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

May 2018

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U.S. DEPARTMENT OF ENERGY

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Abstract

This evaluation project provides data and information that can help those responsible for energy use and savings at commercial facilities determine the effectiveness of advanced control, LED based lighting system retrofits. 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. Energy use and savings were measured and calculated for energy savings related to LED technology replacing existing fluorescent lighting, and separately for savings from advanced lighting controls implementing high-end trim/task tuning, occupancy, and daylighting control strategies. The analyzed results present site specific savings as well as energy savings based on the application of advanced controls only. 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 provide facility operators with some information useful in determining the cost effectiveness and occupant acceptance of these systems and/or their parts as applicable to their facilities and their operation.

Executive Summary

This set of field evaluations, conducted from November 2015 through September 2017, demonstrates the potential energy saving capability of a sampling of advanced lighting control systems in real world/field environments. These systems were installed along with new LED fixtures and kits in various building types. This study does not provide a direct comparison of system types and the amount and type of data cannot be used to significantly or statistically imply any direct comparisons.

A total of five advanced lighting control systems were matched with field test sites. The energy use of lighting at each site was measured before and after the retrofit. Lighting energy use was measured as each part of the system was retrofitted and/or activated so that energy savings could be identified separately for each significant capability of the new system including lamp efficiency and initial design, high-end trim/task tuning, occupancy sensor control, and daylighting control. Table E1 shows a summary of the energy savings represented as percentages of the pre-retrofit energy use. As expected, savings varies by site and system characteristic (change to LED, controls) because each site, occupant activity, business schedules can be different. Note specifically that occupancy control savings varies because some sites (sites 2 and 5) already had basic versions of this control. The average line in the table provides a relative idea of typical savings that might be achievable in typical projects. The data confirms that occupancy sensor savings must be carefully considered because of their variability. High-end trim/task tuning is also dependent on site conditions and can be significantly higher or lower than the verified 29% average found in two sites in this study.

Table E1. Summary of Energy Savings – All Site Applications and Average

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

Lighting 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 new system 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 ratios of 1.3 to 3.0 with applicable utility rebates. The results show the greatest savings from advanced controls from the implementation of high-end trim/task tuning. When implemented, this relatively new control strategy can provide significant savings tuning light levels to IES recommendations or occupant preferences. The study also shows that savings from control features such as occupancy sensing and daylighting may be limited when these control capabilities such as wall-mounted occupancy sensors 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 can potentially increase energy use relative to traditional occupancy controls with “manual-on” or “vacancy” functionality.

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1.0 Introduction

This report summarizes five field evaluations of advanced LED lighting control systems. 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, and applications.

Many new and existing advanced lighting control systems use LED technology to either improve efficacy and/or because the LED technology is easily controllable. This study evaluates advanced lighting control systems for performance and energy savings in real world conditions. For each site and control system, data were collected for energy use, economics, lighting characteristics, occupant satisfaction, and installer/operator experience. These data were analyzed to determine the overall and variability of 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 involved an assessment of positive and negative facility attributes that could potentially support or hinder effective evaluation of selected lighting systems. The results of this survey helped identify the following sites that could provide useful evaluation results:

Site 1 - Two Roads Brewing Company - Stratford, CT – 103,000 square feet

- Previous lighting: Primarily linear fluorescent T8
- Retrofitted lighting system: Digital Lumens - LED with embedded advanced controls

Site 2 - Rhode Island Public Utilities Office - Warwick, RI – 19,400 square feet

- Previous lighting: Primarily linear fluorescent T8
- Retrofitted lighting system: Philips SpaceWise - LED with embedded advanced controls

Site 3 - Multi-Tenant Medical Office Building - Avon, CT - 30,500 square feet

- Previous lighting: Primarily linear fluorescent T8
- Retrofitted lighting system: Cree SmartCast - LED with embedded advanced controls

Site 4 - Stop & Shop Grocery - New Bedford, MA – 73,000 square feet

- Previous lighting: Primarily linear fluorescent T8
- Retrofitted lighting system: GE Currents Daintree ControlScope - LED with added on-board advanced controls

Site 5 - Yale Office Building - New Haven, CT. – 25,000 square feet

- Previous lighting: Primarily linear fluorescent T8
- Retrofitted lighting system: Enlighted - LED with attached advanced controls

See Appendix A for detailed description of each site.

3.0 Technologies

This evaluation involved five different advanced lighting control systems. Each system shares the same basic control architecture capabilities with some optional capabilities. The five technologies/manufacturers evaluated were as follows:

- Digital Lumens
- Philips SpaceWise
- Cree SmartCast
- GE Currents Daintree ControlScope
- Enlighted

The basic control functions available with all of these systems included the following:

- Occupancy-based control – to reduce light levels when no occupants are present
- Daylight harvesting – to reduce electric lighting when daylight is available
- High-End Trim/Task Tuning – to initially and/or periodically adjust light levels to match task needs or occupant preference.

