Easily Commissioned Lighting Controls
Phase 2 Report

A Report of BPA Energy Efficiency's Emerging Technologies Initiative

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Abstract

The Lighting Research Center (LRC) at Rensselaer Polytechnic Institute conducted pilot testing and analysis of three selected control systems to independently verify system commissioning, operation, and compatibility with two different integral LED luminaire layouts. A separate LED luminaire with integrated sensors was also evaluated. The LRC characterized system operational characteristics, commissioning, and energy savings under field conditions. The purpose of this pilot study was fourfold: 1) to evaluate the ease of installation, initialization and use, 2) to evaluate the default control characteristics of each system, 3) to examine power demand differences between zone controls (one sensor to control a group of luminaires) and luminaire-integrated controls and 4) to examine the power demand differences when different luminaires were used with the same control system.

The pilot study was limited to one daylighted office space and one daylighted conference space. System power and light levels were logged in each space, but occupancy was not independently monitored. Daylight conditions and occupancy varied between the spaces and from week to week.

The LRC found:

Ease of Use:

- All of the products tested were easy to install.
- For initialization, three of the four systems came without sufficient setup documentation, leading to an increased setup time. Recent documentation improvements made since this work was conducted were not evaluated.
- Initialization of some of the wireless dimming wall switches was complicated, even with documentation.
- The systems appeared to lack any mechanism to adjust the default sensor: task light ratio, either manually or automatically. In some cases, this produced low light levels and occupant dissatisfaction.
- When the ambient light levels were dim, occupants were satisfied with products that provided manual override capability. Products without this capability were less satisfying.

Energy savings:

- Significant energy savings are possible compared to time clock control, baseline conditions and/or power density requirements.
- Manual-on controls could save energy compared to automatic-on controls.
- Luminaires with integrated controls may or may not save energy over control systems that use one sensor to control a group of luminaires. Energy use depends on the system configuration.
- Connecting different luminaires to the same lighting control system may result in different light levels and power demand, as the driver's current response to the dimming control voltage varies by manufacturer and driver design.
- All of the LED luminaires tested demonstrated low power factor (< 0.9) when dimmed.
- One system provided access via USB to instantaneous power readings. Beyond that, none of the systems logged or reported energy use.

An Emerging Technologies for Energy Efficiency Report

The following report was funded by the Bonneville Power Administration (BPA) as an assessment of the state of technology development and the potential for emerging technologies to increase the efficiency of electricity use. BPA is undertaking a multi-year effort to identify, assess and develop emerging technologies with significant potential for contributing to efficient use of electric power resources in the Northwest.

BPA does not endorse specific products or manufacturers. Any mention of a particular product or manufacturer should not be construed as an implied endorsement. The information, statements, representations, graphs and data presented in these reports are provided by BPA as a public service. For more reports and background on BPA's efforts to "fill the pipeline" with emerging, energy-efficient technologies, visit Energy Efficiency's Emerging Technology (E3T) website at http://www.bpa.gov/energy/n/emerging_technology/.

The Lighting Research Center (LRC) at Rensselaer Polytechnic Institute is the world's leading center for lighting research and education. Established in 1988 by the New York State Energy Research and Development Authority (NYSERDA), the LRC has been pioneering research in energy and the environment, light and health, transportation lighting and safety, and solid-state lighting for more than 25 years. Internationally recognized as the preeminent source for objective information on all aspects of lighting technology and application, LRC researchers conduct independent, third-party testing of lighting products in the LRC's state of the art photometric laboratories, the only university lighting laboratories accredited by the National Voluntary Laboratory Accreditation Program (NVLAP Lab Code: 200480-0). LRC researchers are continuously working to develop new and better ways to measure the value of light and lighting systems, such as the effects of light on human health. The LRC believes that by accurately matching the lighting technology and application to the needs of the end user, it is possible to design lighting that benefits both society and the environment.

Acknowledgments

Leora Radetsky and Russ Leslie were co-principal investigators for this project. Leora Radetsky authored the report. LRC thanks Levin Nock, John Wilson, Karen Janowitz, Edward Bartholomew, Sam Fankhauser and Dan Mellinger for their input and review.

Project Background

In July 2014, Washington State University Energy Program (WSU) / Bonneville Power Administration (BPA) requested that the LRC create a buying guide for end-users who want to purchase "easily commissioned lighting controls" which reviews and compares currently available products.

The LRC proposed that the project be broken into two phases. In the first phase LRC would cover five or six easily deployed lighting control systems currently in the market, based on product literature and interviews with manufacturer representatives. The second phase, would pilot test several of the reviewed products included in Phase 1 in an open office space at the LRC. This phase is the subject of this report.

The LRC's Lighting Energy Alliance (LEA) partnered with BPA on this project to expand the number of products in the pilot test. LEA's goal is to conduct research to increase the benefits of lighting while reducing its environmental and monetary costs. Current LEA members are Efficiency Vermont, Energize Connecticut and National Grid.

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Foreword by BPA: What this Report Is, and Is Not

Research in a rapidly developing field, such as advanced controls for LED lighting, involves tradeoffs among speed, applicability, cost, objectivity and completeness. This pilot project emphasized speed and applicability at a manageable cost, and the results should be interpreted from that perspective.

The report provides insights into some of the successful aspects and some of the challenging aspects of each of the four products tested. This information may be useful to product designers to refine product performance, and to early adopters to choose among the strengths and weaknesses of various products. The report does not provide an exhaustive characterization of any of the products, or an objective comparison and ranking between any products (tested or untested). The four products tested are all promising.

The research protocol for this pilot represents a step toward an objective lab-based product test—and additional steps in further research will be needed in order to fully achieve that goal.

Background

Interior lighting controls with "plug and play" or "automatic configuration" setup options from Cree, Wattstopper and Lutron were selected for evaluation in this pilot study. These brands were previously identified as high priority in Phase 1.[1] The LRC observed the system commissioning, operation, and compatibility of these three control systems when paired with two different LED luminaire arrays. A separate LED luminaire from Philips with integrated sensors was also evaluated based on input from the project sponsors.

Method

Luminaire Specification

The LRC used AGi32 lighting software to evaluate manufacturer-provided photometric files located in a simulated open-office and conference room environment. The space modeled was the LRC studio which is comprised of light-colored walls with many windows, a white ceiling and hardwood floors. The studio is 1059 SF, measured to the centerline of the interior walls and outside surface of exterior walls (per ASHRAE 90.1-2010) with a 13-foot ceiling height. The surface reflectance values used in the simulation were: walls and ceiling 70%, floor: 20%. Luminaires were mounted 10 feet above the floor, and on 12-foot x 8-foot centers in the simulation. A light loss factor (LLF) of 1.00 was used in the simulations. A grid of horizontal illuminance points was located at a virtual workplane (2.5 feet above the floor), with 2-foot x 2-foot point spacing. The following manufacturer-provided LED luminaire photometric files were selected to provide about 30 footcandles (fc) (300 lux) average on the workplane in either space (shown in Table 1).

[1] http://www.bpa.gov/EE/Technology/EE-emerging-technologies/Projects-Reports-Archives/Documents/EasyLightingControlsReview_LRC_BPA_2015Feb.pdf

Table 1: Predicted light levels in simulated LRC studio layout (without daylight).

Space	LED Luminaires (at 100% light output)	Rated Luminaire Power (W)	Rated Luminaire Efficacy (lm/W)	Predicted Average Illuminance (lux)	Calculated Lighting Power Density (W/SF)	Predicted Illuminance Uniformity (average:min)
Open office / Conference	Cree CR24-40L-30K-XX (100LPW)	38.6	101	284	0.29	2.8
Open office/ Conference	Lithonia 2ALL4_49L_D50_LP 835	50	98	352	0.38	2.9
Open office/ Conference	Philips 2DLG49L840-4-D-UNV-DIM	48.1	103	356	0.36	2.8

Luminaires ordered

Based on the AGi32 simulations, the LRC purchased 12 integral LED luminaires, having a CCT of 3500K, in January-February 2015:

- 4 LED luminaires from Cree Lighting with 0-10V drivers (CR24 40L-35K-10V)
- 4 LED luminaires from Lithonia Lighting with 0-10V drivers (2ALL4 49L D50 LP835 NX)
- 4 LED luminaires from Philips with integrated SpaceWise generation 2 lighting controls (2DLG49L835-4-D-UNV-DIM-SWZG2)

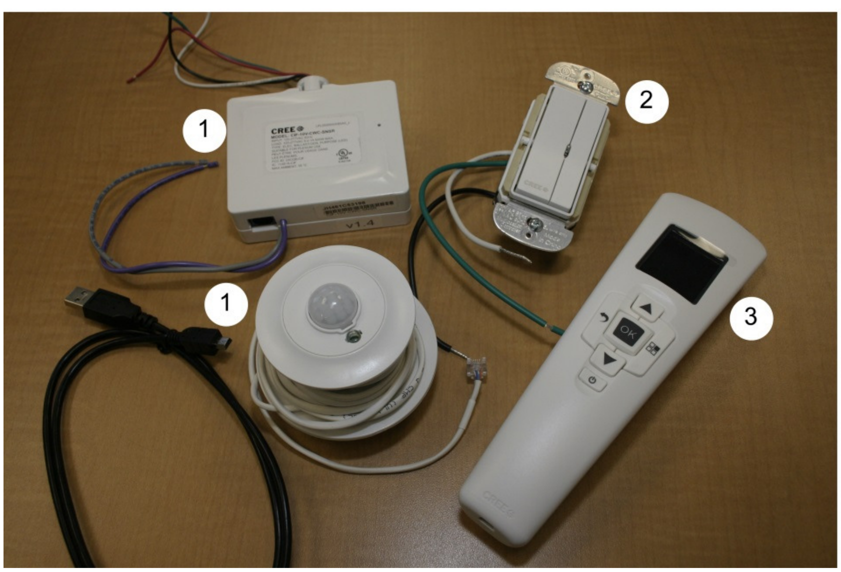
Lighting controls specification

The LRC ordered lighting control systems from Cree, Wattstopper and Lutron capable of operating the 0-10V drivers in the Cree and Lithonia LED luminaires, as shown in Table 2, in February 2015. The LRC consulted with local manufacturers' representatives to determine that the control components ordered (sensors and switches) were appropriate for the application. The features of the Cree SmartCast, Lutron Energi TriPak and Wattstopper DLM control systems are described in the Easily Commissioned Lighting Controls Review publication on the BPA website.[2]

[2] http://www.bpa.gov/EE/Technology/EE-emerging-technologies/Projects-Reports-Archives/Documents/EasyLightingControlsReview_LRC_BPA_2015Feb.pdf

Table 2: Lighting control components deployed in study

Device type	Cree SmartCast Luminaire-integrated control system (components shown in Figure 1)	Lutron Energi TriPak Zone control system (components shown in Figure 2)	Philips SpaceWise Luminaire-integrated control system (components shown in Figure 3)	Wattstopper DLM Zone control system (components shown in Figure 4)
Sensors	CIF-10V-CWC-SNSR (wireless 0-10V dimming/switching interface with SmartCast technology)	LRF2-DCRB-WH (wireless daylight sensor) LRF2-OCR2B-P-WH (wireless occupancy sensor) RMJ-5T-DV-B (Powerpak dimming module)	Included in luminaire	LMLS-400 (single zone daylight sensor) LMDC-100 (dual-technology occupancy sensor) LMRC-211 (relay remote control)
Switch	CWD-CWC-WH (wireless dimmer)	PJ2-2BRL-GWH-L01 (Pico wireless dimming control) 1 control used at a wall box, another was on a tabletop pedestal	UID8451/10 (wireless dimming control)	LMDM-101-W (dimming wall switch) LMRH-102 (2 button handheld remote)
Commissioning Tool	CCT-CWC-1 (wireless configuration tool)	N/A	IRT9090/01 (extended IR programming tool)	LMCT-100 (wireless configuration tool) LMCI-100 (computer interface tool)

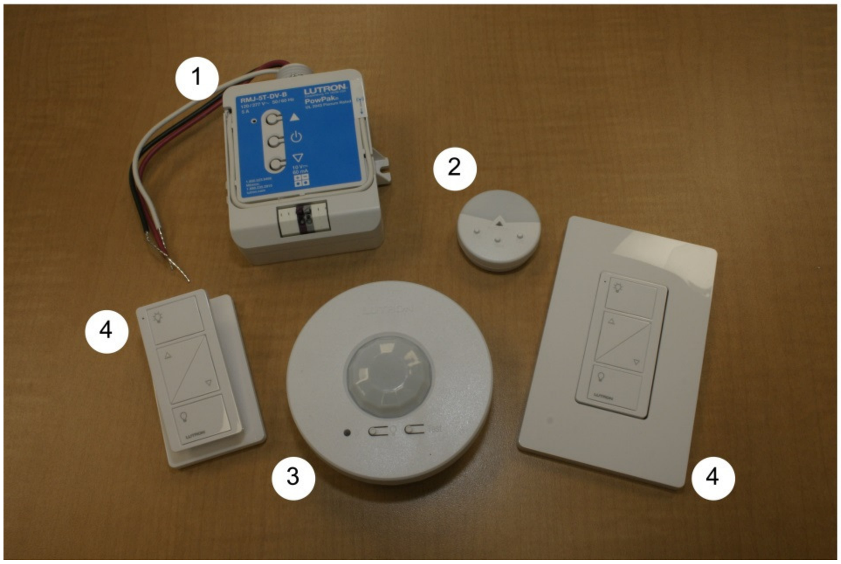


1: CIF-10V-CWC-SNSR 0-10V Interface (control module and sensor)

2: CWD-CWC-WH wireless dimmer

3: CCT-CWC-1 wireless configuration tool

Figure 1: Cree SmartCast lighting control components



1: RMJ-5T-DV-B
Powerpak dimming module

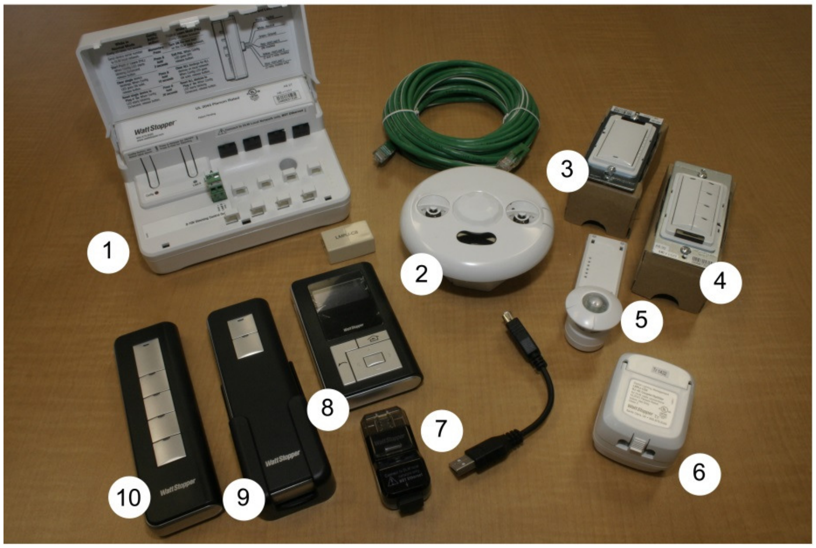
2: LRF2-DCRB-WH
wireless daylight sensor

3: LRF2-OCR2B-P-WH
wireless occupancy sensor

4: PJ2-2BRL-GWH-L01
Pico wireless dimming control

Figure 2: Lutron Energi TriPak lighting control components

Figure 3: Philips SpaceWise lighting control components (wireless dimming control and programming tool) and luminaire-integrated lighting sensors.



