Technology Sector Lighting Product Category Advanced Daylighting Harvesting Last Updated 01/16/2019	 *Figure 1: Advanced Daylighting Device – Integrated Glazing Unit with Motorized Roller Shade and Natural Ventilation*

Product Category Overview

Daylight harvesting is a control strategy which takes into account the natural light being introduced by the sun into the building. The artificial lighting is reduced so that light level is consistent throughout the day. This often allows artificial lights to be significantly reduced during daylight hours. Traditional daylighting techniques utilize one open- or closed-loop light sensor to constantly monitor the indoor light and adjust the artificial lights to match a commissioned set point in the space.

Daylighting in commercial buildings can reduce lighting electricity use by as much as 38 percent [1], but it also presents complex challenges. Realization of these energy benefits requires lighting controls that adjust electric lighting based on available daylight. Additionally, adding daylight can increase HVAC loads significantly depend on a building's geographic location and fenestration orientation.

Realizing the energy benefits of daylighting is challenging. Traditional methods do not consider illuminance changes caused by occupants and are only effective up to 15 feet from a window. Advanced daylighting strategies aim to increase savings by addressing these limitations. Advanced daylighting strategies can be divided into three categories:

1. Automated electric lighting controls with daylight harvesting capabilities to reduce electric lighting when daylight is available,
2. Advanced building fenestration devices that increase daylight penetration, and
3. Automated glazing/shading systems to prevent increased HVAC load.

Additionally, these strategies can be integrated to fully optimize building-wide energy savings while maintaining end-user comfort.

Automated Electric Lighting Controls with Daylight Harvesting Capabilities

Daylight harvesting requires photosensors paired with a controller and a dimmable light source, such as LEDs. Photosensors determine available daylight. Traditionally, there have been two main photosensing strategies: open- and closed-loop sensing. More recently, dual-loop sensors that utilize 'redundant sensing' strategies have become commercially available. These redundant sensing strategies allow for the photosensors to identify illuminance changes caused by occupants in the space and adjust their response accordingly.

Advanced Building Fenestration

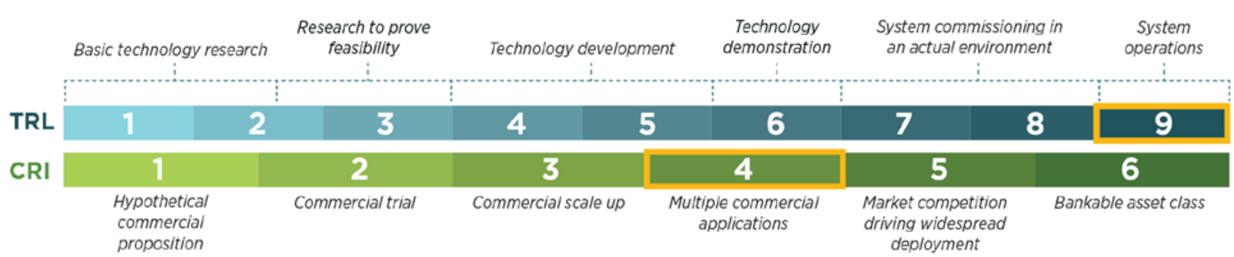
Building fenestration products such as light shelfs and light pipes can project light further into spaces than traditional fenestration (i.e. windows, skylights) by using a series of reflectors. This strategy can also reduce direct solar heat gain to the area. By increasing the daylight penetration area, more electric lighting loads can be reduced when daylight is available. This increases energy savings for the lighting loads.

Automated Glazing & Shading Systems

Based on data collected in 2012 by the US Department of Energy [8], HVAC loads are the highest energy use in commercial buildings. To address this, automated glazing and shading can reduce solar heat gain, reducing HVAC loads. Avoiding solar heat gain is critical to contributing to building energy efficiency, but can also compromise view and reduce electric lighting savings because of reduced indoor daylight levels. This is also true when shading systems are used to provide privacy or reduction of direct solar penetration for managing glare.

The characterization report for Building Fenestration and Windows provides further information on these product categories.

Characterization at a Glance



Product Category Characterization

Energy Benefits

Energy savings are achieved by reducing electric lighting loads by utilizing available daylight. Daylighting in commercial buildings can reduce lighting electricity use by as much as 38 percent. Electric lighting, HVAC and dynamic fenestration devices can be integrated to maximize energy savings and end-user comfort.

Non-Energy Benefits

Advance daylighting systems that utilize automated glazing and shading devices can be designed to improve visual comfort for the users by reducing glare. In addition, exposure to natural daylight can provide occupants with a natural waking/sleep experience (circadian rhythm). This has been shown to lead to increased alertness in morning, productivity benefits, and improved sleep cycle. [7]

Product Category Differentiation

Advanced lighting control strategies provide the appropriate amount of light when and where it is needed. One of these strategies is advanced daylighting. The advanced daylighting strategy allows for the light levels on the task plane to be maintained throughout the day, and thereby reduces the electrical lighting load when daylight contributions provide sufficient light levels for the tasks being executed in the space.

Installation Pathway and Dependencies

The most common installation pathways for advanced daylighting strategies are new construction and major renovations. Often, advanced daylighting efforts require additional sensors and integrated system controllers. These components typically require additional communication wires. Advanced daylighting strategies may also require internet connectivity and communication to building management systems.

Due to the increased complexity of installation associated with advanced daylighting strategies as opposed to traditional wiring, training programs such as the California Advanced Lighting Controls Training Program (CALCTP) have been developed to train contractors and electricians. As such a CALCTP-Certified Installation Contractor may be needed for installation. Note, beginning July 1, 2019, lighting control projects receiving $2,000 or more in utility program incentives will be required to utilize CALCTP-certified installation teams.

List of Products

This table should include a list of manufacturers and potential products that could be tested for the product evaluations-does not need to be exhaustive.

Table 1: Summary of manufacturers and products for the product category.

Manufacturer	**Model**	**Type**	**Differentiating Feature**
Wattstopper	LMLS-600	Dual loop photosensor	Calibrates in any daylight condition. Accounts for reflectance changes within space.
SageGlass	Lightzone	Fenestration	Intelligent daylight management. Blocks 99% of glare producing light.
H&H Metals	BrightShelf	Light Shelf	Curved shape casts light further than conventional flat shelf. Smooth reflection pattern.
Solatube	Light Pipe	Light Pipe	Redirects low-angle sunlight to maximize light capture. Rejects overpowering midday sunlight.

Quantification of Performance

A literature search was conducted and a sample of published study results are summarized in Table 2.

Table 2: Summary of results from literature review

Location	**Application**	**Results**	**Reference**
Los Angeles, California, USA	Lab Test Scale model of office space tested with light pipes, light shelves, and skylights. Electrical consumption was compared to baseline of 7ft high clear glass windows found in typical commercial practice. Measured workplane illuminance and energy consumption	Both advanced daylighting systems introduced daylight in a 15-30 ft perimeter under sunny conditions. Most light shelf systems used 8-9% less electricity than baseline. Most light pipes used 5-9% less electricity than baseline.	[2]
Quebec City, Canada Rome, Italy	Lab Test Single occupancy perimeter office. Simulated baseline office with continuous overhead lighting and no blind control during operation hours. Monitored energy consumption of lights as well as heating and cooling systems.	Examines whole building energy consumption and how it is impacted by lighting use through simulations. Primary energy expenditure was reduced by 40% when occupants actively sought daylighting.	[3]
Berkeley, California, USA	Lab Test Scale models of light shelfs, light pipes, and skylights. Compared introduced illuminance values from daylight by exclusive use of vertical windows. Workplane illuminance was measured at multiple reference points to quantify daylight penetration.	While vertical windows do not provide any significant illuminance values past 4.6 m, light shelves, light pipes, and skylights increase illuminance levels farther from windows and improve luminance gradient. Light shelves achieved illuminance levels of greater than 50 lux at distances of 8.4 m from window wall. Light pipes resulted in illuminance levels of up to 200 lux at 8.4m from the window wall but was less consistent throughout the year compared to light shelves.	[5]
LBNL, Berkeley, CA	Meta-Analysis 88 Papers and Case Studies focusing in energy saving control strategies. LBNL facility	"Based on the meta-analysis, the best estimates of energy savings potential are 24% for occupancy, 28% for daylighting, 31% for personal tuning, 36% for institutional tuning, and 38% for multiple approaches."	[1]

