacancy” controls where possible.
- The application of advanced fully automatic controls may be something occupants need to get used to if all control was manual before the retrofit. It is recommended that lighting retrofit projects involving occupant work areas be announced in advance with information provided to occupants regarding the characteristics of the changes and potential advantages. Further, while these systems can function without providing manual control options for occupants, it may be desirable to install the optional manual switches in occupant spaces.

- New advanced control systems may have communication or compatibility issues (as with all connected systems). Two of the sites experienced early control issues that eventually required replacement of the LED drivers. The issues were found to be a manufacturing defect in the driver in one case and in another case, new drivers with electrical noise that interfered with control signals being used prior to complete compatibility testing. These were in effect quality control issues that were not addressed by the manufacturer prior to shipment of the products. It is highly recommended that any proposed new system be tested for compatibility with existing and new system electronics.
- Advanced control systems typically include a full suite of combined complete control capability. This maximum capability is effective but savings may not be realized if partial controls already exist on site or if there is limited opportunity at the site such as limited daylight. The cost effectiveness of advanced lighting control systems must be evaluated based on the true potential for savings at the specific site.

In general, the findings from these evaluations show that advanced lighting control systems can provide cost-effective energy savings and better control functionality but savings depend greatly on the existing site characteristics, including current lighting conditions and the existence of controls.

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Demonstration Site Descriptions

Appendix A

Demonstration Site Descriptions

Site 1 – Two Roads Brewing Company - Stratford, CT

Two Roads Brewing Company, founded in 2012, is a brewery offering new twists on a variety of craft beers from their Stratford, Connecticut, location in a renovated 1911, 103,000-ft^2 building. The 2012 renovation changed the building into an industrial-scale microbrewery with bottling operations, a tasting room, offices, restrooms, shipping and receiving, and storage. The local utility, United Illumination Company (UI), recruited Two Roads with a proposal to update their fluorescent lighting to capture energy savings. New LED control systems can provide modern convenience with wireless communication and advanced software options that allow for customization of light levels and schedules to meet application and occupant needs.

Site 2 – Rhode Island Public Utilities - Warwick, RI

The Rhode Island Public Utility Commission (RIPUC) occupies a multi-story 19,400-ft^2 office building constructed in 1980 in Warwick, Rhode Island. Although the facilities were lighted with standard T8 fluorescent technology, the LED lighting and intelligent controls retrofit completed in 2016 offered additional savings and better quality lighting and control. The RIPUC installed the new LED lighting and intelligent control system. The advanced software options allow for customization of light levels to meet application and occupant needs.

Site 3 – Multi-Tenant Medical Office Building - Avon, CT

The medical office facility located at 44 Dale Road in Avon, Connecticut, houses multiple healthcare providers in three stories of mixed use space including offices, examination/procedure rooms, and testing laboratories. Constructed in 1985, this 30,500-ft^2 building was initially outfitted with fluorescent lighting. The building owner chose the recent LED lighting and controls retrofit to harvest extra savings and to improve lighting and control quality. The new LED system provides wireless communication, and advanced sensor options allowing for customization of light levels to meet application and occupant needs.

Site 4 – Stop & Shop Grocery - New Bedford, MA

The Stop & Shop store in New Bedford, Massachusetts, is a 73,000-ft^2 full-service grocery store with offices and a smaller mezzanine area upstairs. Originally, the building had fluorescent lighting and the building owners were interested in the savings potential offered by new LED technology and advanced controls. The task tuning ability was particularly of interest as it ensures quality lighting for the various products, consumers, employees, and tasks in each section.

Site 5 – Yale Office Building - New Haven, CT

The demonstration site at 221 Whitney Avenue in New Haven, Connecticut, is a 75,000-ft^2, 6-story administration building. This demonstration involved floors 5 and 6 with approximately 25,000 ft^2 of office space encompassing the Yale Human Resources department. Originally, the space was lighted with T8 fluorescent technology and had stand-alone occupancy controls. The building owners were interested in the potential savings associated with advanced controls as well as a lamp upgrade to LEDs.