1: LMRC-211 dimming room controller
2: LMDC-100 dual-technology occupancy sensor
3: LMDM-101-W dimming wall switch
4: LMSW-105-W 5 button scene switch
5: LMLS-400 single zone daylight sensor
6: LMRJ-CS8 coupler/splitter
7: LMCI-100 computer interface tool
8: LMCT-100 wireless configuration tool
9: LMRH-102 2 button handheld remote
10: LMRH-105 5 button handheld remote

Figure 4: Wattstopper DLM lighting control components. Also pictured are a 5-button handheld remote and a 5-button scene switch which were not used in this study.

System installation and configuration

Four LED luminaires of the same type were mounted above an open-office space, and four LED luminaires of a different type were mounted above a conference space in a daylighted space (Figure 5). White louvered blinds were installed on each window and the louvers were angled upwards to moderate daylight into this space.

The Lithonia and Cree luminaires were operated on a digital timer at full light output for one week (on 8 AM – 6 PM) to determine average power demand for a baseline application. Following that week, the lighting control systems were connected and set up following the manufacturer's instructions. The control systems were operated in their default "automatic" or "plug-and-play" operation mode, without any advanced commissioning changes. Each lighting control system was deployed for at least one week, and then the lighting control system was changed such that the controls were deployed in a balanced order to account for seasonal changes in daylight availability. After each lighting control system was deployed with each luminaire array, the luminaires were redeployed to the other space (e.g. the LED luminaires in the open office area were moved to the conference area and vice-versa), and the lighting control systems were re-deployed in a counterbalanced design. Occupancy and daylight availability varied from week to week and between the conference area and the open office space.

The LRC monitored system current for each space every 15 seconds using current loggers[3]. AC voltage and luminaire power factor were also measured to calculate power demand. Light loggers were located adjacent to each luminaire to measure relative light output, and Daysimeters[4] were mounted on the conference table and one of the open office desks to monitor workplane light levels.

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[3] Onset HOBO H22 Energy Logger with FlexSmart TRMS Module and Magnelab 5 Amp Mini AC Current Transformer
[4] http://www.lrc.rpi.edu/programs/lighthealth/LightandDaysimeter.asp

Figure 5: Conference space with Lithonia LED luminaires (left) and open-office space with Cree LED luminaires (right).

The LED luminaires were wired to the three lighting control systems, one at a time, as shown in Table 3. In all, seven luminaire-control system combinations were evaluated in each application (open-office or conference room).

Figure 6 shows a plan view of the LRC studio with approximate LED luminaire locations, and the notation of the relative light logger position as well as a close up photo of one of the Lithonia LED luminaires with the light logger in place.

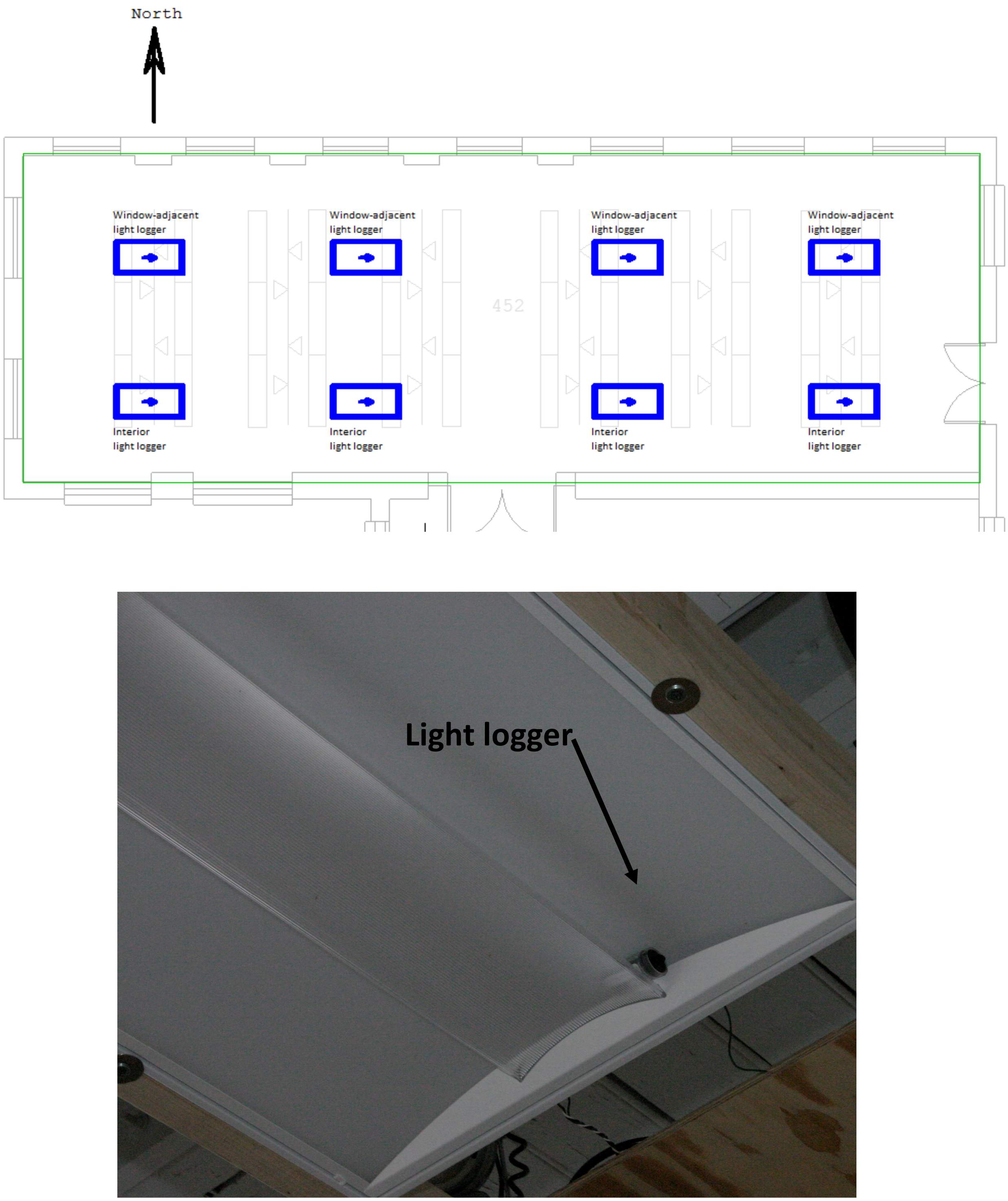

Figure 6: Plan view of LRC studio indicating True North, approximate luminaire locations and relative light logger location label as well as a photograph of a light logger located at Lithonia LED luminaire.

Table 3: LED luminaire and control system combinations used in pilot study

Combination	LED Luminaires	Control System	Default Control Mode
1	Cree CR24 40L-35K-10V	CREE SmartCast	manual-on/automatic-off
2	Cree CR24 40L-35K-10V	Wattstopper DLM	manual-on/automatic-off
3	Cree CR24 40L-35K-10V	Lutron Energi TriPak	automatic-on/automatic-off
4	Lithonia 2ALL4 49L D50 LP835 NX	CREE SmartCast	manual-on/automatic-off
5	Lithonia 2ALL4 49L D50 LP835 NX	Wattstopper DLM	manual-on/automatic-off
6	Lithonia 2ALL4 49L D50 LP835 NX	Lutron Energi TriPak	automatic-on/automatic-off
7	Philips 2DLG49L835-4-D-UNV-DIM-SWZG2	Integrated into luminaire	Selectable during set-up (manual-on/automatic-off or automatic-on/automatic-off)

Setup/commissioning

Each of the four lighting control systems was installed, commissioned and operated for a period of at least one week for each combination of luminaire and control. A summary of the installation, commissioning and operating experiences for each control system is shown in Table 4. More detailed explanations of the installation and commissioning practices for each lighting control system follows after Table 4. Overall, the control systems were easy to install, but not as easy to commission as expected. However, the controls were easier to commission than by other commissioning protocols, such as using a potentiometer to change the system sensitivity or using computer software to commission a complex system.

Table 4: Summary of installation, commissioning and operational characteristics of the tested lighting controls systems

	Cree SmartCast	Lutron Energi TriPak	Philips SpaceWise	Wattstopper DLM
Ease of Installation	Easy	Easy	Easy	Easy w/ RJ45 cable selection
Commissioning instructions	Little then (more now)	Yes	None then (more now)	Yes
Commissioning process	Use remote, then create groups	Pair sensors first, then calibrate daylight sensor	Use remote to set up groups and wireless switch, not intuitive process	Use remote to calibrate daylight sensor
Increase light level with daylight present?	No	Yes	Yes	No (can change in advanced settings)
Control mode / End-user Operation	(manual-on) Aggressive dimming. Can't increase light level with daylight present	(automatic-on) Cree luminaires "whistled" when connected to control system; Lithonia luminaires did not	(choose mode) Once commissioned, system worked well	(manual-on) Could not switch on lights with daylight present

Cree Smartcast

This luminaire-integrated control system was easy to install because each luminaire had its own control, and there was no need to connect the control wires in series. Commissioning with the remote control was convenient but a lack of detailed commissioning instructions at the time of the study made this process difficult.[5] The principal investigator had to speak with the manufacturer's representatives to understand how the groups should be setup. Based on their input, a switch group was created to control all luminaires with one dimmer switch, and each luminaire was allowed to determine occupancy individually (no occupancy group was created).The SmartCast system operates as a vacancy system by default (manual-on/automatic-off). The dimmer switch will override the daylight sensor, but only decreases the light level set by the daylight sensor. At the time of this report, a deployment guide is available online that provides more detailed commissioning instructions.[6]

[5] The CREE luminaires with luminaire-integrated SmartCast lighting controls would also need to be setup with the handheld remote to create a local network and appropriate switch and occupancy groups.
[6] CREE SmartCast Technology Deployment Guide available online at: http://api.icentera.com/v2/getfile.aspx?f=923FB838C21FAF0989CD8278C76571BDFF954C2D17BFECF0F94DD9BD615FAA44AAEF830E1722343A

The handheld remote emits a green light to communicate with the SmartCast sensors. One of the four SmartCast sensors was not consistently responsive to the green light from the handheld remote. During one of the commissioning procedures, the researcher had to go up on a ladder and jiggle the cable in the receiver box while shining the green light at the sensor to get it to respond.

Lutron Energi TriPak

This zone control system was the simplest of the three auxiliary systems to install, according to the LRC technicians. The relay controller and sensors were located in the space using manufacturer guidelines. The relay controller was located in the center of the space near one of the luminaires and was connected to one of the luminaires in series to control all of the luminaires as one "zone" or group. The daylight sensor was located nearer to the window, while the occupancy sensor was located in the center of the LED array. Commissioning the system was somewhat challenging because multiple trips up a ladder were required to pair the sensors and switches with the relay controller and then to calibrate the daylight sensor after it was installed in the ceiling grid. The luminaires had to be powered on and the buttons on the relay controller had to be manually pressed before the Pico remote controls and the sensors could be paired to the controller. The best practice is to bring the wireless sensors and Pico remote controls up the ladder and pair them with the relay controller before they are installed in the ceiling. This means that the installer has to complete the pairing setup before sensors and switches are installed.

Calibrating the daylight sensor once the sensor was placed in position also required an additional trip up the ladder to press the appropriate button on the daylight sensor. The commissioning instructions were included with the relay controller and sensors and included steps to set the target electric light level as part of the daylight sensor calibration steps. The electric light level at the conference table was set to about 300 lux as part of this process. The Pico remotes could override the daylight sensor and occupants could manually increase and decrease light levels and switch lighting on/off as desired.

When the Lutron control system was deployed with the Cree LED luminaires, staff noticed a high pitched sound emitted when the system was switched on. This functionality did not occur when the Lutron control system was connected to the Lithonia Lighting LED luminaires.

Philips SpaceWise

As the controls are integrated with the Philips LED luminaire, no additional installation is required. A baseline week, with the luminaires installed in the conference area, was completed prior to commissioning. Commissioning this system was the most complicated of the four systems, even though a handheld remote was used. The buttons on the remote were not intuitive, and commissioning instructions had to be obtained from Philips as instructions were not available online when the study was commenced (they are available online at the time of this report)[7]. Once the instructions were obtained, the principal investigator found the commissioning process to be complicated and the process had to be repeated several times for the sequence to be completed. This system allows the users to choose between two controls modes as part of the

7 http://www.lighting.philips.com/us_en/lightcommunity/trends/led/assets/SpaceWise_quick_start_guide_Mar2015_web.pdf

setup process (automatic-on/automatic-off or manual-on/automatic-off). Commissioning instructions for the wireless dimmer switch were also not included with the switch or available online[7] and had to be obtained from Philips[8]. Because commissioning instructions for pairing the wall switch with the luminaires were not available during the analysis week, the system was operated with automatic-on/automatic-off control for one week. Pairing the wall-switch with the luminaires also required several repetitions of the given instructions, but once this step was completed, the system was changed to vacancy mode (manual-on/automatic-off) and the system was operated this way for one week.

According to the user manual,[8] the luminaires fade from a task level to a background level after a 10 minute vacancy period. This energy saving mode occurs automatically after the luminaires are powered on, even prior to commissioning. Daylight calibration is conducted once the commissioning setup is complete. The dimmer switch could override (increase and decrease light level) the current light level set by the daylight sensor.