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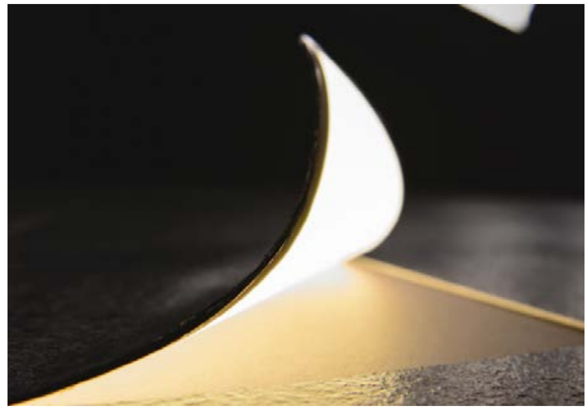
Product Characterization Report
California Energy Product Evaluation (Cal-EPE) Hub

Technology Sector Lighting Product Category Advanced Light Sources Last Updated 01/08/2019	 *Figure 1: LG's Luflex OLED light source (Photo Credit: LG)*

Product Category Overview

Advanced light sources are those that use novel materials exhibiting comparable or improved performance as compared to traditional sources; advanced sources are coupled with additional non-energy benefits such as improved color and design flexibility. Advanced sources usually do not have a significant market share in the general lighting market and are used primarily in niche applications such as furniture lighting and custom architectural lighting. Examples include:

- Laser Diodes
- Organic Light Emitting Diodes (OLEDs)
- Quantum Dot Light Emitting Diodes (QLEDs)

Laser Diodes

Lighting with laser diode technology is similar to lighting with today's LED technology. The main difference is that laser diodes emit light in a narrow beam of one to two degrees. This narrow beam increases the concentration of light in a small area – enabling novel, compact luminaire designs and useful lighting service at longer range.

Laser diodes are appropriate for use in targeted lighting strategies where the laser diode can be adjusted to emit light only where appropriate. This is useful in applications such as theatrical and retail lighting.

Organic Light Emitting Diodes (OLEDs)

Organic light emitting diodes (OLEDs) are an emerging light source that provides uniform, planar (non-point) lighting. OLEDs are a thin, highly flexible product that is appropriate to use in small niche applications, such as furniture lighting, illuminated facades and decorative lighting.

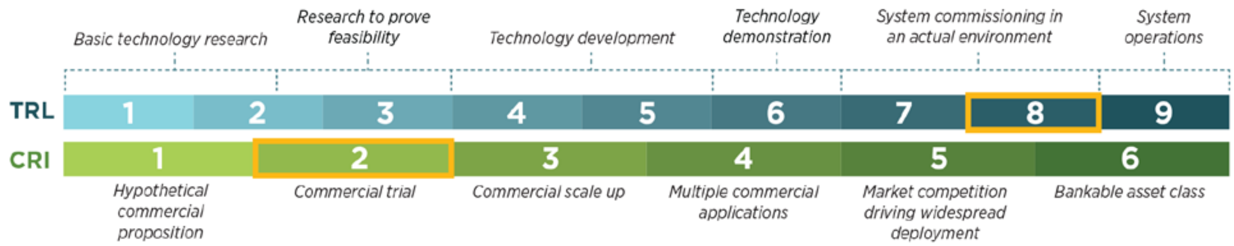
Quantum Dot Light Emitting Diodes (QLEDs)

Similar to OLEDs in flexibility, quantum dot light emitting diodes (QLEDs) allow for thin designs. QLEDs typically have improved color rendering properties as compared to today's LED technologies. This is due to the quantum dot (QD) layer added to the diode substructure. The QD layer can be manipulated to provide both narrow spectrum bands and wide spectrum bands that follow closely to natural light.

Because of this highly customizable spectral distribution, QLEDs have gained interest in the horticultural lighting market place as grow lamps.

Characterization at a Glance

TRL and CRI may vary slightly by technology being viewed.



Product Category Characterization

Energy Benefits

Energy savings vary based on the advanced light source technology. Laser diodes do not decrease in efficiency or efficacy at increased power levels, like today's LED technology, resulting in higher power densities. For appropriate applications, such as theatrical and retail lighting, laser diodes can provide more concentrated light at high efficiency, resulting in energy savings compared to incumbent technologies.

OLEDs and QLEDs are more efficient and efficacious when compared to traditional incandescent. Although today's standard LED technology is still better than OLED and QLED technologies for general illumination, OLEDs and QLEDs are more viable for use in niche applications where their non-energy benefits outweigh the desire for energy savings.

Non-Energy Benefits

The main non-energy benefits of advanced light sources are the increased appropriateness for specialty applications that require source design flexibility. Laser diodes narrow beam of light emission makes it an appropriate light source for more focused lighting applications (i.e. automotive, theatrical, retail) as compared to the wider 10 degree LED emission beam angle. OLEDs are flexible and thin, allowing for the light source to be utilized in small applications such as furniture lighting. Due to the planar luminous surface of OLEDs, they typically produce less glare than point sources, thus potentially reducing eye strain. Most OLEDs emit a low amount of heat and contain less blue light as compared to today's LED light sources. Less blue light may translate to biological benefits.

QLEDs are also flexible and thin, with improved color rendering properties, making them more appropriate for use where color accuracy is critical such as retail and residential applications.

Product Category Differentiation

Compared to incandescent lighting, all three advanced light source lighting technologies offer improved efficiency. Additionally, laser diodes can result in higher power densities since their efficacy and efficiency do not decrease at reduced power levels, like today's LED technology.

OLEDs and QLEDs offer small, flexible packages as compared to existing lighting technology. This makes the technology appropriate for use in thin applications such as with televisions and appliances.

Installation Pathway and Dependencies

Installation pathways and dependencies are heavily influenced by the application where the light source is being installed. Given the niche nature of the sources, new construction and major renovation are the most prominent pathways due to their larger capital budgets and design flexibility.

List of Products

Table 1: Summary of manufacturers and products for the product category.

Manufacturer	Model	Type	Differentiating Feature
Winona Lighting	Revel Trilia Nomi Canvis Kindred	OLED Lighting	Offers Ceiling, Wall, and Pendant mounted fixtures. 85-90 CRI. 3000K, 3500K and 4000K CCT options .
LG	Luflex	OLED Lighting	Various shape options from 50 mm to 400 mm rectangles and circles. Rigid and flexible options 93 CRI.
OLEDWorks	LumiCurve Wave LumiBlade Brite Keuka	OLED Lighting	Various sizing options up to 250mm. Rigid and flexible options >90 CRI with R9 >75.
SLDLaser	LaserLight SMD LaserLight Fiber LaserLight Blue	Surface Mount Laser Diode and Fiber laser light module	Sources available with 1000 Mcd/m^2.
Nanoco	CFQD quantum dot Film	QLED Horticulture Lighting	Optimal spectra for chlorophyll absorption (both chlorophyll A & B). Films can be swapped to produce different spectrums.

Quantification of Performance

A literature search was conducted and a sample of published study results are summarized in Table 2.