Other optional features available as part of some systems included the following:

- Scheduling
- Battery backup emergency testing/management
- Power/Energy monitoring
- Data download/access
- Occupant mapping

See Appendix B for detailed description of each control system technology.

4.0 Evaluation Plan

For each site and system, PNNL evaluated:

- Energy Savings
- Cost-effectiveness
- Lighting Characterization
- Occupant Satisfaction
- Installer/Operator experience.

Energy 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. 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. Energy monitoring schedule also factored in holidays. If holidays occurred, data collection was extended and/or holiday time periods were disaggregated. 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 existing and post-retrofit measurement. 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, 2 weeks to 2 months depending on site and project stage, the data were used to extrapolate out to a complete year. Holiday hours were removed from the pre and post annual energy use for accurate site representation. Annual hours were then multiplied by the average energy use over the time frame of data collection. Pre and post retrofit data were then compared for an overall energy savings value. This method is used to determine energy saving for each of the control capabilities:

- Replacement of fluorescent with LED technology
- 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 2 week period 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 2x4 or a 2x2 fixture would be replaced with an LED fixture of the same retrofit size. Linear lighting and downlights were commonly replaced in a similar fashion. Once the lighting systems were changed out, the LED system was energized at full output to get the pre-control energy savings. The lights were run for a full 24 hours of operations for HOU comparison.
3. High-End Trim/Task tuning. Light levels were adjusted (typically reduced) to meet occupant or programmatic needs. In most cases this resulted in light levels that followed IES recommendations. Energy meters captured energy use at tuned lighting levels for a minimum of 24 hours prior to any other control activation.
4. Occupancy controls. Energy meters collected data associated with occupancy controls, and in some cases scheduling.
5. Daylighting controls. Energy as well as solar insolence (daylight) through windows were measured to effectively capture daylighting savings over a typical 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 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) metric.

4.3 Lighting Characterization

The characterization of lighting before and after a lighting retrofit is useful in helping 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.

4.4 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 created to remain anonymous 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 some settling time to get used to the new lighting and avoid instant reactions that may 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. A copy of a typical survey instrument is in Appendix C.

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.

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 this technology that might be different, easier,

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

or more troublesome compared to 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 were developed and presented in two formats. The first is the actual specific savings at each site that includes the variable characteristics of the site, its occupants, and activities. These savings are representative of real-world savings and can provide valuable information on the variability of savings across differing types of facilities.

The majority of energy savings were provided by 1) the reduction in energy from the basic replacement of the previous lighting to the new LED lighting (separate from any control savings) and 2) implementation of high-end trim/tasking tuning lighting control strategies. On two of the projects the high-end trim/task tuning control strategy saved more energy than occupancy sensing or daylight harvesting together. As older lighting systems are replaced with new LED and control technology, the high-end trim/task tuning strategy provides a significant opportunity for additional energy savings while at the same time meeting occupant needs for light levels. This is especially an opportunity where the pre-existing lighting is more than needed, or when LED replacements may be conservatively oversized in their lumen output.

The second set of savings are calculated as the percentage of savings that a system of advanced controls could save by themselves. These represent the percentage savings possible with advanced controls even when no savings is available form a change to LED lighting or a reduction in designed light levels as part of the retrofit. This is most typically known as the “Control Factor” and is often used by utilities in their energy savings calculations.

Table 2 shows the energy savings for each site. Additional details and descriptions of the savings measured at each site can be found on the DLC website.

The FL to LED fixture change values in Table 2 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. The lack of savings show that mathematically under the same occupancy activity, the advanced system occupancy control did about the same job of saving energy as the previous occupancy controls. However, the evaluation sites included as part of this project did not include very large open office areas, which are a prime opportunity for advanced control systems. The fact that the relative savings in these examples are slightly negative may be because of other performance aspects of advance occupancy control. Some advanced control systems apply a more complex approach to occupancy sensing where luminaires with integrated sensors turn-on automatically and dim rather than turn off when not sensing motion for an initial time period, as opposed to simple manual on/off occupancy control. While this creates a more pleasing and less distracting adjustment, it may involve small additional energy use relative to traditional occupancy control methods. The limited occupancy based savings in site 4 is expected since this is a grocery retail environment. In retail facility types, periods without occupancy can be limited and there is a desire to not have dark (lights dimmed/off) areas and therefore the controls are commonly commissioned for higher ambient levels across large areas even with limited occupancy.