Wattstopper DLM

This zone control system was also quick to install. The local manufacturer's representative recommended ordering various lengths of the RJ45 cables and multiple connectors; this made attaching the sensors to the room controller very simple because the closest fixed-length cable could be matched to the application. The technician was not bothered by the fixed cable lengths; excess cable was coiled and zip-tied to keep it out of the way. The room controller and sensors were located in the same locations as the Lutron relay and sensors.

During the initial commissioning process, the DLM system was operated for a few days in the conference room as an occupancy sensor (automatic-on/automatic-off). Occupants stated that they noticed the lights dimming up and down a lot while in this state and one of the occupants noted that the changing light levels gave her a headache.

The inclusion of a wall switch defaulted this system to a vacancy sensor setup (manual-on/automatic-off). With the default settings, the switch does not override the daylight sensor, so when the lights were dimmed down or switched off due to daylight, the dimmer switch would not increase light levels or turn the lights on manually. The dimmer switch would only decrease light levels. The hand-held remote also did not override the daylight sensor by default. In addition, when re-entering the space after at least 20 minutes, the wall switch would not turn the lights on if the daylight sensor indicated there was sufficient daylight (daylight sensor overrides occupancy sensor, and wall switch does not override daylight sensor by default). This was confusing to the occupants because it appeared as if the wall switch was not working correctly.

This control system provides instantaneous power readings for each room controller, and its connected devices and lighting loads, through Wattstopper's proprietary software, by connecting a manufacturer-supplied USB device to any of the RJ45 connectors. This software program can also be used to commission and troubleshoot the control system.

[8] SpaceWise Technology User Manual, Draft version 3.0

Light Level Analysis

Light levels during baseline

Figures 7 – 17 show the measured light levels obtained during this pilot study. The light loggers were located adjacent to each luminaire and their measurements are shown in red, blue, green and purple. The light loggers located at the luminaires closest to the North-facing windows are shown in blue and red, and are demarcated as "Window-adjacent light loggers". The light loggers located at the luminaires on the South side of the room are demarcated as "Interior light loggers", even though there are windows on the East and West sides of the room and on the South side of the office space. These light loggers face the luminaires and measure both electric light from the luminaire itself as well as ambient light from daylight and other luminaires. When the LED luminaires are on, the relative light levels are typically higher than 25%. The light levels measured from the desk-mounted Daysimeter in the office and the conference table mounted Daysimeter in the conference room are shown as a thick black line on the figures. Measured light levels during the baseline weeks are shown in Figures 7 – 9. Light loggers installed adjacent to the luminaires are used to log relative light levels for each luminaire (including both daylight and electric light), while workplane-mounted Daysimeters log absolute light levels. As expected, light levels at the workplane are higher on weekdays, when the electric lighting is on, than on weekends. The individual Cree and Lithonia LED luminaires operate similarly to each other when on the digital timer, turning on at 8 AM and off at 6 PM as programmed.

On the other hand, the Philips LED luminaires make use of the integrated sensors in the luminaires during the baseline period even though no commissioning was completed on these luminaires. As shown in Figure 9, the Philips luminaires dim up and down during the baseline week, which was not the case for the other control systems. Occupants noticed the lights dimming up and down during their programmed on-time (8 AM – 6 PM).

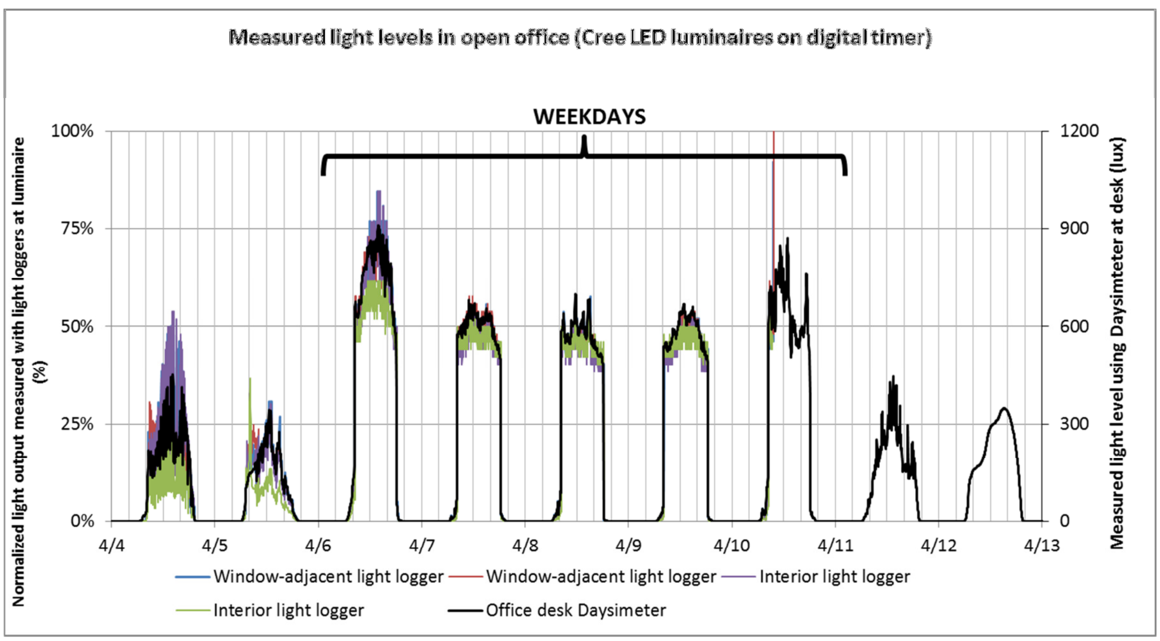

Figure 7: Workplane and luminaire light levels during baseline week with Cree LED luminaires.

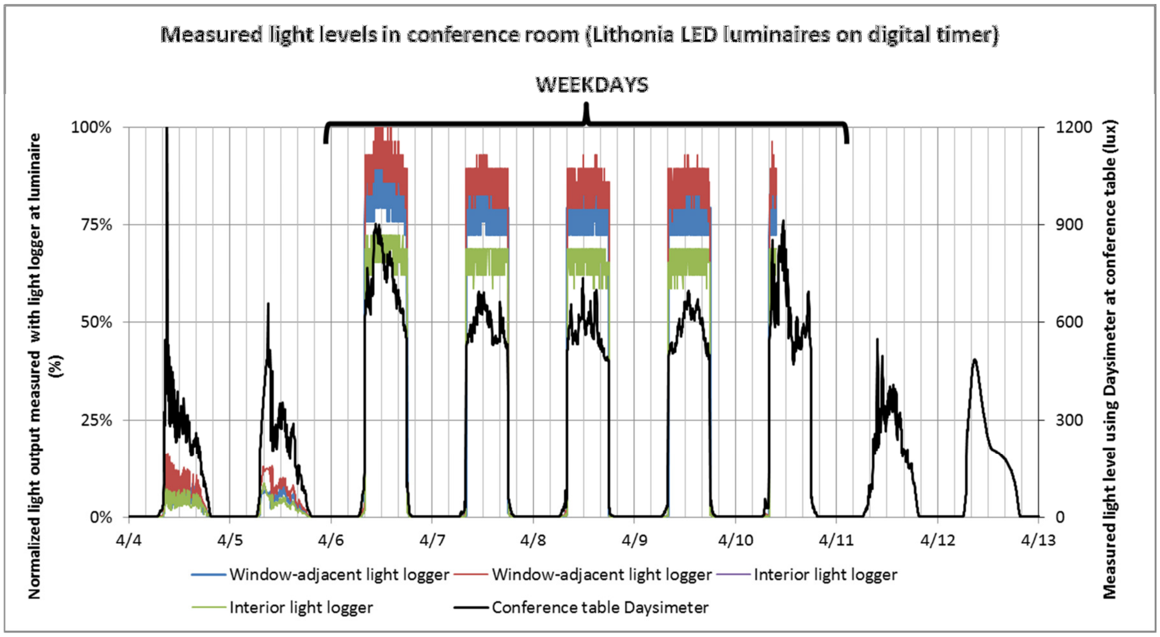

Figure 8: Workplane and luminaire light levels during baseline week with Lithonia LED luminaires.

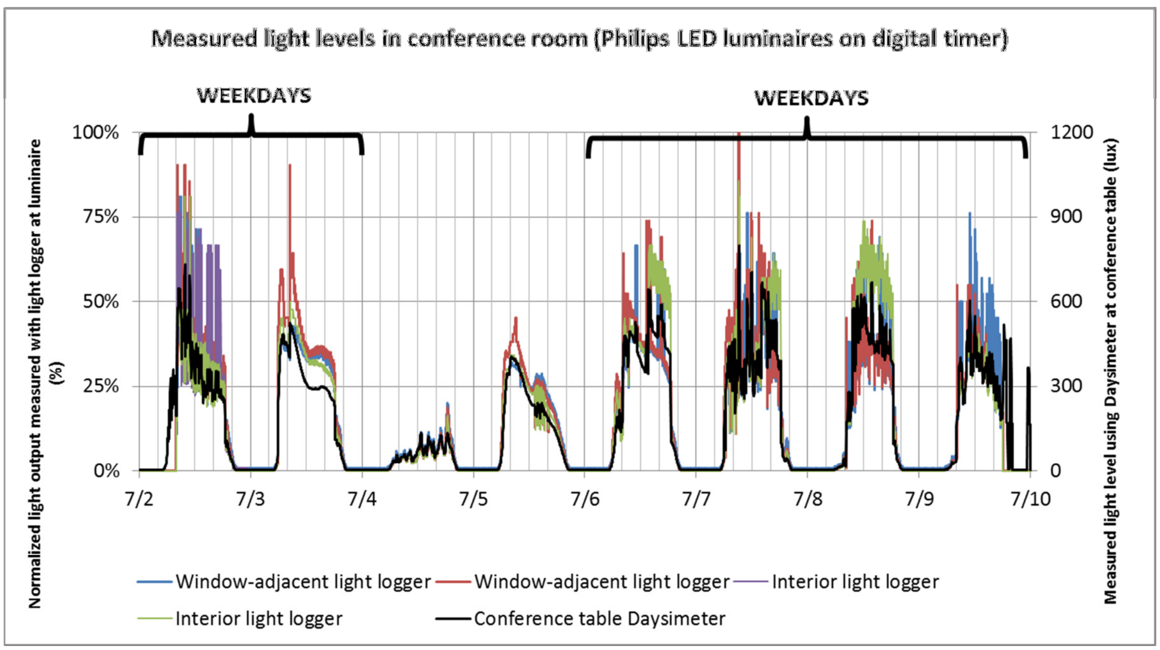

Figure 9: Workplane and luminaire light levels during baseline week with Philips LED luminaires.

Light levels with lighting controls

As for the baseline weeks, luminaire-adjacent light loggers and Daysimeter were used to log relative and absolute light levels for each luminaire-control combination. With the zone controls attached (e.g. Wattstopper DLM and Lutron Energi TriPak), all of the luminaires switched on and off as a group and dimmed in a similar fashion. An example of this is shown in Figures 10 and 11 under the Cree LED luminaire array with the Energi TriPak system. The Energi TriPak system has an automatic-on response mode and Figures 10 and 11 show how often the lights are on each weekday. A similar response for the Cree LED luminaire array with the DLM system is shown in Figures 12 and 13.

In comparison, the systems with individual luminaire controls show a difference in individual luminaire response as they respond to individual occupancy and localized daylight. Figure 14 shows the recorded light levels for a week in the open-office space under the Lithonia luminaire array with SmartCast individual luminaire controls. This control system uses a manual-on control mode by default, and Figure 14 demonstrates that most days occupants did not switch the electric lights on, as the relative light levels measured at the luminaire are typically less than 25% of the maximum. Figure 15 shows a close-up of the normalized luminaire data and workplane light levels measured by the Daysimeter (shown in black) for one day when the lights were switched on; one of the luminaires on the South side of the room (shown in green) emitted more light than the other luminaires (shown in purple, blue and red) during this day based on individual occupancy and daylight availability.

The individual luminaires response of the Philips SpaceWise LED luminaires with automatic-on control mode is shown in Figures 16 and 17.

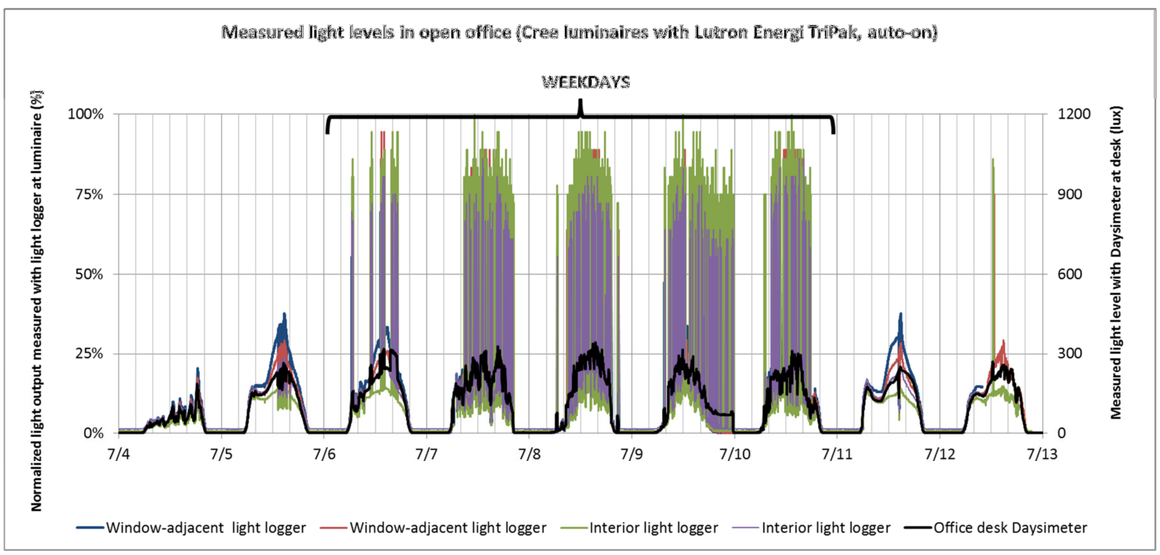

Figure 10: Workplane and luminaire light levels for one week under Cree LED luminaires with attached Energi TriPak controls.