Table 2: Summary of results from literature review

Location	Application	Results	Reference
Santa Barbara, California, USA	Case Study Examine plausibility of laser diodes as an efficient and color-stable high-power solid-state white light source. Use Color Rendering Index (CRI) to measure light source's color accuracy.	Three sample laser diode and phosphor combinations were tested resulting in correlated color temperatures of 3600K, 2700k, and 4400K. These samples produced CRI values of 91, 95, 57, luminous flux values of 47 lm, 53 lm, 252 lm, and efficacy values of 16 lm/W, 19 lm/W, and 76 lm/W respectively.	[1]
Germany	Field Test Baseline is LED powered headlights Recorded the peak brightness and light output of different laser-based white light engines.	Using a high-power GaN-based blue laser diodes that pump a yellow phosphor in a remote position a source was created by BMW that resulted in a peak brightness over 1000 cd/mm2 , 10 times than that of high-power white LEDs, and a luminous flux of 530 lm. At high power densities laser-based system is about 30% more efficient than LEDs.	[2]
USA	Case Study Examines the potential for OLEDs for Solid-State Lighting.	Flexibility is available to tune the color temperature of the OLED to have a CRI exceed 90. Reported efficacy of 64 lm/W. Predicts lower cost associated with OLED manufacturing in SSL due to adoption of OLED in Electronic market.	[3]
Korea	Lab Test Baseline BE-OLED without the polymeric lighting extraction film (PLEF). Tests various geometrically profiled, negatively nanostructured periodic semi-pyramid polydimethylsiloxane (PDMS) layers to improve OLED luminous efficacy and external quantum efficiency.	PLEF I , PLEF II, and PLEF III were designed with PDMS layers which are placed on backside of BE-OLED to improve the glass substrate. These films enhanced baseline efficacy from 37.6 lm/W to 55 lm/W. External quantum efficiency increased from 16% with the BE-OLED without PLEF baseline to 22.8% with PLEF I, II, and III.	[4]

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Location	Application	Results	Reference
Istanbul, Turkey	Lab Test Explored the limitation of previous QLED manufacturing which led to poor efficiencies and low Quantum yield (QY). Experiments focused on increasing both efficiency and quantum yield of white generating Quantum Dots (QDs)	By suppressing the host material effect by simple liquid-state integration a luminous efficiency of 64 lm/W for red, green, blue (RGB)-based and 105 lm/W for green, blur (GB)-based white light generation was achieved. To optimize QY synthesis parameters of red- and green- emitting QDs were integrated with QDs, with QY up to 84%, on blue LED dies. This allowed white light generation through RGB while maintaining high QY. Theoretical calculations predict QLEDs can reach over 200 lm/W.	[5]
Seoul, Korea	Lab Test Explored limitations of semiconductor-based QDs that have narrow light emitting bandwidths. Luminance, Spectral distribution, current efficiency, and external quantum efficiency were gathered	QDs of three colors where created, Green, Yellow, Amber, using a multi-step hot injection process. The Green, Yellow, and Amber QLEDs exhibit the highest ever luminance levels of 999, 698, and 498 cd/m^2 and current efficiency rates of 1.12, 1.17, and 0.36 cd/A respectively.	[6]

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Technology Sector
Lighting

Product Category
Advanced Occupancy Tracking

Last Updated
01/08/2019

Figure 1: Example LiDAR technology.
Photo credit: LeddarTech

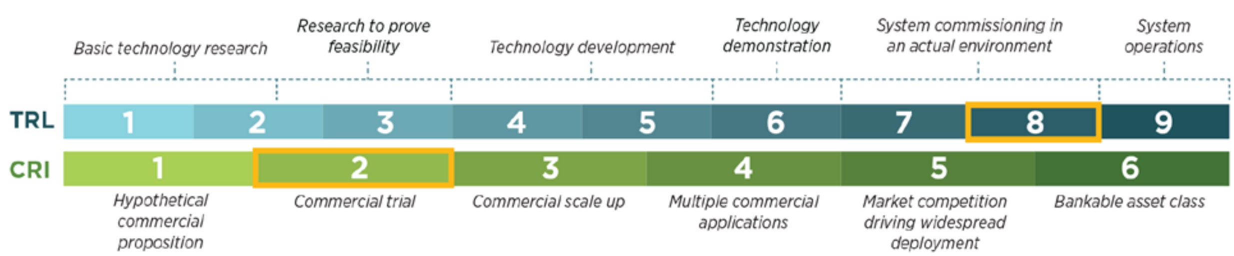
Product Category Overview

Typical occupancy-based control strategies for commercial lighting applications use an occupancy sensor with a binary control output. The occupancy sensor is designed to detect movement in their field-of-view, and respond by sending an output signal to the lighting device. Common occupancy detection methods for interior lighting systems include: passive infrared (PIR), ultrasonic (US), microphonics, and microwave. With the traditional occupancy sensing techniques, triggers from non-human activities and false unoccupied statuses can cause reduced energy savings and lead to end user dissatisfaction.

Advanced occupancy sensing strategies include (1) occupancy sensors with improved detection capabilities and (2) data analysis to determine occupant's path-of-travel and adjust lighting accordingly. Strategies used today to achieve increased performance metrics include:

1. Dual-sensing technologies,
2. Networked sensing, and
3. Light detection and ranging (LiDAR) sensors.

Characterization at a Glance



Product Category Characterization

Energy Benefits

Energy savings from advanced occupancy sensing strategies are achieved by reducing false positives (false ON) by using more reliable sensing technologies and strategies [4]. Additionally, the use of more accurate sensing technologies can lead to users reducing the frequency with which they override controls that negates the energy savings potential of the technology.

Additional savings can be achieved when these strategies are combined with a networked lighting control system. A networked system facilitates localized occupancy control and small, zonal occupancy tracking strategies. Preliminary data from a study conducted at the California Lighting Technology Center (CLTC) indicates that compared to single-level streetlights that lack controls, a networked, occupancy-based system reduces energy use between 27% and 42% depending on application and sensor settings.

Non-Energy Benefits

Non-energy benefits of advanced occupancy sensing for lighting systems include increased user comfort and potential for increased safety offered by more granular control.

Product Category Differentiation

Compared to traditional occupancy strategies, advanced solutions allow for increased energy savings potential and access to additional space utilization information. Data points, such as the current position of the occupant in the plane and possibly occupant count, enable more refined lighting strategies.

Compared to other on/off switching strategies such as scheduling, occupancy sensing allows for a more dynamic control profile as the systems react to occupants and not predefined time-based schedules that may not consider holidays, occupant absences, or extensions beyond traditional work hours.

Installation Pathway and Dependencies

The most common installation pathways are new construction and major renovations. Installation pathways through equipment replacement and retrofits are possible.

Due to the increased complexity of installation associated with advanced occupancy strategies (specifically those that utilize a networked control system) as opposed to traditional wiring, training programs such as the California Advanced Lighting Controls Training Program (CALCTP) have been developed to train contractors and electricians. As such a CALCTP-Certified Installation Contractor may be needed for installation. Note: beginning July 1, 2019, lighting control projects receiving $2,000 or more in utility program incentives will be required to use CALCTP-certified installation teams.

List of Products

Table 1: Summary of manufacturers and products for the product category.

Manufacturer	Model	Type	Differentiating Feature
Philips	OccuSwitch wireless	Occupancy sensor	Wireless sensors offer flexible mounting locations. Actuator is designed for any wiring system.
Metrosphere	Infrared motion detector	Occupancy sensor	Dual technology: PIR and microphonics. Alternating technology extends bulb lifespan.
Enlighted	Smart Sensors	Occupancy sensor	Distinguishes between objects and people. Can stream live data to Enlighted analytics software applications.
Optex	Redscan RLS-3060SH	Occupancy sensor	Detects size, speed, and distance of moving objects to minimize false alarms. 8 adjustable detection areas.

Quantification of Performance

A literature search was conducted and a sample of published study results are summarized in Table 2.