Daylight control savings is found to be more consistent across these test sites and the smaller numbers indicate the limited daylight availability in the sites evaluated. As shown in Table 2, site 1 savings came primarily from manufacturing areas. Site 2 had significant core area with limited window access. Site 3 had significant perimeter spaces, and site 5 was configured with open office hallway next to the windows limiting daylight effectiveness.

Savings vary because of different pre-retrofit fluorescent lighting products, different levels of pre-retrofit lighting, and different levels of post-retrofit light levels (to meet occupant needs). The most significant variability is found in the FL to LED basic replacement that depends significantly on pre- retrofit light levels that will vary from site to site. 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 presumed that this is to be expected for most other sites. See the second set of savings comparisons in Table 3 for more widely applicable savings potential.

Table 2. Summary of Energy Savings – All Site Applications

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

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

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

[3] 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.

Table 3 shows the projected control savings calculated as a percentage of savings from just the control function.

Savings for occupancy-based advanced control shows 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.

High-End Trim/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).

Table 3. Summary of Control Energy Savings – Projected for Typical Application (Control Factors)

Site	Occupancy Control	Daylight Control	High-End Trim/ Task Tuning	Total
1 - Brewery	19%	13%	~ [1]	32%
2 – Office	-5%[2]	16%	12% [1]	23%[2]
3 – Med Office	34%	12%	(34%) [1]	80%
4 – Retail Grocery	4%[3]	~[3]	47%	51%[3]
5 – Office	-2%[2]	7%	43%	48%[2]

[1] 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 34% estimate for site 3 is not directly comparable to other collected data for this site.

[2] These sites had standard occupancy sensor controls in most spaces prior to the retrofit

[3] This site as a retail grocery has little opportunity for occupancy sensor savings and daylighting

5.2 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 values were provided by the installation contractors. It should be noted that at the time of these projects these were new technologies where installation contractors were not familiar with the systems and included this consideration in their pricing. Further the projects were not competitively bid and therefore the costs presented may not be typical for projects of this type at current times. Table 4 provides costs per site as well as the rebates that were available and applied for each project.

Table 4. Site Installation Costs and Rebates

		Installed Cost Without Rebate		Installed Cost With Rebate	
Site	Sq. Ft	Total	Per Sq. Ft	Total	Per Sq. Ft
1	103,000	$158,489	$1.54	$95,093	$0.92
2	19,400	$110,900	$5.72	$69,900	$3.60
3	30,500	$92,500	$3.03	$54,550	$1.79
4	73,000	$583,061	$7.99	$490,808	$6.72
5	25,000	$116,600	$4.66	$67,600	$2.70

Table 5 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 5. Site Cost Effectiveness – Savings, Simple Payback, and Savings-to-Investment Ratio

	Annual Energy Savings		SPB/SIR With Rebate		Product Life	SPB/SIR Without Rebate	
Site	(kWh)	$	SPB (years)	SIR	Years	SPB (years)	SIR
1	95,000	$13,800	6.9	2.90	20.0	11.5	1.74
2	39,500	$4,700	14.9	1.34	20.0	23.6	0.85
3	69,000	$8,200	6.7	3.01	20.0	11.3	1.77
4	439,300	$65,985	7.4	2.69	20.0	8.8	2.26
5	34,600	$5,190	13.0	1.54	20.0	22.5	0.89

Without the rebates, the payback is higher, 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.

5.3 Lighting Characterization

Lighting levels were taken at selected locations in each facility that were expected to represent typical lighting conditions. Table 6 presents these values in footcandles 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 6. Light Levels Pre- and Post-Retrofit

	Pre-Retrofit (fc)	Post-Retrofit (fc)	Percent 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%
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

5.4 Occupant Satisfaction

For these evaluations, occupancy surveys were developed by PNNL and administered by each site to as many building occupants as possible. The quantities ranged from between 21 and 38 pre-retrofit and 9 to 28 post-retrofit occupants. 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 6 provides a summary of the responses on lighting conditions both before and after the retrofits.

Table 6. Occupant Survey Response Summary

Issue/Response:	Site 1 (Brewery)		Site 2 (Office)		Site 3 (Medical Office)		Site 4 (Retail/Grocery)		Site 5 (Office)		Weighted Average	
	Before	After	Before	After	Before	After	Before	After	Before	After	Before	After
Morning lighting is too bright or too dim at times	26%	0%	26%	22%	NA	21%	NA	NA	24%	38%	26%	22%
Afternoon lighting is too bright or too dim at times	15%	0%	23%	17%	NA	21%	NA	NA	29%	21%	22%	18%
Nighttime lighting is too bright or too dim at times	28%	11%	NA	NA	NA	NA	NA	NA	NA	NA	28%	11%
Neutral or very satisfied with Brightness of lighting	81%	89%	78%	100%	NA	89%	NA	NA	89%	79%	82%	91%
Neutral or very satisfied with automatic control of lighting	81%	89%	59%	87%	NA	86%	NA	NA	85%	71%	72%	84%
Neutral or very satisfied with overall lighting conditions	85%	100%	89%	96%	NA	86%	NA	NA	100%	85%	90%	90%