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Site Lighting Systems

Appendix B

Site Lighting Systems

Site 1 – Digital Lumens

At Site 1, the brewery, a Digital Lumens Intelligent LED Lighting System was installed. The system incorporates lighting fixtures with embedded intelligence that includes occupancy and daylight sensing controls integrated or pre-installed in the new light fixtures. The Digital Lumens LED high-bay and low-bay fixtures were installed in the industrial area, and office areas were outfitted with Philips Evokit troffers with pre-installed Digital Lumens controls. The Digital Lumens LightRules® software program enables high-end trim/tuning, scheduling, occupancy sensing, and daylight harvesting.

Site 2 – Phillips SpaceWise

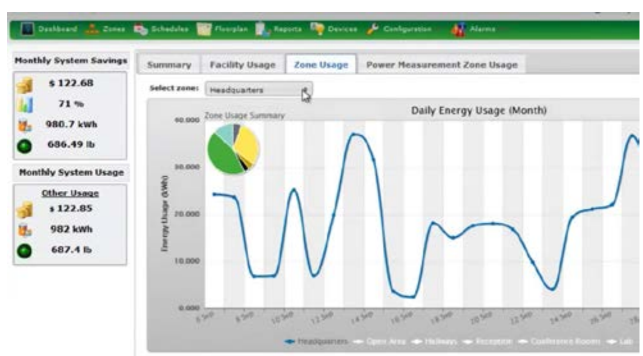
The Philips SpaceWise technology installed at Site 2, the office building, is a fully integrated wireless control system that is applied at the luminaire level to provide plug-and-play lighting energy savings. It has application modes for open plan offices, private offices, meeting rooms, corridors, and emergency egress. On-board technology provides dimming in response to both occupancy sensing and daylight harvesting. Full light output is delivered only to occupied workstations with background settings typically at only one-third of full output. In addition, the system allows for task tuning to adjust lighting to desired levels and daylighting control requires no separate zoning or configuration. For this demonstration, the scope of the project included replacement of the existing luminaires with new Philips DuaLED luminaires with onboard controls.

Site 3 – Cree SmartCast

Cree SmartCast technology was installed at Site 3, the medical office building. This technology is applied at the luminaire level and incorporates wireless controls that support easy one-for-one replacement. The installed system offers area control applied to subgroups of fixtures based on room environments. This grouping and control activation was completed wirelessly using Cree's handheld remote commissioning device. Onboard sensing including occupancy sensing and daylighting can be activated on an individual fixture and/or group basis. Final commissioning included activation of occupancy sensing for all fixtures and daylighting control for those next to windows. Building managers set light levels based on tenant preferences. The SmartCast technology allows tenants to change light settings as needed with available remotes. For this study access to lighting controls was limited to building managers and lighting installers to ensure data consistency.

Site 4 – Daintree ControlScope®

At Site 4, the grocery store, Current's Daintree ControlScope® Manager (CSM) was installed. This lighting control software solution uses Zigbee mesh networking. This networking system can set up fixture groups within the CSM to facilitate localized control. LED luminaires such as the Cooper Corelite™, Cooper Encounter™, and Precision Paragon™ were shipped with pre-installed Zigbee-enabled controls compatible with the Daintree Control System. All luminaires were set up with built-in occupancy and daylight harvesting sensors and can be task tuned with Daintree software. The CSM software scheduling feature image provides for light levels to be tuned to specified levels at specified times. Occupancy sensing was activated in certain areas, task tuning was enabled in fixture groups as suited to location and occupant use, and daylight harvesting was activated in the fixtures by the store front windows.



Site 5 – Enlighted

The Site 5 office building, used an Enlighted Advanced Lighting Control System that provides a distributed architecture with a SMART sensor at each fixture. The programming resides locally at the fixture and adjusts (by dimming) the lighting level for each fixture according to that sensor's unique perception from its position in its environment. The sensor is powered by the fixture and collects occupancy and daylight data that combines with schedule and set point data to determine the optimal light level for that fixture. This network of sensors performs fine-grained control of light levels based on measured occupancy and ambient light levels through the Enlighted Gateway and the Enlighted Energy Manager (EEM). The Enlighted Gateway aggregates wireless communications between the network of Enlighted SMART Sensors and the EEM appliance. The Enlighted system is designed to be easy to install, configure, commission, and service.