Table 2: Summary of results from literature review

Location	Application	Results	Reference
Omaha, Nebraska, USA	Field Test Networked occupancy sensors are compared to singular occupancy sensors that are found in typical installations. Occupancy of testing area was recorded by sensors and network rules applied after data collection to verify best strategy.	Network occupancy sensors paired with a rule-based system that judges occupancy activity every five seconds proved much more accurate than individual sensors. On average, rule-based network sensors showed 93.5% accuracy on determining occupancy status. Single occupancy sensors at worse showed 35% accuracy and at best 85% with average of 63%.	[1]
The Netherlands	Field Test Medium sized office building ($1500m^2$ total floor area) Compared to baseline without occupancy-based control (113.15 kWh energy consumption by lighting in one week). Evaluate the savings potential and practical implications of the wireless sensors and actuator network (WSAN).	During the first week of the experiment with occupancy- based controls, energy savings of 28% in lighting was achieved. 20% energy savings were achieved when sensor delay was increased from 2 minutes to 5 minutes in the following week.	[2]
The Netherlands	Lab Test Simulation of an open-plan office Compared to distributed optimization approach. Measured illuminance levels of different zones, steady state error, and overshoot.	Average power consumption of PI control system differed from optimum centralized control lighting systems by less than 10%.	[3]

Location	**Application**	**Results**	**Reference**
Davis, California, USA	Lab Test Outdoor test of occupancy sensors with variable height and mounting angle. Baseline PIR and microwave sensors. False triggers from occupancy sensors as well as coverage distance of LiDAR system.	LiDAR provides a detection distance of 95 ft., which makes it suitable for outdoor applications. False triggers caused by outdoor environment may be eliminated by customizing LiDAR system's perimeter.	[4]
Singapore	Lab Test Indoor university laboratory with office layout. Inference system is compared to existing occupancy solutions. Latency and accuracy are monitored.	Learning-based occupancy inference system shows promising results. Inference latency of 100ms. 90% predicted occupancy count accuracy under static and dynamic patterns.	[5]
The Netherlands	Lab Test Models of office space with occupancy-controlled lighting. Baseline comparison to manual controlled lighting. Examined energy savings potential.	Minimal variance in energy savings potential due to occupancy pattern fluctuations. Occupancy control at desk level yielded energy savings potential 25-30% greater than manual control.	[6]
Davis, California, USA	Field Test Baseline of 14 existing LED fixtures with dimming capabilities.	Preliminary data show that compared to streetlights that lack controls, the networked sensor system reduces energy use between 27% -43%.	[7]

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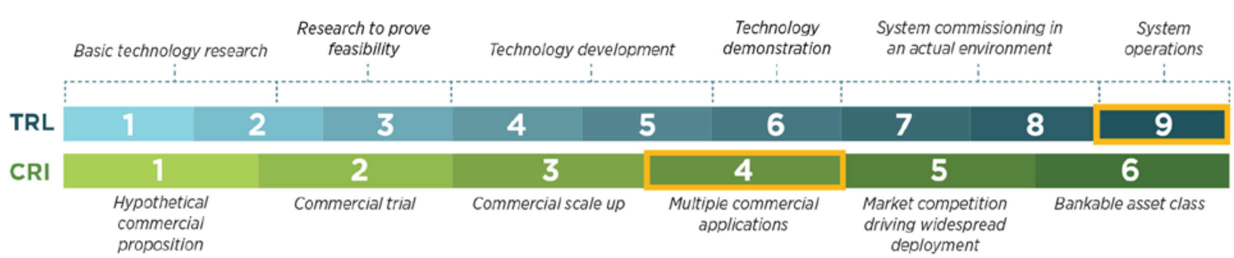
Technology Sector Lighting Product Category Automated Demand Response (ADR) Last Updated 11/21/2018	 *Figure 1: Common lighting controllers and VEN devices used or required for ADR.*

Product Category Overview

Automated demand response (ADR) is a building control strategy to reduce a building's peak demand during periods of high electricity use or reduced electricity availability. ADR requires participation in a utility ADR program, which is designed to encourage modified electricity use during these types of critical events. Program participation is voluntary, and building owners who elect to participate often receive financial incentives for their participation. ADR events are scheduled by utility with advance notice. The event defines a load reduction or load-shed requirements based on existing, baseline loads of the facility. ADR participants have the option to participate in the load-shed event or opt out at any time to maintain operations and comfort within the facility. Note buildings that opt out often face increased electricity rates during the event and/or program penalties.

Today, the most prevalent ADR communication protocol is OpenADR 2.0, which is used by multiple utilities to implement ADR programs. For a facility to participate in ADR, it must have a Virtual End Node (VEN) device (as defined by the OpenADR 2.0 standard) to receive the load-shed signal from the utility's ADR server or virtual top node (VTN). The facility must also have a suitable building or load control system connected to the VEN. The VEN must be installed and configured for the specific utility program with which it will be used to enable complete functionality. In California, utilities most often use a VTN called a Demand Response Automaton Server (DRAS). ADR participants connect directly to the DRAS or to a third party or cloud service that uses a VTN. Third party programs serve as aggregators of DR loads, enabling participation for smaller buildings/loads which may not otherwise qualify. When participating in third party programs, individual buildings do not require a VEN, only an internet connection to enable communication with the aggregator.

Characterization at a Glance



Energy Benefits

ADR is focused on short-term demand reduction; energy is saved during ADR events. During load reduction events, building or load control systems save energy by dimming or extinguishing lighting. Facilities that participate in the ADR program and reduce their load in response to these events typically receive reduced energy pricing or alternate incentives such as rebates.

Non-Energy Benefits

ADR contributes to overall grid stability. In addition, depending on the utility, facilities can receive a variety of technology incentives for participating in ADR programs, such as assistance for acquiring equipment and reduced pricing outside of events.

Product Category Differentiation

The ADR control strategy enacts a short-term load reduction and requires enrollment in a utility program to receive benefits. It differs from other lighting control strategies in that ADR is initiated only in response to a utility request and is intended to produce a short-term reduction in peak demand, as opposed to long-term energy savings over time. This control strategy can be paired with other strategies such as scheduling, dimming, occupancy sensing, and daylight harvesting. However, ADR is enacted only in direct response to the utility needs. Systems with no ADR functionality, or those with functionality but not subscribed to local demand events, are not capable of initiating ADR and are not eligible for associated incentives from the local utility.

Installation Pathway and Dependencies

ADR technology can be installed in the following project types: new construction, equipment replacement, and retrofits. ADR technology is most commonly installed in new construction and major renovations of a lighting control systems. Typically, an ADR project involves adding lighting control components to each fixture or lighting zone and installing an ADR control unit. Depending on the existing building or lighting control equipment installed at a facility, ADR functionality may be enabled with only a software update. All ADR systems using the OpenADR2.0 protocol require internet connectivity to retrieve event information from utility VTN.

List of Products

Table 1: Summary of manufacturers and products for the product category.

Manufacturer	Model	Type	Differentiating Feature
Enlighted	EM	Lighting Control System (VEN)	Lighting control system with native ADR functionality.
Acuity Brands	nADR	Demand Response Client Interface (VEN)	Additional module to allow ADR functionality to Acuity lighting control systems.
Universal Devices	ISY-994	Demand Response Client Interface (VEN)	Third party device to allow ADR functionality to light control system without first party devices.
Eaton	EISSBox	Demand Response Client Interface (VEN)	Additional module to allow ADR functionality to Eaton control systems.

Quantification of Performance

Existing literature estimates statewide demand savings using ADR-enabled lighting systems at several hundred megawatts. However the available data varies and most estimates for lighting systems do not include all possible applications, buildings, or sectors. A literature search was conducted and a sample of published study results are summarized in Table 2.