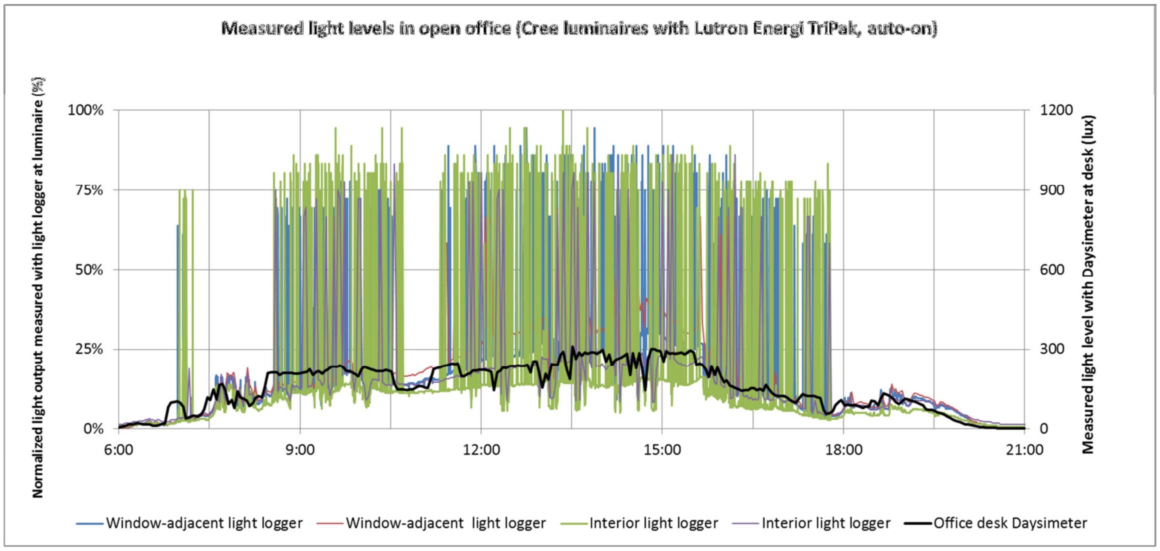

Figure 11: Normalized luminaire light levels for one day under Cree LED luminaires with attached Energi TriPak controls.

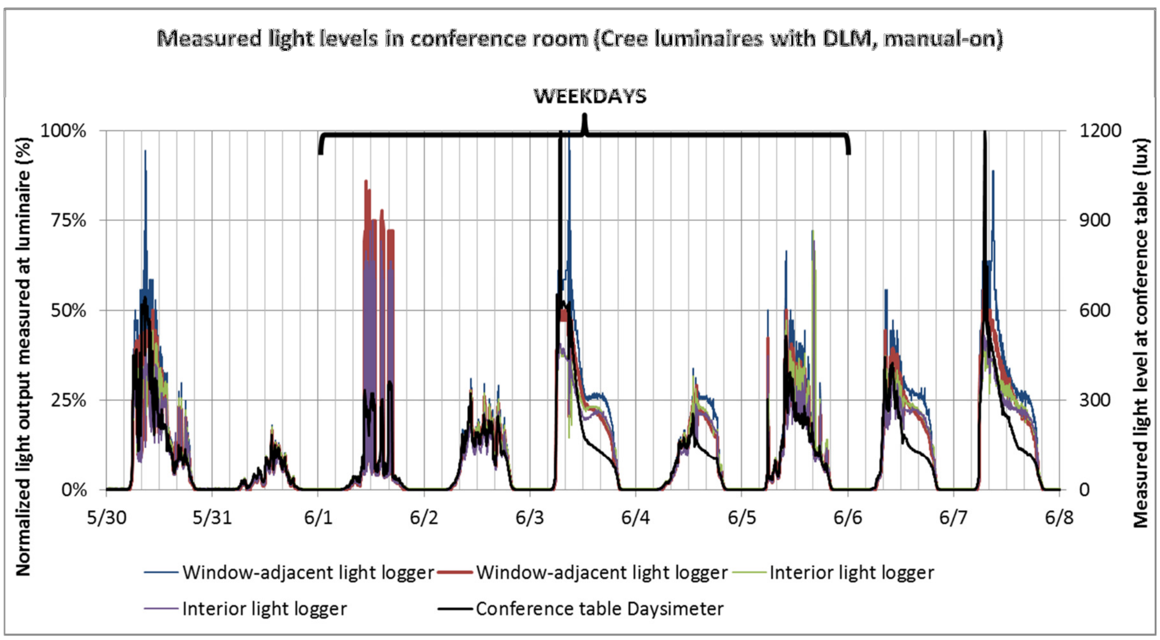

Figure 12: Workplane and luminaire light levels for one week under Cree LED luminaires with attached DLM controls.

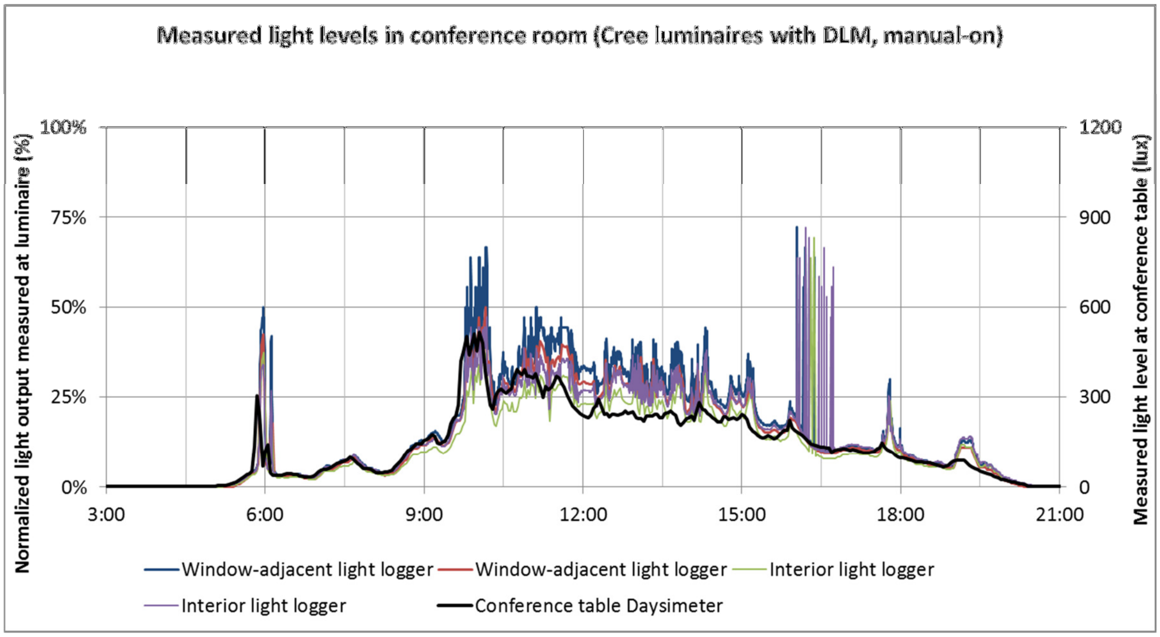

Figure 13: Normalized luminaire light levels for one day under Cree LED luminaires with attached DLM controls.

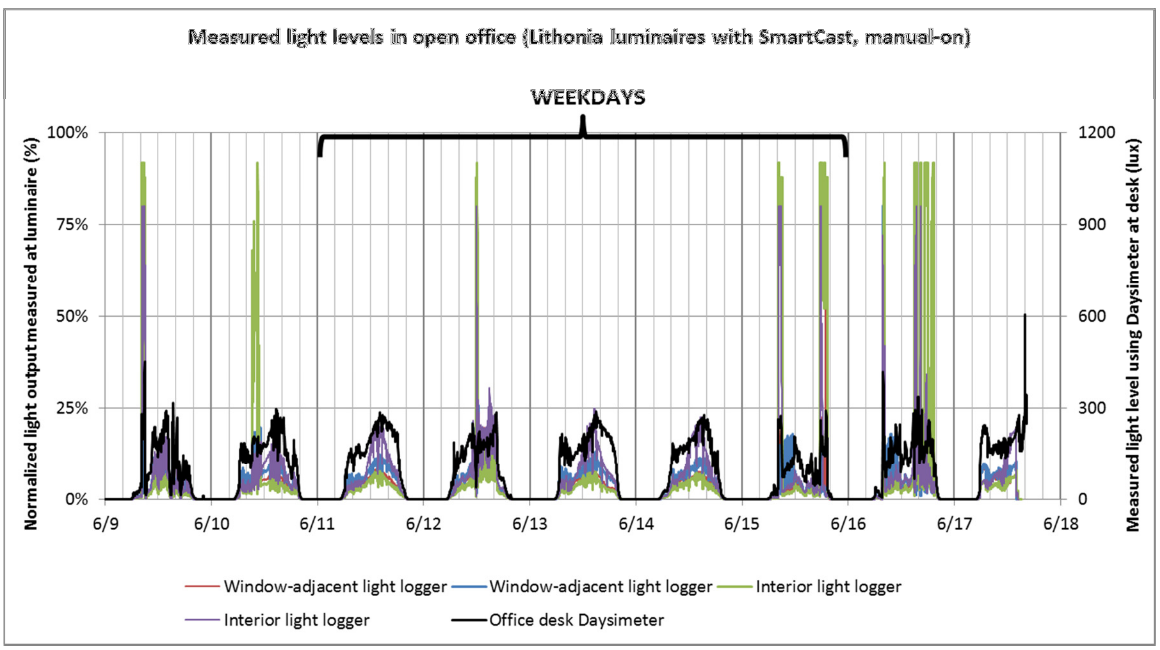

Figure 14: Workplane and luminaire light levels for one week under Lithonia LED luminaires with attached SmartCast controls.

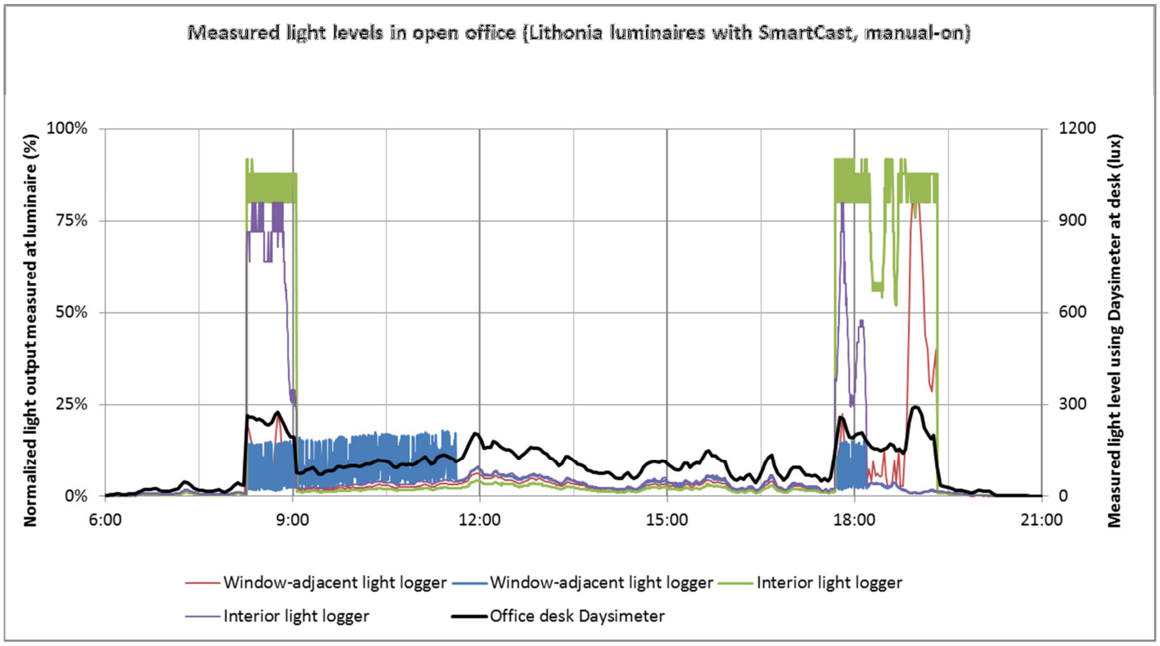

Figure 15: Normalized luminaire light levels during one day under Lithonia LED luminaires with attached individual SmartCast controls.

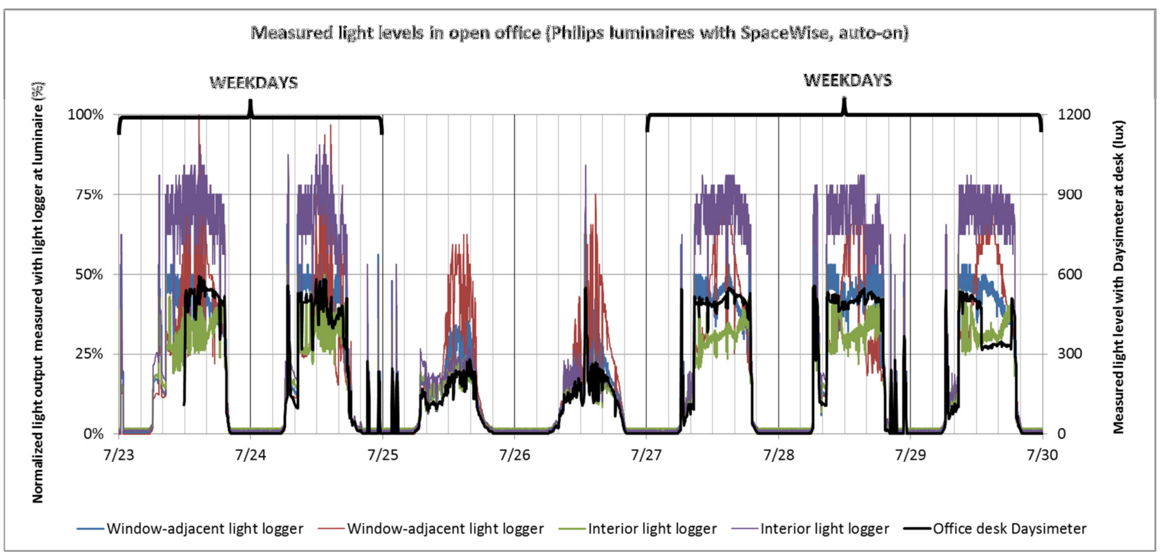

Figure 16: Workplane and luminaire light levels for one week under Philips LED luminaires with integrated SpaceWise controls.