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Surveys

Appendix C

Surveys

Surveys were administered to building occupants, system installers, and facility operators. Surveys were provided to site staff who took responsibility to distribute the surveys, which were returned via the same staff or directly through the mail. In some cases, surveys were either not distributed or not completed, resulting in a few sites with missing data. For reference, the following table shows the status of the surveys.

Table C.1. Status of Surveys

Site	Pre-retrofit Survey	Post-retrofit Survey	Installer Survey	Facility Operator Survey	Luminance Readings Pre-retrofit	Luminance Readings Post-retrofit
Site 1	Yes	Yes	Yes	Yes	Yes	Yes
Site 2	Yes	Yes	Yes	Yes	Yes	Yes
Site 3	No	Yes	Yes	Yes	Yes	Yes
Site 4	No	No	No	Yes	Yes	Yes
Site 5	Yes	Yes	Yes	No	Yes	Yes

Surveys provided to the different groups are in the following pages.

Occupant Lighting Conditions Survey

This survey is being distributed by facility staff to help understand how effective the lighting in your workspace is in meeting your needs. Results from the survey will help facility staff evaluate this type of lighting and identify any useful future changes. Participation is voluntary and no identifying information will be shared or published. If you have questions about your rights as a participant of this research survey, please email the Institutional Review Board at Katherine.Ertell@pnnl.gov. The survey takes less than 5 minutes to complete.

1. Please identify your type of workspace.
   ___ Private office
   ___ Cubicles with partitions
   ___ Open office with no partitions
   ___ Other – please describe ____

2. Do you sit in an area or office that has windows?
   ___ Yes. ___ No.

3. Can you see out of a window from your workspace?
   ___ Yes. ___ No.

4. Age category?
   ___ 30 or under ___ 31-50 ___ Over 50

5. Gender?
   ___ Male
   ___ Female

6. What percentage (roughly) of your time is spent in your workspace doing the following?
   ___ View materials on paper
   ___ View materials on screens
   ___ Typing
   ___ Filing
   ___ Face-to-face meetings
   ___ Other

7. How is the BRIGHTNESS of just the overhead electric light in the MORNING?
   ___ Too bright ___ Neutral ___ Too dim

8. How is the BRIGHTNESS of just the overhead electric light in the AFTERNOON?
   ___ Too bright ___ Neutral ___ Too dim

9. How satisfied are you with the electric lighting system's brightness response to changing occupancy (when occupants arrive, leave, and sit at their workstations)?
   ___ Very satisfied
   ___ Neutral

___ Very dissatisfied
___ N/A

10. How satisfied are you with the overhead electric lighting system's brightness adjustment (dimming) in response to daylight?
___ Very satisfied
___ Neutral
___ Very dissatisfied
___ N/A

11. Overall, how satisfied are you with lighting conditions in your workspace?
___ Very satisfied
___ Neutral
___ Very dissatisfied
___ N/A

12. Please describe any issues related to your workspace **lighting** that are important to you.

____

____

13. Please describe any other issues related to your workspace in general that are important to you.

____

____

Contractors/Installers Survey

Your responses to these questions will be used to help facilities staff and other's understand any installation issues or preferences for this lighting system. Participation is voluntary and no identifying information will be shared or published. Answering the questions should take less than 5 minutes of your time.