Table 2: Summary of results from literature review

Location	Application	Results	Reference
Long Beach, California, USA	Field Test: Office Building Corridors and Stairwells controlled by occupancy sensors Wattage/fixture and wattage/square feet were measured during evaluation.	An average demand reduction of 17% was achieved for the lighting system controlled during the DR test with control level at 30%.	[1]
Berkeley, California, USA	Lab Evaluation LBNL facility Data for current OpenADR 1.0 deployments serviced by California IOUs.	The total enabled load shed enabled within service territories of the California IOUs using OpenADR 1.0 is approximately 250 megawatts. Within the California IOU service territories, the average first cost for system enablement using OpenADR 1.0 ranges from $170/kW to $300/kW.	[2]
California, USA	Field Test Small commercial buildings less than 10,000 sf in size. General lighting systems equipped with ADR systems were evaluated for functionality and cost.	Estimated statewide demand savings based on program participation levels between 1% and 50% ranged from 1.44 to 361 megawatts.	[4]

References

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[2] G. Ghatikar, D. Riess and M. A. Piette, "Analysis of Open Automated Demand Response Deployments in California and Guidelines to Transition to Industry Standards," Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, CA, 2014.

[3] D.E.S. Southern California Edison, "DR Opportunities in Residential Lighting and Plug Load - Phase 1," Southern California Edison, 2011.

[4] California Lighting Technology Center, "Automated Demand Response for Lighting Systems in Small Commercial Buildings," 2017.

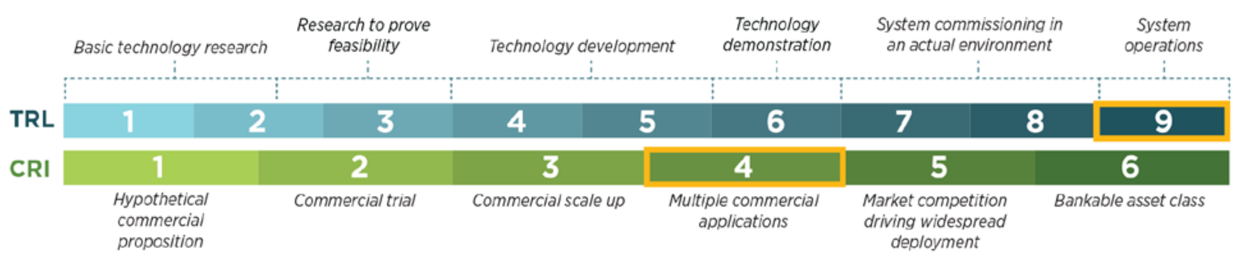
Technology Sector Lighting Product Category Circadian/Color Tuning Lights Last Updated 12/17/2018	 *Figure 1: Hospital Room with circadian overhead lighting that can adjust color characteristics throughout the day.*

Product Category Overview

Circadian lighting systems vary, or tune, light emitting diodes (LEDs) to achieve a specific biological response from occupants. This control strategy benefits the human circadian rhythm by manipulating the spectral power distribution (SPD) intensity and wavelength, and therefore impacting the amount of circadian stimulus provided by the lighting system. Studies suggest that by shifting the spectral power distribution (SPD) of the light output to follow the natural color shift for the day/night cycle, the approach allows exposed individuals to be more alert during the day, achieve better sleep during the night, and potentially be more productive. Typically, warm colors (low correlated color temperature (CCT) of 3500K or less) are used near dawn and dusk, with cooler colors (high CCT of 4000K or more) used during mid-day. This may also be called spectrally optimized lighting or color tuned lighting.

Circadian systems often require dimmable sources with variable CCT connected to a color tuning control system. Alternatively, some methods employ a simple switching system where one color source is used for low CCT during certain periods of the day and another source (in the same or a different luminaire) is used for high CCT at different times.

Characterization at a Glance



Product Category Characterization

Energy Benefits

Circadian lighting is made possible through the use of solid-state light sources (commonly LEDs), and therefore energy and demand savings can be achieved through the intrinsic efficacy improvements offered by the LEDs. Circadian lighting is typically controlled in two dimensions at any given time—SPD and intensity—to produce the most effective and desirable outcome. Consequently, additional savings may result from lowered light level at times. Creating comfortable and satisfactory lighting conditions can accelerate adoption of the technology, which in turn will result in overall greater energy savings.

Non-Energy Benefits

The non-energy benefits of circadian lighting allow occupants a more natural waking/sleep experience, causing more alertness in morning, productivity benefits, and improved sleep cycle. [3]

Product Category Differentiation

Circadian lighting is a control strategy that applies traditional scheduling to multiple channels of LEDs at varying levels of light output (i.e. dimming) to achieve a seamless transition of SPD over time. While some lighting control systems can manipulate multiple-channel LED fixtures, not all control systems have this capability. Typically, circadian lighting systems need to be calibrated after installation to appropriately define the melanopic level transition, or circadian stimulus, over time.

Other control strategies are based on varying one dimension only: intensity. Daylight harvesting, for example, has the ability to dim lighting fixtures in response to sufficient daylight. This is similar to circadian lighting systems in that it varies the intensity of the light system, however due to varying weather conditions and electric lighting from sources not connected to the daylight harvesting system, it may induce a biological response that varies dramatically depending on conditions. Circadian lighting, on the other hand, seeks to control both SPD and intensity independent of weather or other conditions.

Installation Pathway and Dependencies

The installation pathways for circadian lighting products are commonly new construction and major renovations. Retrofit and plug-in (i.e. screw-based bulbs in table or floor lamps) options are also available as an equipment replacement option and usually found in the residential sector, however the biological impacts from these types of systems may be low due to the influence of environment and other lighting systems previously described.

List of Products

Table 1: Summary of manufacturers and products for the product category.

Manufacturer	Model	Type	Differentiating Feature
Philips	SceneSwitch and Hue Color Tuning products	Luminaires with multiple CCT levels combined with lighting color control system.	Lamps with three CCT levels that can be adjusted manually. Hue products can be adjusted automatically using the Hue bridge and software.
Acuity Brands	CromaControl	Luminaires with multiple CCT levels combined with lighting color control system.	Digital Multiplex (DMX) controllable Change hue to anywhere on chromaticity diagram.
Vantage Lighting Controls	*Vantage Dimming Module*	Lighting Control System for color tunable luminaires.	Allows separate control over multiple color tuning channels

Manufacturer	Model	Type	Differentiating Feature
Finelite	*FineTune Control System*	Luminaires with multiple CCT levels combined with lighting color control system.	DMX Controllable 2700K-6500K CCT with up to 90+ Color Rendering Index (CRI)
H.E. Williams	*Dynamic Lighting*	Luminaires with multiple CCT levels combined with lighting color control system.	Built in fixture CCT color tuning switch

Quantification of Performance

A literature search was conducted and a sample of published study results are summarized in Table 2.