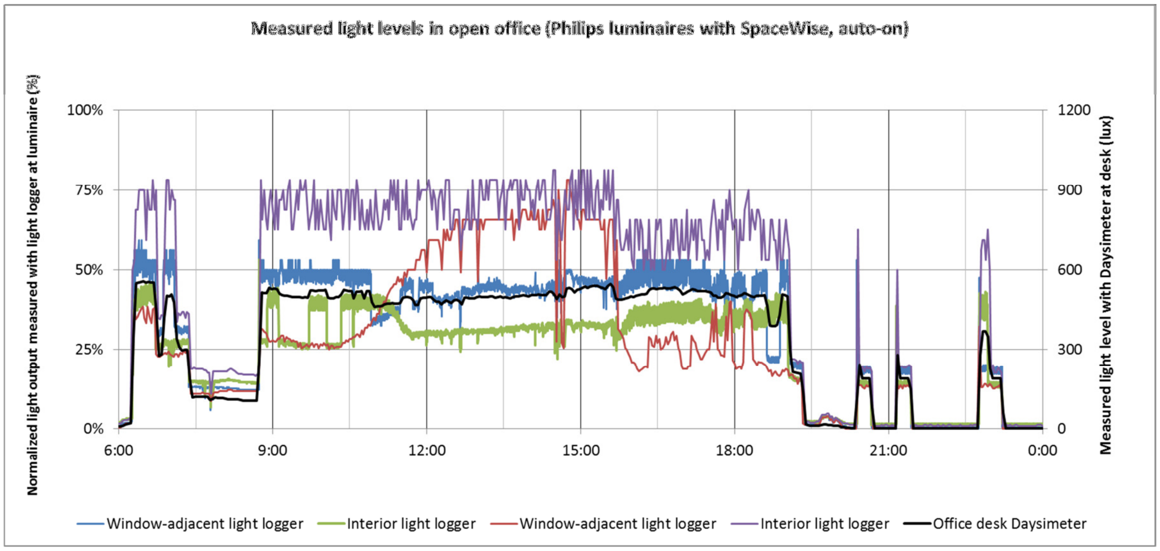

Figure 17: Normalized luminaire light levels during one day under Philips LED luminaires with integrated SpaceWise controls.

Average measured workplane illuminance at one location over each analysis week is shown in Table 5 and Figures 18 and 19. The workplane illuminances included in this table include all discrete Daysimeter measurements. Daysimeter data on the workplane was not measured for all days, as noted in Table 5.

The measured illuminance provided by the LED luminaires without controls exceeded the target illuminance (300 lux) as expected. Since the design illuminance is based on an average across the workplane, a point measurement in the interior of the room would be expected to be higher. When controls were deployed, the average workplane illuminances generally decreased below the target light level (except for the Philips installation where light levels increased with commissioned controls).

As expected, the average light levels were higher with automatic-on controls than with manual-on controls. During the manual-on conditions, occupants worked under daylight alone most of the time, without switching the lights on, even when light levels were less than 200 lux. Having the ability to override the daylight sensor with the switch (and increase light levels) was important. Average workplane illuminance on the conference table was about the same with the individual luminaire sensors (Cree SmartCast) as with the zone sensors (Lutron Energi TriPak and Wattstopper DLM), because the space was intermittently occupied and lights were off most of the time. In the open office, however, where occupants worked throughout the day, measured desktop illuminance varied widely depending on the installed combination.

Table 5: Summary of average workplane illuminances in open office and conference area over 5 business days

LED Luminaires	Control System	Average light level in open office (lux)	Average light level in conference area (lux)
Cree CR24 40L-35K-10V	digital timer (baseline)	562	Not measured
Lithonia 2ALL4 49L D50 LP835 NX	digital timer (baseline)	Not measured	544
Philips 2DLG49L835-4-D-UNV-DIM-SWZG2	digital timer (baseline)	Not measured	333
Cree CR24 40L-35K-10V	Cree SmartCast (manual-on)	173 (2.5 days)	183
Cree CR24 40L-35K-10V	Wattstopper DLM (manual-on)	missing data	170
Cree CR24 40L-35K-10V	Lutron Energi TriPak (auto-on)	193	221
Lithonia 2ALL4 49L D50 LP835 NX	Cree SmartCast (manual-on)	144	210 (257 lux in auto-on mode)
Lithonia 2ALL4 49L D50 LP835 NX	Wattstopper DLM (manual-on)	204	247 (2.5 days)
Lithonia 2ALL4 49L D50 LP835 NX	Lutron Energi TriPak (auto-on)	275	missing data
Philips 2DLG49L835-4-D-UNV-DIM-SWZG2	Integrated into luminaire (auto-on)	383 (283 lux in manual-on mode)	373

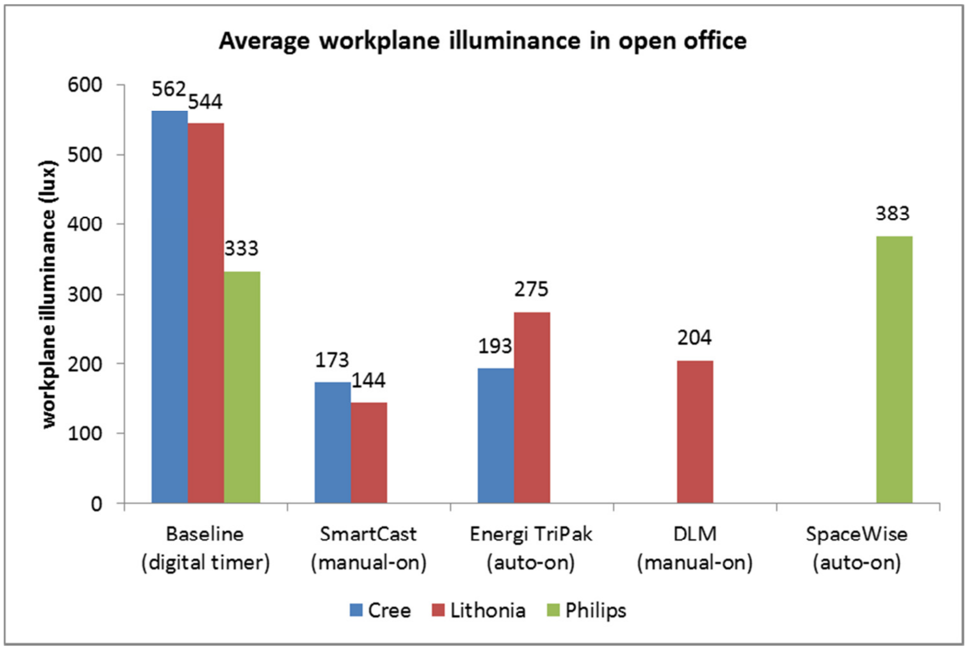

Figure 18: Measured average workplane illuminance over 5 business days in open office by luminaire and lighting control

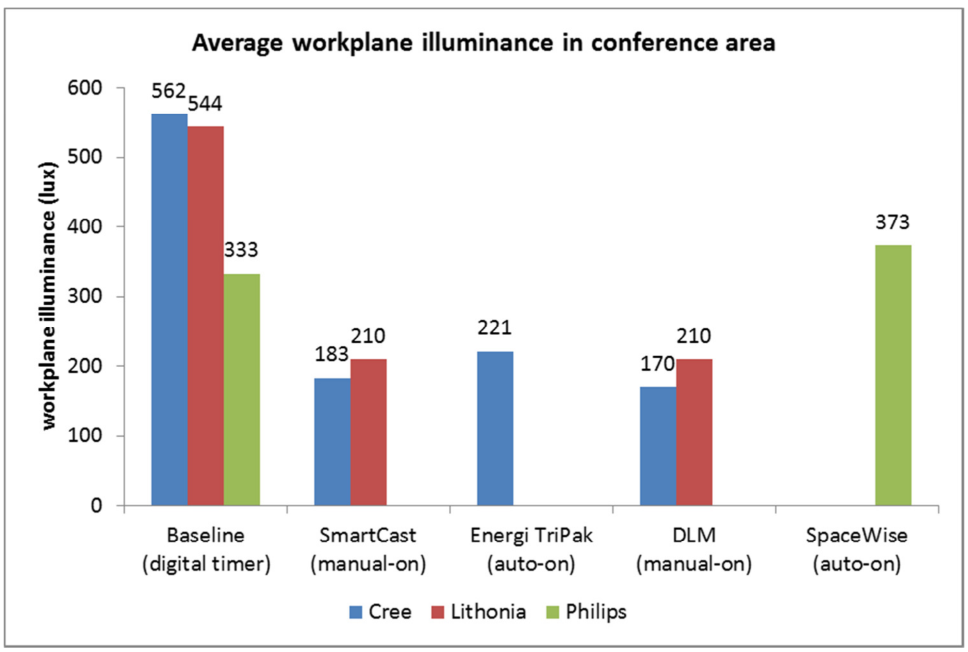

Figure 19: Measured average workplane illuminance over 5 business days in conference area by luminaire and lighting control

Figure 20 shows the average light levels in each space combined across the three luminaire types for the baseline, and across the two luminaire types for the three auxiliary lighting controls. As previously noted, the target light level is not achieved with most of the lighting controls tested in place, but occupants were generally satisfied working under lower light levels under daylight, if they could override the automatic lighting control. Even with the Energi TriPak automatic-on lighting controls, occupants were satisfied with below-target light levels, given that light levels could be much higher as this system allows manual increase of light levels via the wireless dimmers.

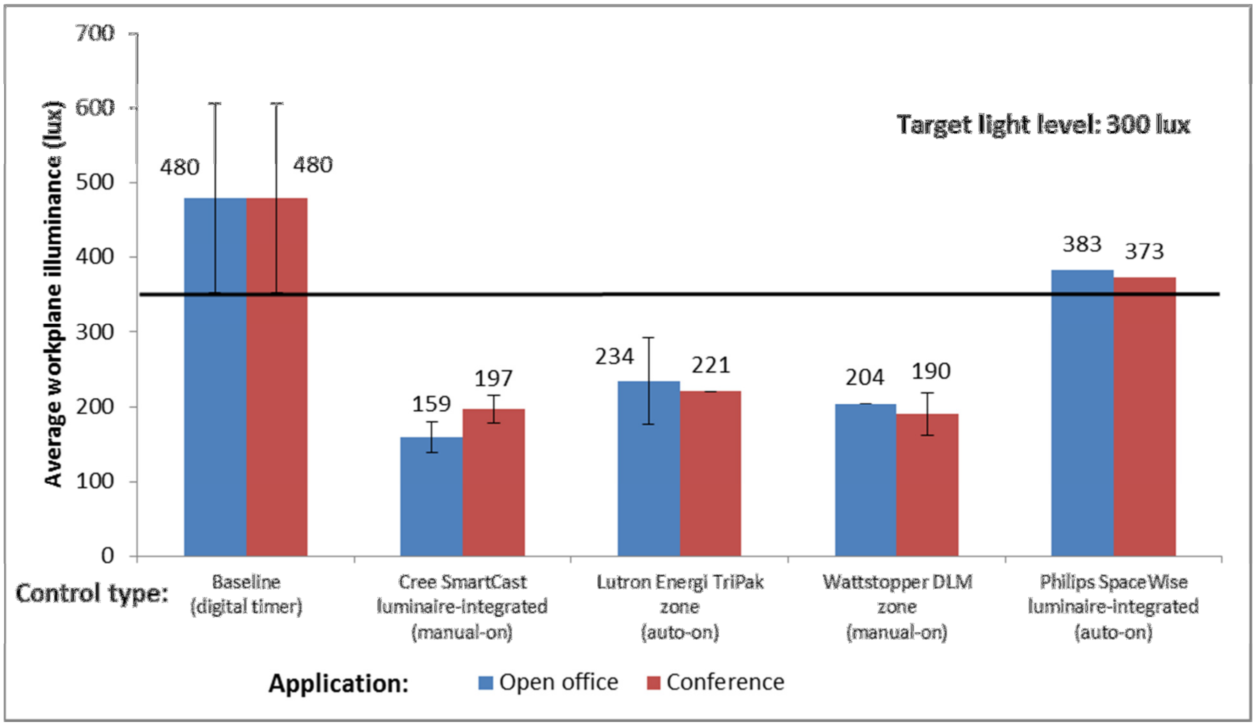

Figure 20: Measured average workplane illuminance over 5 business days in open office and conference area by lighting control (averaged across luminaires)

Power Demand Analysis

In each space, current monitoring devices logged the instantaneous current for each system (4 luminaires with the lighting controls attached) every 15 seconds. Instantaneous system power was calculated for each system using measured power factor, described in more detail below, and measured ac voltage (119.5 V). The Philips LED luminaire dims in response to vacancy, even in factory (baseline) mode, so a 5-day baseline period using the digital timers was measured for the conference area, and an additional 3-day baseline period was measured in the open-office application.

Open office system power

Figures 21-23 show the measured system power demand in the open office for each of the LED luminaires in the baseline configuration and with the commissioned lighting controls.