The individual average site and weighted average responses across all sites provide several findings related to occupant satisfaction of the new advanced lighting systems:

- Lighting conditions being specifically too bright or too dim at times during typical business hours with the old fluorescent system was found by an average of 22% to 26% of occupants. With the new advanced lighting controls system, this was reduced to an average of 18% to 22%. In evening overnight shift work (Site 1), this was reduced from 28% to 11%.
- In response to a more general question on brightness, the occupant responses were mixed but show a weighted average increase in satisfaction with the new advanced system going from 82% to 91% 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 others by the installation contractor with support of the lighting system manufacturer. The reported estimates varied from a few hours to 10 minutes per fixture to over a span of 2 days. This large variance may be driven by different site lighting needs that 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 the Rhode Island public utilities and Avon, CT Medical office sites, 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 Summary 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 application recommendations for the use of advanced lighting control systems based on these five site evaluations:

- High-end Trim / 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 and provide maximum savings from initial and ongoing light level adjustments. This adjustment can be applied differently to specific individual or task location needs. This study shows the potential for 50% and better from light level reduction when high pre-retrofit light levels exist. It is highly recommended that potential energy savings from 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 footcandles) should be determined and existing light levels should be measured to support these calculations.
- The potential for savings based on occupancy control 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 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 to primarily two reasons:
    - The sometimes distracting on-off control with more typical occupancy sensors, is replaced with more gradual tuning up and down with advanced systems which can mean slightly more energy in some cases.

- Fully automatic advanced controls typically replace any manual-on occupancy sensor function which can also slightly increase energy use in some application areas.

  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 lowest timeout settings possible and implemented with manual-on “vacancy” control where possible.

- The application of advanced fully automatic control 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 occupants manual control options, 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 substantially vetted regarding existing successful installations and 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.

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 / 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 multistory 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 ft2 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.

Appendix B

Evaluation Technology Description

Site 1 – Digital Lumens

The Digital Lumens Intelligent LED Lighting 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 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.

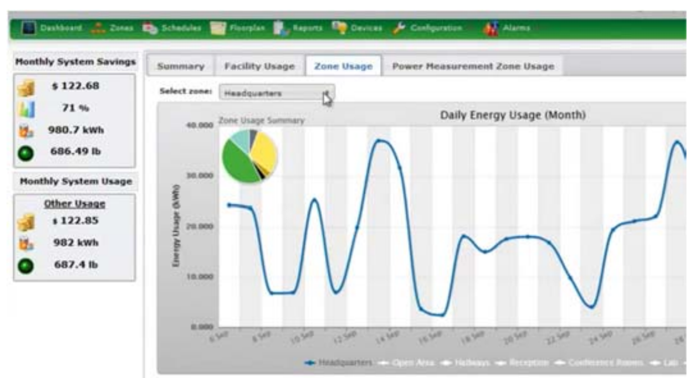
Site 2 – Phillips SpaceWise

The Philips SpaceWise technology is a fully integrated wireless control system applied at the luminaire level that provides 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 1/3 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

The Cree SmartCast technology, applied at the luminaire level, 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.
Onbaord 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®



Current's Daintree ControlScope® Manager (CSM) is a lighting control software solution using 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 Enlighted Advanced Lighting Control System 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.

Appendix C

Survey Information

Surveys were administered to occupants as well as 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 through the mail directly. In some cases, surveys were either not distributed or completed resulting in a few sites with missing data. For reference, the following table shows the status of 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

Examples of typical surveys used in this study are provided below.

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

7. Were the installation instruction needed to complete the install?

___Yes ___No

Installation:

8. Were there any safety issues related to installing this particular system?

___No
___Yes (Please Describe) ____
___ N/A

9. Were there any complications related to installing this particular system?

___No
___Yes (Please Describe) ____
___ N/A

10. 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:

11. Is there anything about the system that you believe may create future maintenance issues?

___No
___Yes (Please Describe) ____
___ N/A

12. 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:

13. How was commissioning of the control system accomplished?
___Automatic – little to no operator action required
___Manual setup by operator
___ Other ____

14. Was the commissioning simple and straightforward?
___Yes
___No (Please Describe) ____
___Almost (Please Describe) ____
___ N/A

15. 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:

16. 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) 1 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
e) A bit tricky. Please describe ____
c) 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) ____

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

____

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