Table 2: Summary of results from literature review

Location	Application	Results	Reference
Seattle, Washington, USA	Field test, medical building Corridors and dining/activity space Baseline was non-tunable downlight system. Spectral distribution and illuminance measurements were gathered. Calculated the circadian stimulus values from measured CCT. Acuity nLight System tested	Estimated annual energy savings of 41% relative to a non-tunable downlight system with same number of luminaires. Relative to non-tunable system designed to only meet visual task illuminance criteria, which uses half quantity of luminaires, tunable system increased estimated annual energy use by 19%.	[1]
Washington, D.C., USA	Field Test, Regional Office Building Participants wore Daysimeters, a device that monitors circadian light, usually mounted at eye level or worn as a pendant. The Daysimeters were worn while awake and during sleep, and participants also filled out a series of self-reports probing their sleep quality, depression, and mood scores. Circadian stimulus for each phase was recorded for all participants.	Pittsburgh Sleep Quality Index (PSQI) scores for control group was higher suggestive of sleep disturbances. Self-reports of stress and depression levels were also higher among control group.	[2]

References

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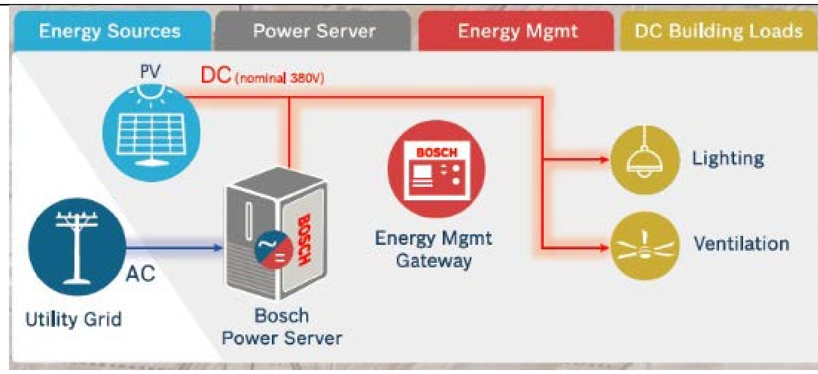
[2] Lighting Research Center, "Measuring Personal Light Exposure, Mood, and Sleep Quality," Elsevier, Washington D.C., 2016.

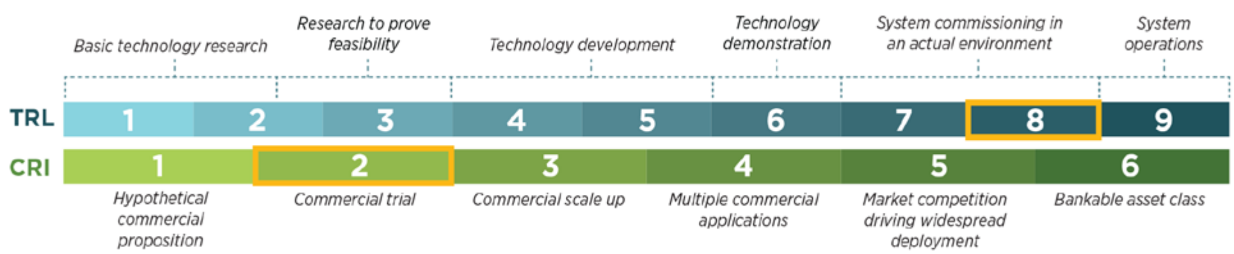
[3] The IES Light and human Health Committee, "IES TM-18-18: Light and Human Health: An Overview of the Impact of Optical Radiation on Visual, Circadian, Neuroendocrine, and Neurobehavioral Responses," Illuminating Engineering Society of North America, North America, 2018.

Technology Sector Lighting Product Category High-Voltage Direct Current Lighting Last Updated 12/20/2018	 *Figure 1: Example of a DC microgrid system with HVDC lighting. Credit: Bosch* [1]

Product Category Overview

High-voltage direct current (HVDC) lighting uses a high-voltage distribution circuit (such as 380V DC) as opposed to 120V or 277V alternating current (AC) circuit. The lighting system pairs with LED luminaires, each with a dedicated HVDC LED driver. This system reduces AC-to-DC conversion losses at each luminaire level, i.e. at the LED driver. The HVDC LED drivers are intrinsically more efficient and last longer compared to AC LED drivers because they do not need the rectification stage circuitry for AC-to-DC conversion, and hence have less internal heat generation. The efficiency of the product prevails in a microgrid scenario where the supply power comes directly from renewable generation or energy storage, which also operates in the HVDC range. This eliminates voltage conversion losses and line losses due to wire resistance, thereby increasing energy utilization of on-site energy resources.

Characterization at a Glance



Product Category Characterization

Energy Benefits

The primary energy savings unique to HVDC lighting are a result of an all-DC distribution circuit, avoiding losses from AC-to-DC conversions at the LED drivers as well as DC-to-AC conversions at the inverter in microgrid operations. Compared to low-voltage DC lighting, including Power-over-Ethernet lighting, energy savings are generated by eliminating line losses due to wire resistance. Major energy and demand savings, compared to conventional lighting systems with traditional light sources, are achieved through efficient LED light sources as well as a combination of lighting control strategies, including occupancy sensing, daylight harvesting, high-end trim, etc.

Non-Energy Benefits

Since installation of HVDC lighting is expected to be in conjunction with other DC systems as part of the microgrid platform, resilience is the primary non-energy benefit. General illumination service is not directly tied to the electrical grid and can be flexibly powered by the grid power or onsite generation. All the luminaires can serve as emergency lighting for a prolonged period of time without a dedicated emergency lighting circuitry like their AC counterpart. The upfront investment on a microgrid system will be lower as many AC-to-DC and DC-to-AC components and the corresponding costs are eliminated.

Product Category Differentiation

HVDC lighting differentiates from conventional AC LED lighting because it eliminates AC-to-DC conversions at the LED driver level and therefore is more efficient. It also differs from low-voltage DC lighting in that it exhibits much lower, typically negligible, line losses caused by wire resistance; however, it is subject to more stringent safety requirements due to its high voltage.

Installation Pathway and Dependencies

The installation pathways are new construction or major renovation. While it might not be absolutely necessary, it makes most sense if HVDC lighting is planned and installed as part of a DC microgrid system. Therefore, this can be an installation dependency.

List of Products

Table 1: Summary of manufacturers and products for the product category.

Manufacturer	Model	Type	Differentiating Feature
Bosch	Building Grid Technologies	LED luminaires with HVDC driver as part of the DC microgrid system, whose source power is managed by Bosch Power Server.	Source power can be switched between AC electrical grid and DC onsite generation at the Bosch Power Server.

Quantification of Performance

A literature search was conducted and a sample of published study results are summarized in Table 2.

Table 2: Summary of results from literature review

Location	Application	Results	Reference
USA	Simulated energy usage of HVDC lighting (HVDC LED drivers paired with LED luminaires), as part of a larger microgrid building simulation exercise. Four building types are simulated-retail, supermarket, refrigerated warehouse and non-refrigerated warehouse-based on an actual HVDC microgrid system (from Bosch). The lighting is set up to be high bay lighting for all building types. The baseline is the energy usage of AC lighting (conventional AC LED drivers paired with LED luminaires) as part of an AC microgrid configuration.	Lighting electricity consumption, in terms of energy usage intensity (EUI) reduced by 0.1-0.3 kWh/ft^2/year.	[2]

References

[1] S. Ravula, "Bosch DC Microgrid Project: EPC 14-053," in *Joint Electric Program Investment Charge Program Innovation Symposium*, Folsom, CA, 2015.

[2] D. Fregosi, S. Ravula, D. Brhlik, S. Frank, E. Bonnema, J. Scheib and E. Wilson, "A Comparative Study of DC and AC Microgrids in Commercial Buildings Across Different Climates and Operating Profiles," in *IEEE First International Conference on DC Microgrids*, Atlanta, GA, 2015.

Technology Sector
Lighting

Product Category
LED Horticulture Lighting

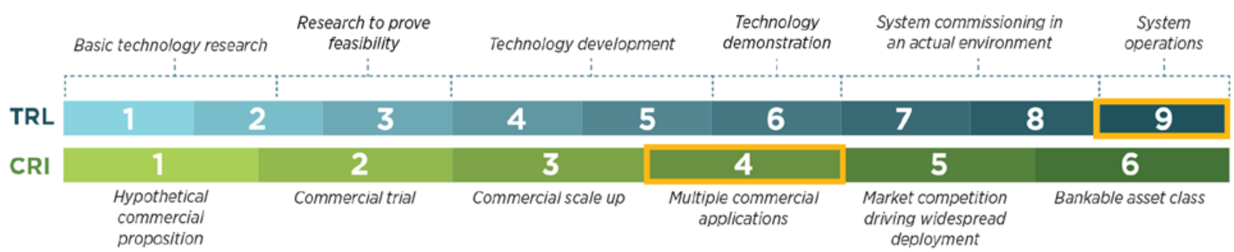
Last Updated
12/16/2018

Figure 1: Example of a LED horticulture light fixture. Credit: Lumigrow [1]

Product Category Overview

LED lighting for horticultural applications are specialty LED products its spectral power distribution (SPD) tuned to provide the optimal lighting condition for year-long vegetation growth and cultivation. Horticulture lighting is used as supplemental lighting in greenhouses and as the main light source in indoor farming facilities to optimize the amount of photosynthetically active radiation (PAR) that reaches the plant surface, also known as the photosynthetic photo flux density (PPFD). Compared to the most traditional grow lights, the spectrally tunable and energy-efficient nature of LED light sources allows this product category to not only provide high energy savings but also increase the quality and quantity of the crops.