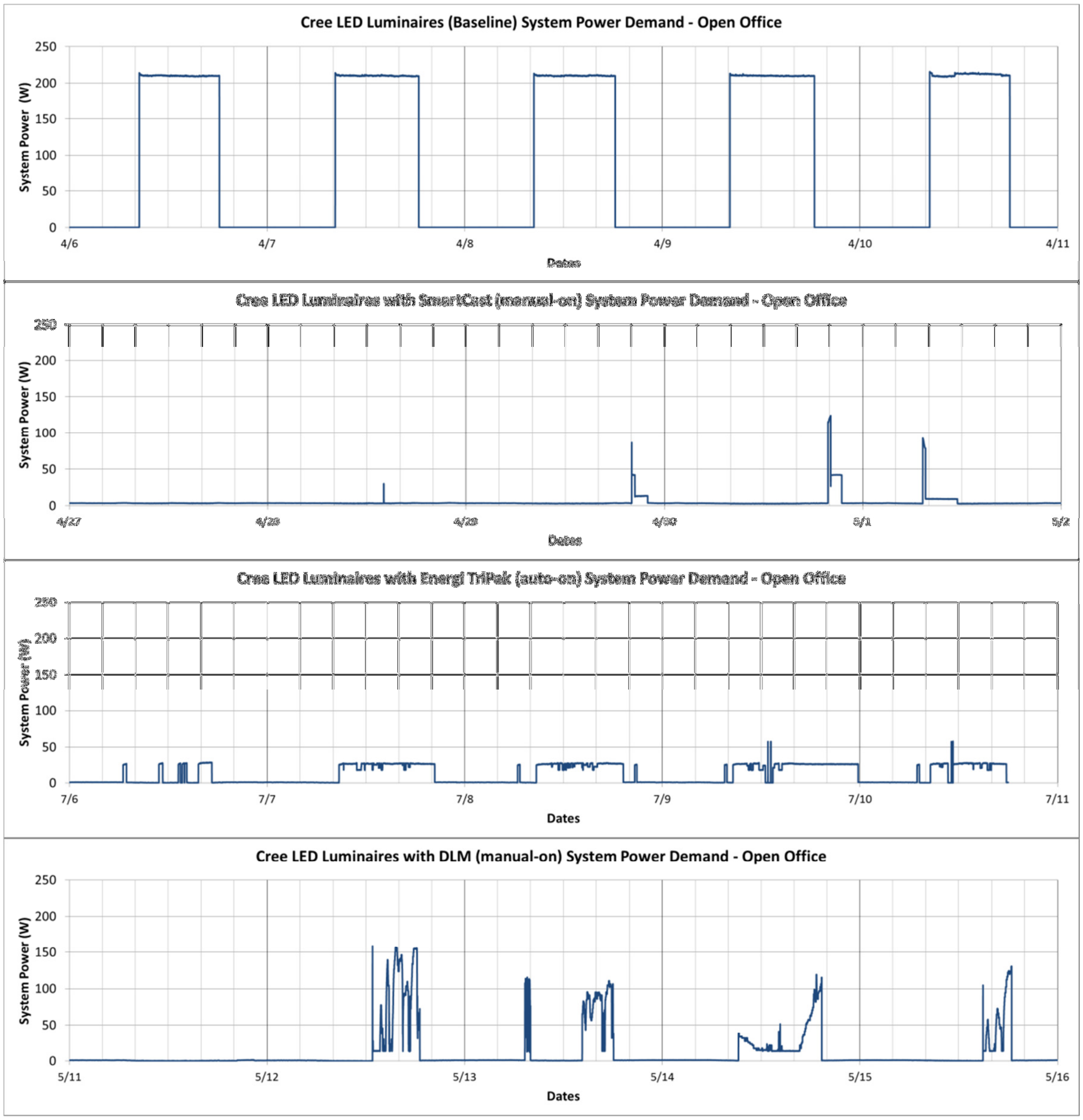

Figure 21: System power demand in the open office of Cree LED luminaires without controls and with three attached control systems in their default configuration.

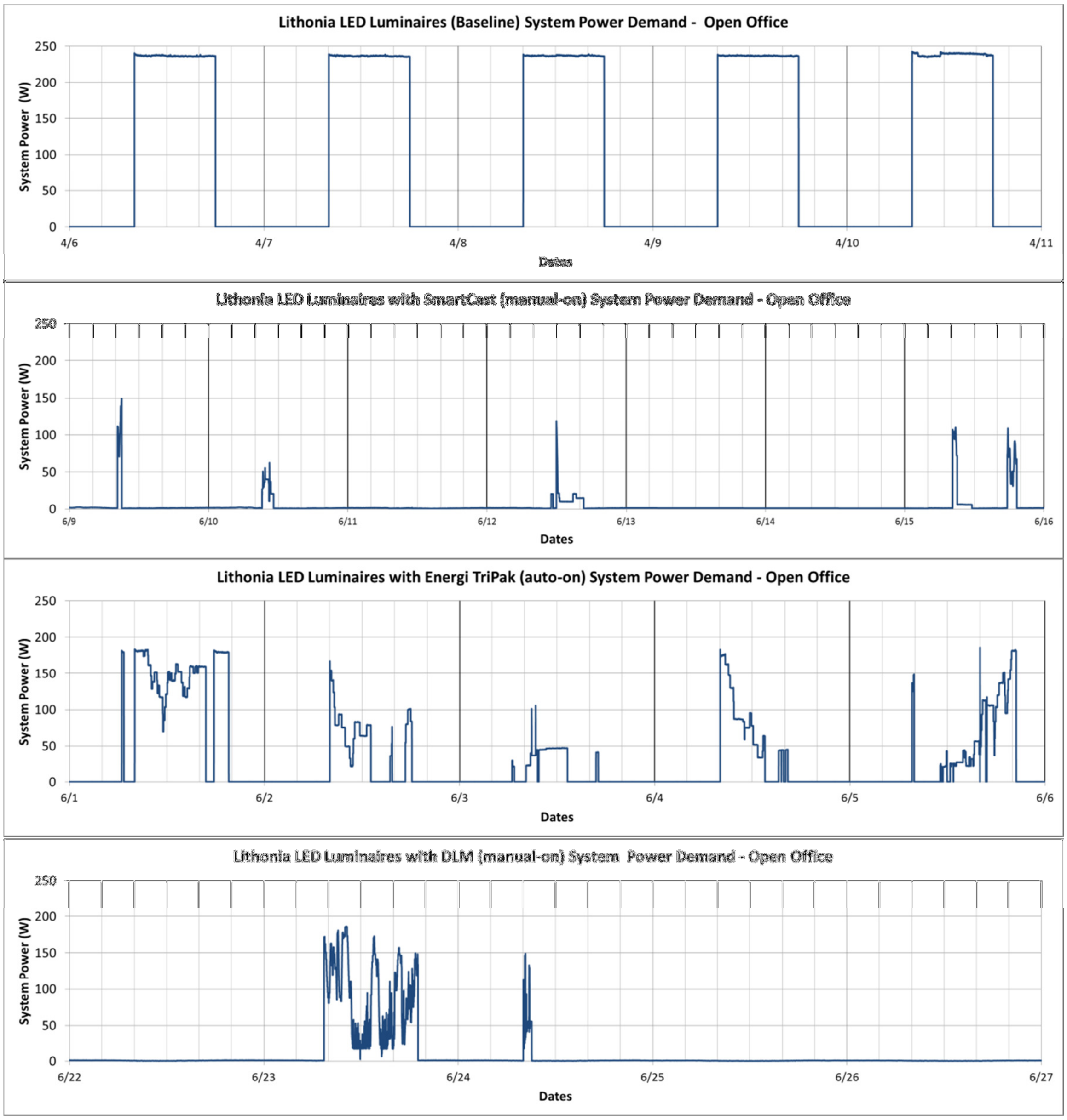

Figure 22: System power demand in the open office of Lithonia LED luminaires without controls and with three attached control systems in their default configuration.

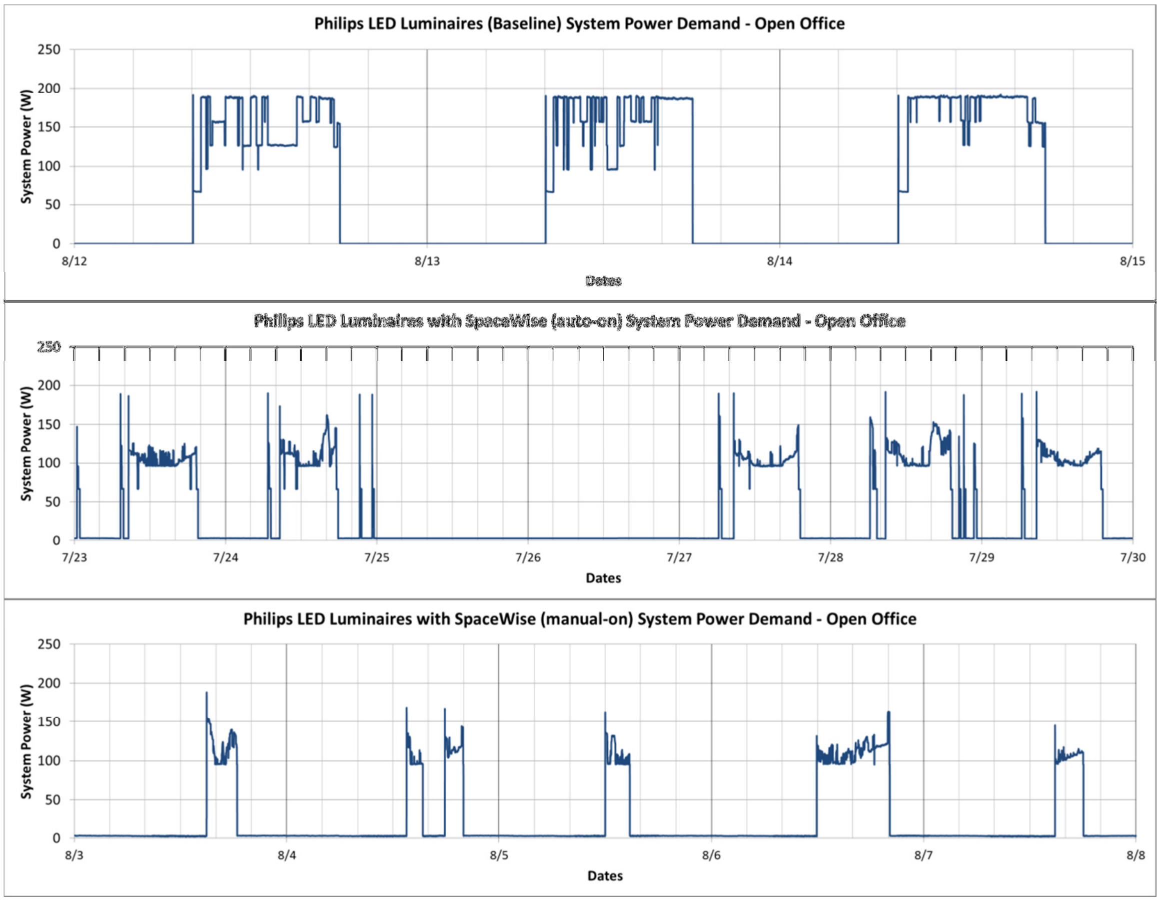

Figure 23: System power demand of Philips LED luminaires with and without SpaceWise commissioning in the open office.

Conference area system power

The system power demand in the conference area for the baseline week and with the commissioned controls is shown in Figures 24-26. The electric lighting was not manually switched on during the week that the Lithonia + SmartCast combination was deployed (manual-on system by default), so an additional week of this combination with automatic-on control was measured for comparison.

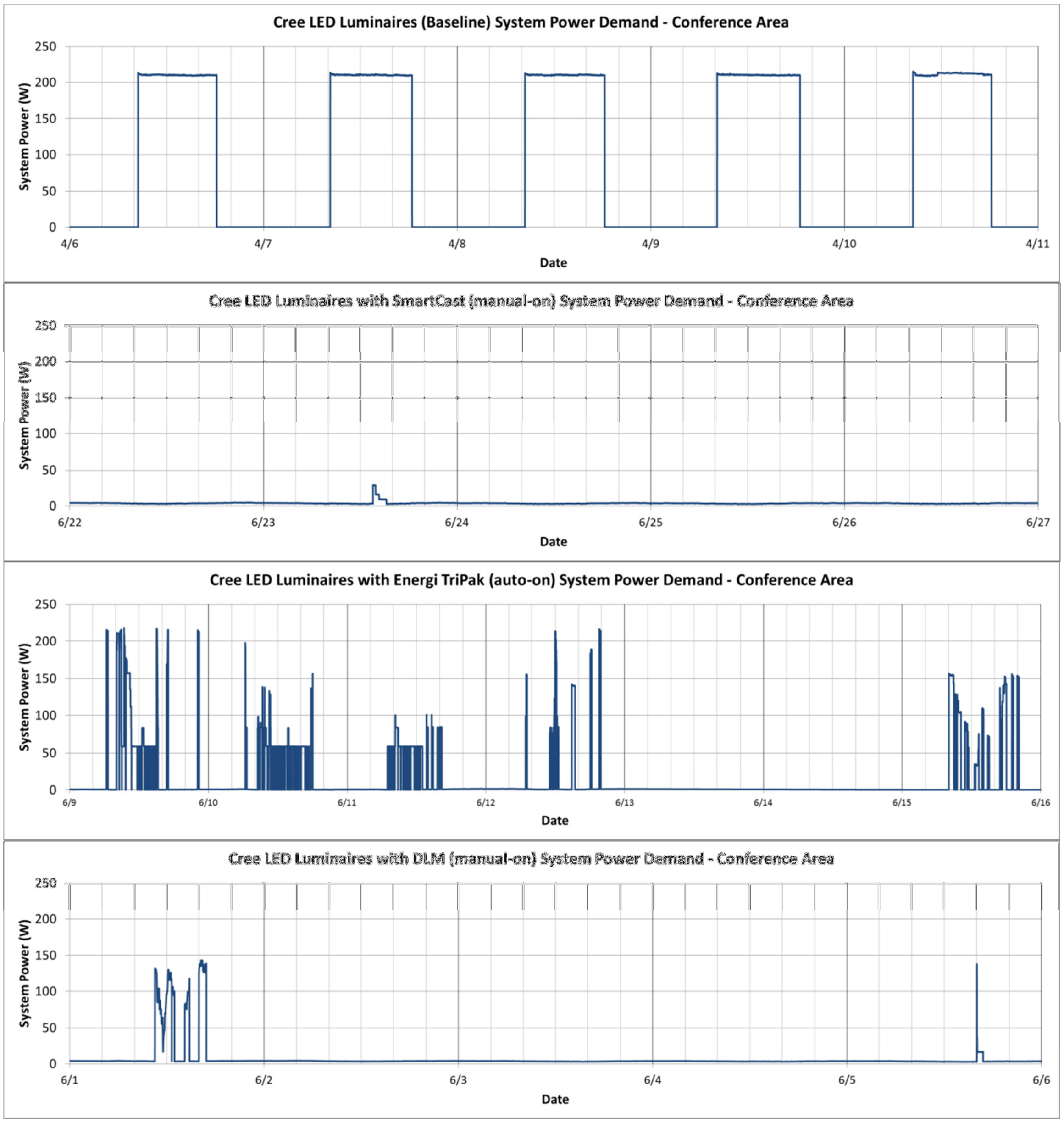

Figure 24: System power demand in the conference area of the Cree LED luminaires without controls and with three attached control systems in their default configuration.