Background:

1. Which lighting system did you install? ______________________________
2. At which location did you install the product? ______________________________
3. On what date did the install start? ______________________________
4. On what date did the install end? ______________________________
5. On what date was the system activated for use by occupants? ______________________________

Installation Instructions:

6. Were the installation instructions easy to understand?
   ___ Easy
   ___ Ok
   ___ A bit tricky
   ___ N/A

7. Did the installation instructions address all installation steps?
   ___ Yes
   ___ No
   ___ Almost (Please Describe) ______________________________
   ___ N/A

8. Were the installation instruction needed to complete the install?
   ___ Yes ___ No

Installation:

9. Were there any safety issues related to installing this particular system?
   ___ No
   ___ Yes (Please Describe) ______________________________
   ___ N/A

10. Were there any complications related to installing this particular system?
    ___ No
    ___ Yes (Please Describe) ______________________________
    ___ N/A

11. Was the system as easy to install as a standard fluorescent system with basic controls?
    ___ Yes
    ___ No (Please Describe) ______________________________
    ___ Almost (Please Describe) ______________________________

___ N/A

Maintainability:

12. Is there anything about the system that you believe may create future maintenance issues?
    ___ No
    ___ Yes (Please Describe) ____
    ___ N/A

13. Does the system seem to be as easy to maintain as a standard fluorescent system with basic controls?
    ___ Yes
    ___ No (Please Describe) ____
    ___ Almost (Please Describe) ____
    ___ N/A

Commissioning – if you were also involved with commissioning the system:

14. How was commissioning of the control system accomplished?
    ___ Automatic – little to no operator action required
    ___ Manual setup by operator
    ___ Other ____

15. Was the commissioning simple and straightforward?
    ___ Yes
    ___ No (Please Describe) ____
    ___ Almost (Please Describe) ____
    ___ N/A

16. How long did the commissioning process take?
    ___ Less than 30 minutes at one time?
    ___ 1 or more hours at one time? Please indicate number of hours _______
    ___ Multiple actions/activities over 1 or more days.
        Please indicate number of days involved _____
        Please indicate TOTAL number of hours _____
    ___ Was any of the time needed for commissioning a result of issues with the system, specific equipment, or the process? If so, please describe

    ____

    ____

Other:

17. Please describe any other issues related to the installation or commissioning of the system that are important to you.

    ____

    ____

Facilities/Building Manager Lighting System Operation Survey

Your responses to these questions will help the lighting system manufacturer and others understand how well the system works and what's involved for its effective operation in a building. Answering the questions should take less than 5 minutes of your time.

Commissioning – if you were also involved with commissioning the system:

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

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

3. How long did the commissioning process take?
   a) Less than 30 minutes at one time?
   b) One or more hours at one time? Please indicate number of hours ______
   c) Multiple actions/activities over 1 or more days.
      Please indicate number of days involved _____
      Please indicate TOTAL number of hours _____
   d) Was any of the time needed for commissioning a result of issues with the system, specific equipment, or the process? If so, please describe ______________________________

   ____

Controllability

4. How easy is it to make sure the system is operating as desired?
   a) Easy
   b) Ok
   c) A bit tricky. Please describe ____
   d) N/A

5. What tasks did you need to perform most often (if any) to keep the system functioning effectively?

   ____

6. How does managing the operation of this control system compare to the old one?
   a) Easier
   b) About the same
   c) Not as easy
   d) N/A

Observability

7. How easy is it to understand how the control system was functioning by looking at the interface?

a) Easy
b) Ok
c) A bit tricky. Please describe ____
d) N/A – no interface or panel readout provided

8. What steps did you take to understand how the system was functioning?

____

9. How does this system's interface usability compare to the past system?
   a) Better
   b) About the same
   c) Not as good
   d) N/A

Reliability

10. How many system failures or malfunctions have you experienced with this system? ______
    Please describe them.

    ____

    ____

11. How does this system's reliability compare to the past system?
    a) Better
    b) About the same
    c) Not as good
    d) N/A

Maintainability

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

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

14. How does this system's ease of maintenance compare to the past system?
    a) Better
    b) About the same
    c) Not as good
    d) N/A

15. Please describe any outside help needed to maintain the system.

____

Lighting Conditions

16. Were the lighting conditions produced by the system adequate for this building?

___Yes. ___No (please describe) ____

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

Occupant Acceptance

18. Were the lighting conditions produced by the system adequate for building occupants?

___Yes. ___No (please describe) ____

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

____

____

____

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