Characterization at a Glance



Product Category Characterization

Energy Benefits

Energy savings are primarily achieved through direct power reduction due to LED's superior efficacy over traditional sources such as high pressure sodium (HPS) and metal halide or fluorescent lights. Secondary savings may result from shortened daily operation, as LEDs' SPD may be tuned for higher PPFD to achieve the crops' daily photosynthesis need in shorter time. Lower heat production from the LED grow lights also saves in HVAC and (de)humidification energy consumption.

Non-Energy Benefits

The chief non-energy benefit is higher crop yields as LED's spectral tunability concentrates light in the PAR range to result in higher PPFD, thereby shortening the growth cycle. Spectrally tuned LED grow lights may also improve the crop's quality in terms of consistency, nutrient level, coloration, plant strength, reduction in burned leaves, etc. All these aspects have a direct positive impact on the business' revenue and bottom line. Additionally, the business can lower its carbon footprint through reduced material use (lamps and fixtures) while achieving the same or better results compared to traditional grow lights.

Product Category Differentiation

LED horticulture lighting differentiates from other horticultural light sources due to its significantly higher efficacy and tunable spectrual distriubtion. LED horticulture lighting also differs from other lighting solutions in that its primary use is to satisfy the photosynthesis needs of plants and crops rather than providing illumination service to humans. While general lighting typically does not have a direct impact on the profitability of a business (at least such a link is yet to be fully proven and quantified), the chief purpose of horticulture lighting is to influence a business' bottom line by increasing crop production and improving quality.

Installation Pathway and Dependencies

The installation pathways are new construction, major renovation, or retrofit. There is no installation or support dependencies for this product category.

List of Products

Table 1: Summary of manufacturers and products for the product category.

Manufacturer	Model	Type	Differentiating Feature
Heliospectra	ELIXIA – adjustable grow light EOS – static grow light DYNA – research grow light HelioCORE – control software	LED fixtures	Pair with (optional) in-house control software.
Lumigrow	TopLight – grow light fixture smartPAR – control software	LED fixtures paired with (optional) in-house control software	Wireless control and management system.
Illumitex	HarvestEdge – grow light fixture NeoPAR – grow light fixture Eclipse – grow light fixture PowerHarvest – grow light fixture Power Controls – wireless dimming Node	LED fixtures with optional dimming control node	Wireless dimming node is capable of power monitoring, remote control and scheduling.
Osram	ZELION – grow light fixtures	LED fixtures and LED retrofit PAR 38 lamps	N/A
Fluence Bioengineering (Osram)	SPYDR series – grow light fixtures VYPR series – grow light fixtures RAZR series – grow light fixtures RAY series – grow light fixtures	LED fixtures	N/A
BIOS Lighting	Icarus series – grow light fixtures	LED fixtures	N/A
Philips Lighting (Signify)	GreenPower series – grow light fixture	LED fixtures and lamps	N/A

Manufacturer	Model	Type	Differentiating Feature
Forever Green Indoors	100 W LED Grow Light 185 W FGI Lightbar 500 W FGI Lightpanel 500 Watt FGI Lightbrick 700 Watt FGI Lightpanel	LED fixtures	N/A

Quantification of Performance

A literature search was conducted and a sample of published study results are summarized in Table 2.

Table 2: Summary of results from literature review

Location	Application	Results	Reference
Sacramento, California, USA	Measured energy usage from two flowering rooms with similar canopy area (around 1,200 ft^2). The room equipped with LED grow lights was installed with 49 LED grow light fixtures, each rated 595 W. The baseline is 54 HPS (high pressure sodium) grow light fixtures, each rated 1,000 W, installed in one of the two rooms.	36% (14,166 kWh) lighting energy savings 41% (22.0 kW) lighting demand savings 30% (17,719 kWh) overall (lighting, HVAC, dehumidification, plug loads) energy savings 34% (26.5 kW) overall (lighting, HVAC, dehumidification, plug loads) demand savings	[2]
N/A	Modeled savings of a theoretical “all LED” scenario for horticultural applications in a total area of 46M ft^2, including greenhouse, indoor growing and vertical farming. The baseline is the estimated current mix of LED, HPS, metal halide and fluorescent lighting.	40% total annual savings, which are aggregated savings of 10% savings in vertical farming, 29% savings in greenhouse, and 41% savings in indoor growing (non-staked indoor farming) weighted by the grow areas and annual operating hours of the three respective farming applications	[3]
Virginia, USA	Estimated energy savings from 750 LED grow lights in a greenhouse. The baseline is HPS lighting.	50% increase in energy efficiency 25% increase in crop production	[4]
Case Study	Savings from five, 500 W LED grow lights over a 50 ft^2 table in a room canopy that grows Narnia cannabis strain. The baseline is a HPS lighting system consisting three, 1200 W fixtures.	35% energy savings in terms of grams per watt (1.94 g/W for LED lights vs. 1.26 g/W for HPS lights) 10% increase in potency 3% increase in dry weight yield	[5]
Case Study	Savings from LED grow lights with an LPD (lighting power density) of 43 W/ft^2 in a 576 ft^2 room canopy that grows Green Crack cannabis strain. The baseline is a HPS lighting system with an LPD of 69 W/ft^2.	52% energy savings in terms of grams per watt (1.40 g/W for LED lights vs. 0.68 g/W for HPS lights) 23% yield increase	[6]

Location	Application	Results	Reference
Latvia, Mezvidi	Savings from 30 LED topligthing in a 72 m^2 area within a greenhouse that grows tomatoes. The baseline is 400W HID toplighting lamps.	30% energy savings Fruits were 10% bigger than those under HID Completely eliminated a series problem of leaf-burn	[7]

References

[1] Lumigrow, "TopLight Spec Sheet," Lumigrow, Inc, Emeryville, CA, 2018.

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[3] K. Stober, K. Lee, M. Yamada and M. Pattison, "Energy Savings Potential of SSL in Horticultural Applications," Energy Efficiency and Renewable Energy, U.S. Department of Energy, Washington, DC, 2017.