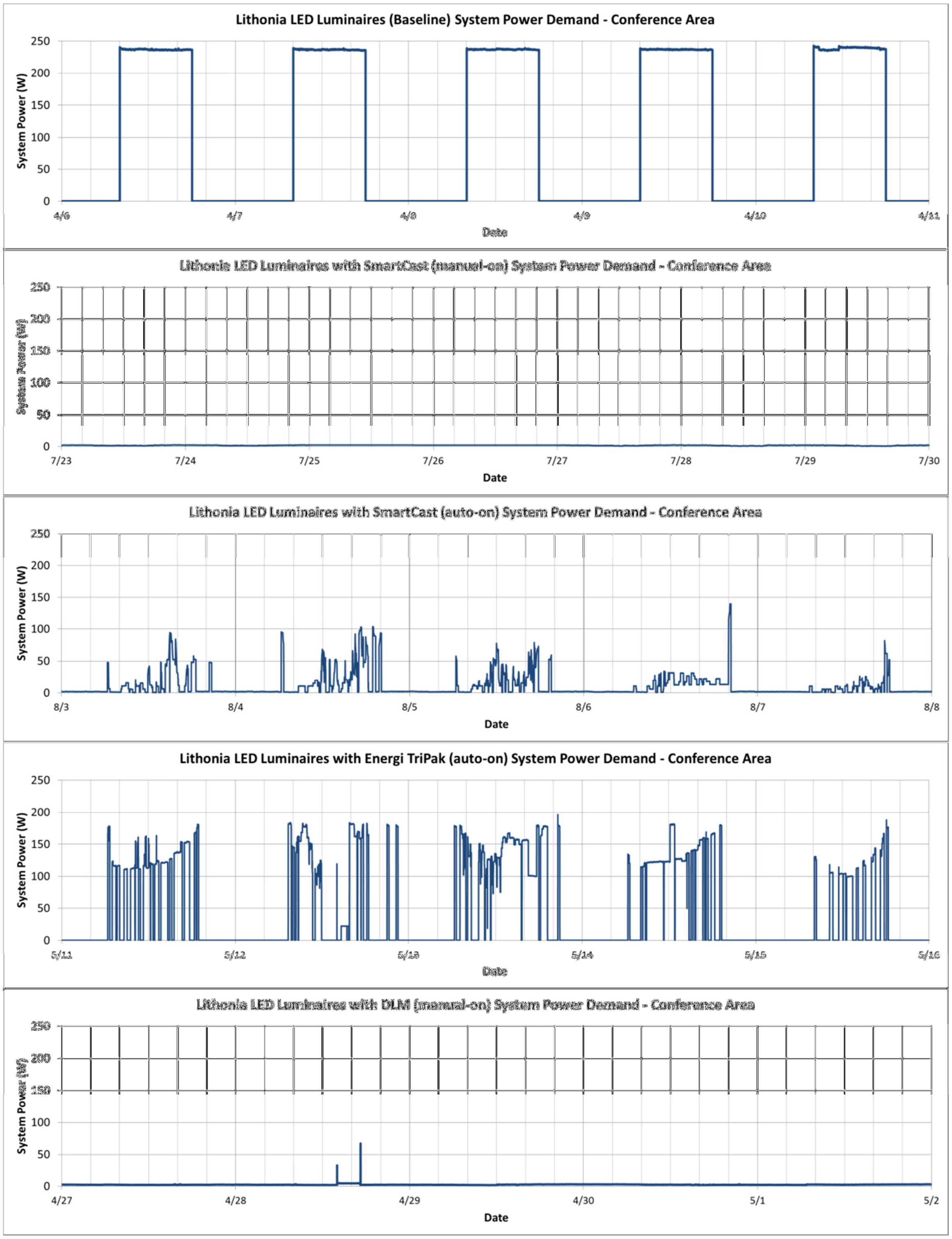

Figure 25: System power demand in the conference area of the Lithonia LED luminaires without controls and with three attached control systems in their default configuration. The SmartCast system in automatic-on mode (not a default option) was also deployed for five days for comparison purposes.

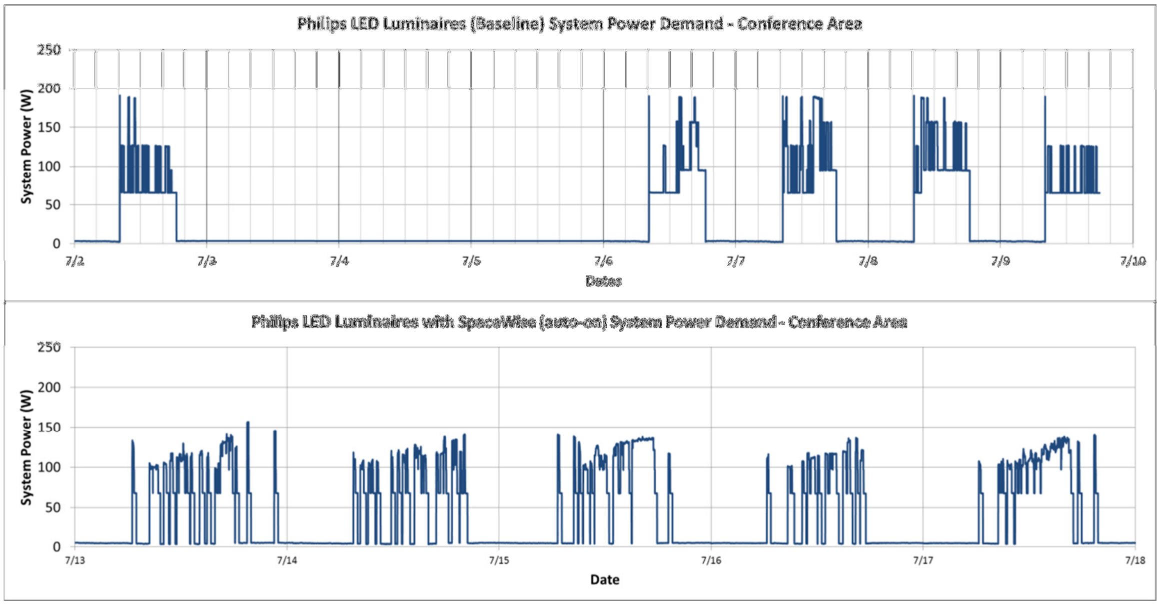

Figure 26: System power demand of Philips LED luminaires with and without SpaceWise commissioning in the conference area.

Average power demand and total energy use

Average power demand, for each 5-day analysis period (3-day analysis period for Philips baseline in the open office), is shown for the open office in Figure 27 and the conference area in Figure 28. Use of the lighting controls in their default configuration resulted in significant power demand savings. For a given control system, the power demand is dependent on daylight conditions, occupancy, and the luminaire's current response to the dimming voltage (control voltage). As shown in Figure 29 and Figure 30, the Cree and Lithonia LED luminaires used in this pilot study have different dimming curves (current vs. control signal voltage).

Total energy use over the 5 day analysis period was also calculated (shown in Figures 27 and 28).[9]

In the open office area, use of the SmartCast controls resulted in 95% less power demand than the baseline, use of the Energi TriPak controls resulted in 78% less power demand than the baseline, and use of the DLM controls resulted in 89% less power demand than the baseline, on average. The commissioned SpaceWise controls used 24-67% less power, on average, than the Philips luminaires used without commissioning. As previously noted, the Philips luminaires use their integrated lighting controls to reduce light output to a background level when the space is unoccupied even prior to commissioning (during the baseline period).

In the conference area, the SmartCast controls used 97% less power, the Energi TriPak controls used 64% less power, and the DLM controls used 95% less power than the baseline, on average. In automatic-on mode (not the default mode), the SmartCast controls used 89% less power on average, than the baseline. The commissioned SpaceWise controls used 13% less power, on average, than the Philips luminaires without commissioning.

[9] For the Philips LED luminaires, the total kWh over the 3-day baseline period was multiplied by 5/3 to obtain an estimated kWh over 5 days, assuming the same pattern of occupancy.

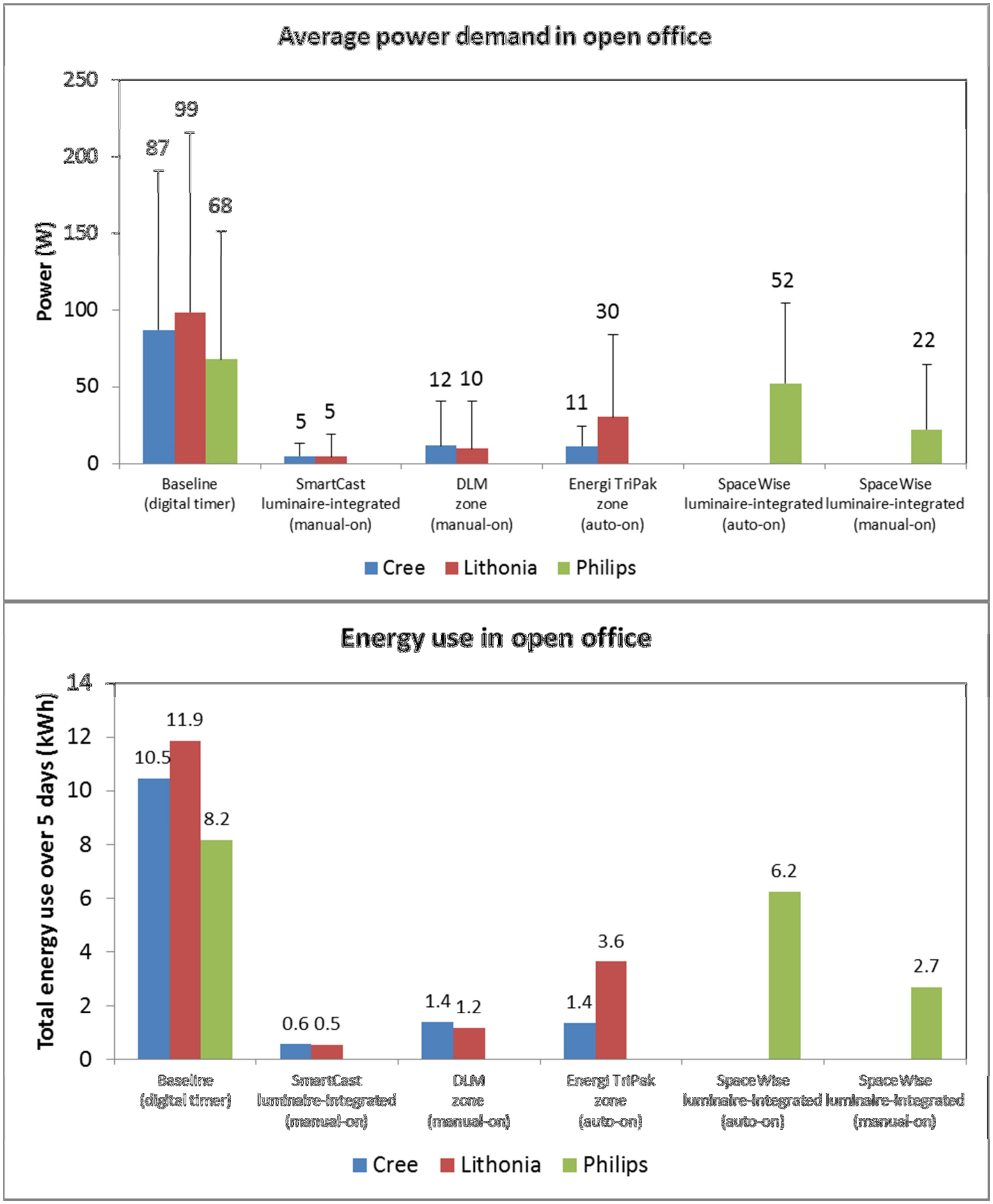

Figure 27: Average power demand and total energy use, over 5 days in the open office of LED luminaires during baseline and with commissioned control systems in their default configuration.

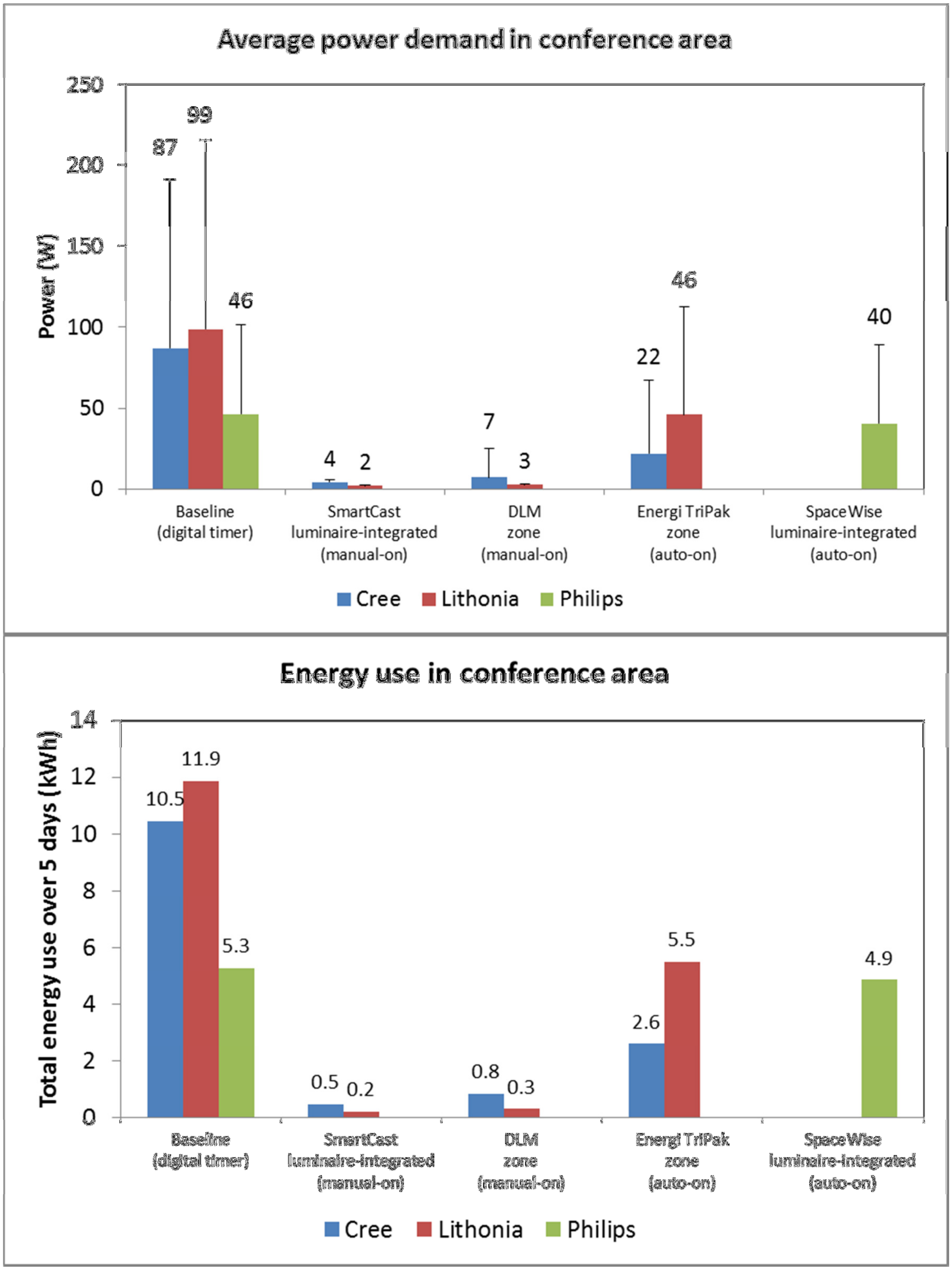

Figure 28: Average power demand and total energy use, over 5 days in the conference area of LED luminaires during baseline and with commissioned control systems in their default configuration.

Power factor implications

The Philips and Lithonia luminaire specification sheets did not state the rated power factor (PF). The Cree CR24LED specification sheet stated a nominal power factor of 0.9. A digital power meter[10] was used to measure power factor for one of each of the LED luminaires without lighting controls. The measured power factor for the measured Cree, Lithonia and Philips LED luminaires at full light output was 0.983, 0.997 and 0.994, respectively.

To determine how power factor changed as a function of dimming, a programmable dc power supply was used to provide 1V – 10V (in 0.5V increments) to the Cree and Lithonia LED luminaire using the purple and gray control wires. At 10V, the luminaire should be at 100% light output, while at 1V the luminaire should be fully dimmed, The Cree luminaire demonstrated high PF (>=0.9) at control voltages of 5V and higher, but PF rapidly decreased as the control voltage was lowered below 5V (shown in Figure 29); the luminaire power demand when a control voltage of 4.5V or lower was applied was in the range of 3 – 21 W. The Lithonia LED luminaire demonstrated high PF at control voltages of 2V and higher (Figure 30); the luminaire power demand when a control voltage of 1.5V or lower was applied was 4-5 W.

The Philips luminaire has integrated SpaceWise controls and could not be characterized with a programmable power supply, because it doesn't have 0-10V control wires. To determine power factor when dimmed a flashlight was shined onto the daylight sensor. The power factor was 0.856 when the luminaire was dimmed, with a power demand of 6 W.

Because dimming greatly reduces power demand for each luminaire, a low power factor when a luminaire is dimmed may not be an important consideration, especially if the low power factor occurs when the luminaire is deeply dimmed and the corresponding power demand is low.

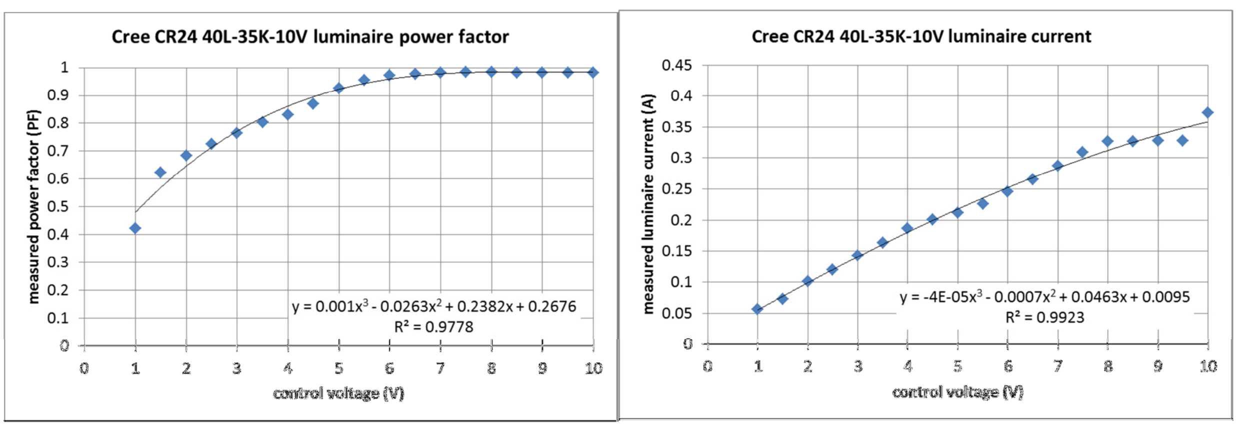

Figure 29: Measured power factor and current as a function of dimming voltage (0-10V) for one CreeCR24 LED luminaire

[10] Yokogawa WT210

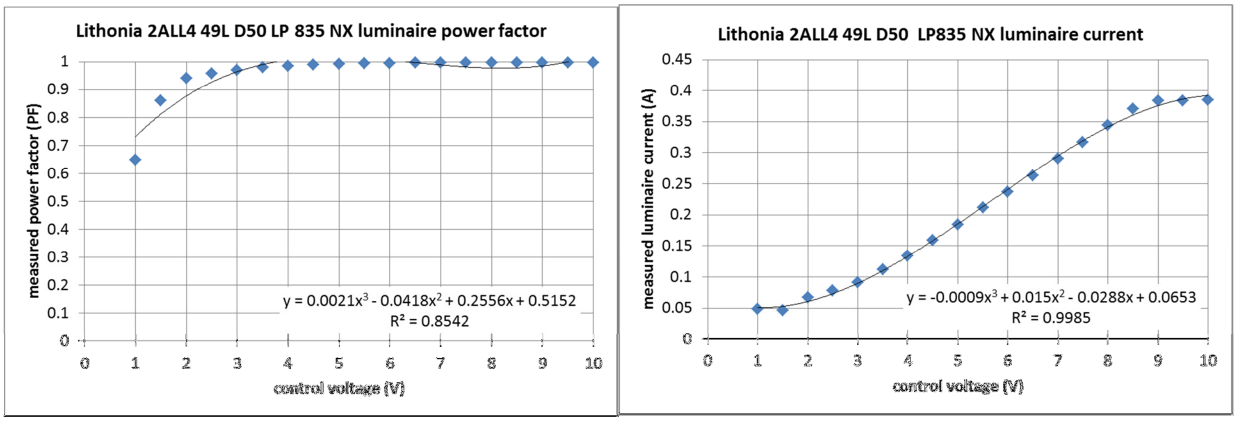

Figure 30: Measured power factor and current as a function of dimming voltage (0-10V) for one Lithonia 2ALL4 LED luminaire

The actual power demand with the controls in place is likely lower than the calculated power demand shown above. The system power calculations shown in this section use the full light output PF value rather than the PF value at each control voltage, which makes the calculated power likely higher than it really is. In this pilot study, current was measured for each space (including four luminaires and the connected control system), so individual luminaire dimming, with its potential decrease in power factor, cannot be taken into account. Future research should consider that luminaires might have lower power factor when dimmed and measure power factor of luminaires individually to accurately characterize power demand.

Energy code requirements

The studio space used in this study has an area of 1059 ft^2 (calculated per ASHRAE 90.1-2010) with large windows on four sides of the room. Half of this area was arranged as an open office space, the other half as conference/meeting space. The calculated lighting power density (LPD) using each luminaire type (shown in Table 1) was much lower than the allowable LPD for each space (1.24 W/ft^2 for conference rooms and 0.98 W/ft^2 for open office spaces).

Per the criteria in ASHRAE 90.1-2010, these spaces are subject to the following mandatory provisions: lighting control (manual-on or automatic-on to 50% power); automatic lighting shutoff; space control including use of an occupancy sensor in the conference room and automatic daylighting controls. For the most part, the controls systems tested complied with the AHRAE 90.1-2010 mandatory control provisions, as shown in Table 6. Some of the systems tested would need to have other configuration settings selected during the commissioning process to comply with these provisions.

Table 6: Tested control system's compliance with ASHRAE 90.1 mandatory control provisions (in default configuration)

Control provision in ASHRAE 90.1-2010	Cree SmartCast (components shown in Figure 1)	Lutron Energi TriPak (components shown in Figure 2)	Philips SpaceWise (components shown in Figure 3)	Wattstopper DLM (components shown in Figure 4)
Lighting control (Manual-on or Auto-ON to 50% power)	✓	Occupancy sensor can be configured this way using Advanced Setup installation instructions or can specify a vacancy sensor instead	User can select manual-on option from Application Modes setup during group setup	✓
Automatic lighting shutoff	✓	✓	✓	✓
Space control – manual control device to independently control the general lighting (must have one control step between 30% and 70% of full power)	Dimmer switch would not increase light level set by daylight sensor (only decrease light level)	✓	✓	Dimmer switch does not override light level set by daylight sensor by default (can change this using configuration tool)
Space control – occupancy sensor	✓	✓	✓	✓
Automatic daylighting controls for primary sidelighted areas	✓	✓	✓	✓

Discussion

Each of the systems tested had a "plug and play" or automatic configuration option that was selected in this pilot study. Each of these systems had an "automatic daylight calibration" option that turns the lights on and off to determine the daylight at the sensor in order to tune the algorithm the system uses for the space.[11] As previously noted, the target workplane illuminance was not always met with the light levels set by the luminaire-control combinations. Each of these systems assumes a sensor:task illuminance ratio that the system uses to set the dimming response to daylight. None of the systems tested had a setup option that allowed the workplane illuminance to be measured and input to the system as part of the commissioning process (although the Energi TriPak system instructed the users to set the light level they wanted prior to the daylight calibration). This step is critical if the daylight sensor is to accurately set the dimming response for the space. In the LRC studio, the sensor:task ratio was 1.2:1 due to high windows and the angle of the window blinds. In other words, when there was 300 lux at the sensor, there was about 250 lux on the workplane. Daylight sensors that assume a sensor:task ratio lower than the actual ratio will overly aggressively dim or possibly switch off the electric lighting because they assume there is much higher illuminance on the workplane than there really is (e.g. if the configured sensor:task ratio is 1:5, the sensor assumes there is 500 lux on the workplane when there is 100 lux at the sensor). To make matters worse, when a wall-mounted dimmer switch is not able to override (increase light level or switch lights on) the daylight sensor, the occupant cannot compensate for the incorrectly commissioned lighting control. One possible way to overcome this is to move the sensor farther into the space to decrease the sensor:task ratio, but this requires an undesirable iterative commissioning process. In this space, moving the daylight sensor towards the back of the room for the zone systems (Lutron Energi TriPak and Wattstopper DLM) would have made little difference, because the sensor:task ratio in the back of this space is very similar (1:1.4 in the back of the room compared to 1.2:1 in the front of the room) because the studio has windows on all four walls. This setup challenge could be addressed by placing a calibrated photosensor on the work surface during setup, perhaps as an integral part of a handheld remote.

Daylight conditions during commissioning are important. For all of the systems, commissioning was completed as soon as the lighting systems were setup, in a few cases during overcast sky conditions with lower ambient light levels. In one of these cases, the lighting did not come on when occupants walked in every time (automatic-on mode) presumably because the daylight sensor was overriding the occupancy sensor. The system was recommissioned under higher ambient light levels and the lighting came on as expected thereafter. In another case, the electric light level set automatically by the system after commissioning during low ambient light levels was very high (about 800 lux). After the lighting system was recommissioned the next morning under higher ambient light levels, the default light levels were lower (about 600 lux).
The manual-on control mode worked well during daylight, but was problematic in the evening in some instances when occupants were working late and the lights switched off while they were working. Occupants stated they were dissatisfied that they had to walk to the wall switch in the dark and switch the lights on, because the lights would not switch on automatically when they waved their arms.

With regards to the different control systems, luminaire-integrated lighting controls may save energy and reduce power demand compared to zone controls, but the reduction depends on the

[11] See the following resources for more information about daylighting control terminology: http://www.lrc.rpi.edu/programs/nlpip/lightingAnswers/wirelessControls/photosensorPerform.asp, http://www.lrc.rpi.edu/nlpip/publicationDetails.asp?id=916&type=1, http://www.lrc.rpi.edu/education/outreachEducation/photosensorTutorial.asp

daylight availability, occupancy, control algorithm and the LED driver. In this study, with varying occupancy and daylight conditions, the SmartCast system, with individual luminaire controls, used less energy and had lower power demand than the DLM zone control system, when both control systems were operated in manual-on mode driving the same LED luminaires. In comparison, the commissioned Philips SpaceWise system used more energy in manual-on mode than both of the other manual-on systems (SmartCast and DLM), with either luminaire type. When the commissioned Philips SpaceWise system was operated in automatic-on mode, it used less energy than the Lithonia+Energi TriPak combination (and more energy than the Cree+ Energi TriPak combination).

Limitations

These are pilot results and are not directly comparable from product to product for the following reasons:

- The systems were commissioned under different daylight conditions.
- There are variations in daylight conditions from week to week and from conference room to open office setups.
- Occupancy varied over time.
- More recent versions of these products may now be on the market.

Summary

A pilot study examining ease of use, energy usage and light levels under default commissioning protocols was conducted with three lighting controls systems paired with two LED luminaire arrays, as well as an LED luminaire system with integrated lighting controls. The systems were all easy to install, but challenges were encountered in initialization and operation. Significant energy and power demand savings were seen for all the lighting control systems in nearly all of the applications.

Lessons learned:

Ease of Use:

- All of the products tested were easy to install.
- For initialization, three of the four systems came without sufficient setup documentation, leading to an increased setup time. Recent documentation improvements made since this work was conducted were not evaluated.
- Initialization of some of the wireless dimming wall switches was complicated, even with documentation.
- The systems appeared to lack any mechanism to adjust the default sensor:task light ratio, either manually or automatically. In some cases, this produced low light levels and occupant dissatisfaction.
- When the light levels were dim, occupants were satisfied with products that provided manual override capability. Products without this capability were less satisfying.

Energy savings:

- Significant energy savings are possible compared to time clock control, baseline conditions and/or power density requirements.
- Manual-on controls could save energy compared to automatic-on controls.
- Luminaires with integrated controls may or may not save energy over control systems that use one sensor to control a group of luminaires. Energy use depends on the system configuration.
- Connecting different luminaires to the same lighting control system may result in different light levels and power demand, as the driver's current response to the dimming control voltage varies by manufacturer and driver design.
- All of the LED luminaires tested demonstrated low power factor (< 0.9) when dimmed.
- One system provided access via USB to instantaneous power readings. Beyond that, none of the systems logged or reported energy use.