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Technology Sector
Lighting

Product Category
Light Fidelity (Li-Fi) Wireless Communication Technology

Last Updated
12/19/2018

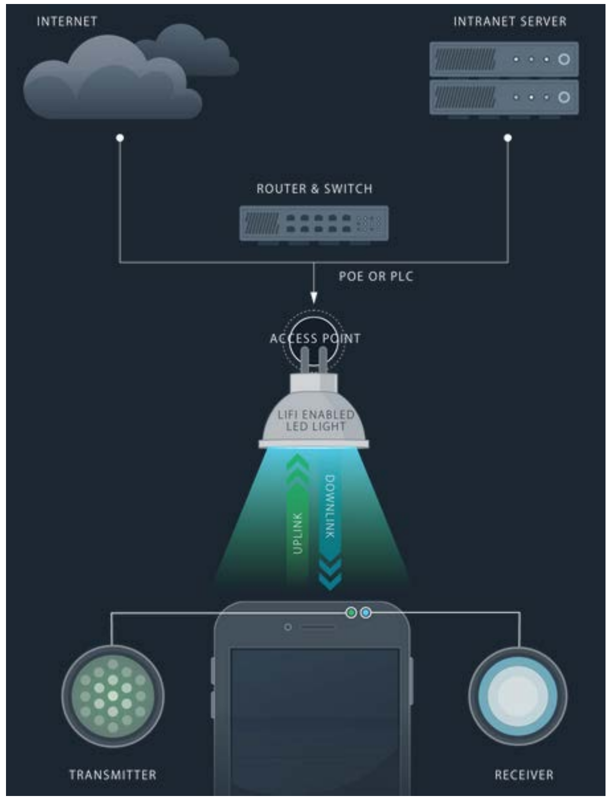
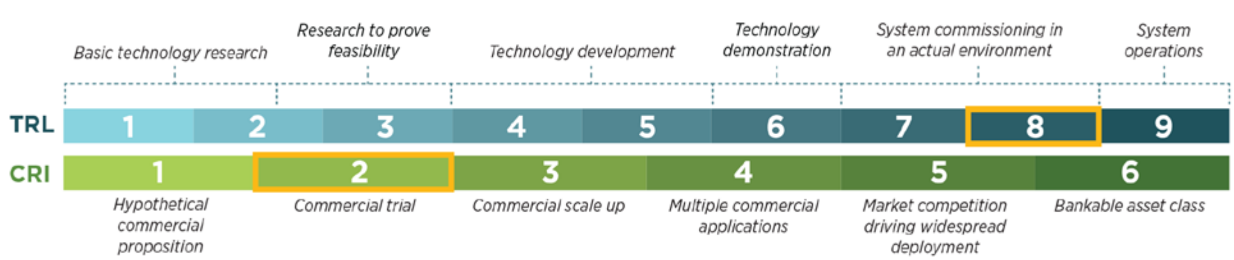


Figure 1: Illustration of Li-Fi system architecture. Credit: pureLiFi [1]

Product Category Overview

Light Fidelity, or Li-Fi, is a visible light communication system that modulates and transmits data at a high speed over the visible light spectrum, ultraviolet, and infrared radiation. Li-Fi allows the repurposing of light for communications, therefore saving energy by simultaneously providing general illumination service and network connectivity through energy-efficient LED lighting. The breadth of its potential applications is not yet fully explored, but current commercial applications include secure content delivery (compared to Wi-Fi and other wireless media), retail customer engagement, indoor positioning (determining a person's location within the space in order to enable and provide personalized services, such as user-preferred light setting), and asset tracking. Energy savings are achieved mainly through energy-efficient LED light sources. Other related energy efficiency applications and impacts require further investigation.

Characterization at a Glance



Product Category Characterization

Energy Benefits

Energy and demand savings are achieved primarily through energy-efficient LED light sources and, similar to typical networked lighting controls (NLCs), a combination of lighting control strategies suitable for the space, such as occupancy sensing, daylight harvesting, scheduling, proper zoning, etc.

Non-Energy Benefits

Compared to Wi-Fi or other wireless communication, Li-Fi provides easier access control to the enterprise network in office, healthcare, and other environments to better prevent unauthorized access to sensitive data because light does not penetrate through walls and doors. Li-Fi also provides Internet connectivity in critical applications where other wireless media are prohibited or infeasible, such as in healthcare facilities where machineries are susceptible to electromagnetic interference from radio frequency signals like Wi-Fi. In retails or public spaces, Li-Fi can increase the level of customer engagement, and therefore foot traffic and revenue, by way of real-time location-based content delivery, product locating, and wayfinding.

Product Category Differentiation

Li-Fi differentiates from typical NLCs in that it is often an add-on layer to NLCs. While typical NLCs provides connectivity for components within the system, Li-Fi provides Internet access to devices extraneous to the NLC systems, such as mobile devices and personal computers.

Installation Pathway and Dependencies

The installation pathways are new construction or major renovation where Li-Fi enabled LED luminaires are installed. Since Li-Fi uses the enterprise network infrastructure for the backhaul communication to provide Internet access, a support dependency is conformance to the organization's IT policy.

List of Products

Table 1: Summary of manufacturers and products for the product category.

Manufacturer	**Model**	**Type**	**Differentiating Feature**
LinmoreLED	LiFi by Linmore	Li-Fi enabled LED light bars and light fixtures	The only manufacture that offers Li-Fi in linear luminaires.
Oledcomm	MyLiFi desk lamps LiFiNET LED panels and street lights GEOLiFi LED tubes and street lights LiFiCare lamps for hospitals	Li-Fi access point embedded in luminaires and desk lamps	Offers both desk lamps and ceiling-mount Li-Fi enabled luminaires.
pureLiFi	LiFi-XC	LiFi-XC Access Point for embedded in LED fixtures and LiFi-XC Station as the plug-in transceiver	Supports Li-Fi enablement for a wide range of LED luminaires from other manufacturers.
Philips Lighting (Signify)	PowerBalance Li-Fi enabled recessed luminaires LuxSpace Li-Fi enabled downlights	Li-Fi enabled Philips luminaires across multiple product lines	Offers luminaire options with different Li-Fi coverages suitable for different applications.
Vlncomm	LumiNex LED panels LumiLamp desk lamps LumiStick transceiver	Li-Fi access point embedded in luminaires and desk lamps	Offers both desk lamps and ceiling-mount Li-Fi enabled luminaires.

Quantification of Performance

A literature search was conducted and a sample of published study results are summarized in Table 2.

Literature that characterizes energy savings specifically for Li-Fi enabled lighting systems is not available. Since Li-Fi by itself does not directly result in energy savings, energy performance of Li-Fi enabled lighting systems is expected to be very similar to typical NLCs. Therefore, documents listed below are savings from typical NLCs, which are used as proxies for savings from Li-Fi enabled lighting systems.

Table 2: Summary of results from literature review

Location	**Application**	**Results**	**Reference**
USA	Projected annual energy savings potentials from LEDs and connected controls for different general LED luminaire categories in the U.S. market.	4428 tBtu for all LED application types including 280.8 tBtu for LED downlights, 1399 tBtu for linear fixtures, 695 tBtu for low/high bay fixtures, 255 tBtu for street/roadway lighting, 131.4 tBtu for garage lighting, and 1,666.8 tBtu for other luminaires.	[2]
San Francisco, California, USA	Measured energy usage of a wireless NLC system with LED fixtures in a 6,765 ft^2 space within a 16-story office building comprising 5 open office areas, 3 private offices, a reception room, 2 storage rooms and corridors. The baseline is a lighting system with 84 recessed 2'x4' 3-lamp fluorescent parabolic luminaires.	69.3% annual savings (a reduction from 2.3 kWh/ft^2/year to 0.7 kWh/ft^2/year), including 32.3% savings from controls.	[3]
Sacramento, California, USA	Measured energy savings of a wireless NLC system with LED fixtures in 3 separated spaces with a combined area of 24,989 ft^2 within an 8-story office building. The baseline is a lighting system with 2'x4' and 2'x2' recessed fluorescent luminaires.	32.8 % annual savings (a reduction from 2.18 kWh/ft^2/year to 1.46 kWh/ft^2/year).	[3]

References

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[2] J. Penning, S. Schober, K. Stober and M. Yamada, "Adoption of Light-Emitting Diodes in Common Lighting Applications," Solid-State Lighting Program, Building Technologies Office, Energy Efficiency and Renewable Energy, U.S. Department of Energy, Washington, D.C., 2017.

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Technology Sector Lighting Product Category Linear LEDs Last Updated 01/08/2019	 *Figure 1: Linear LED lamp installed in integrating sphere for electrical and photometric testing. Photo Credit: CLTC*

Product Category Overview

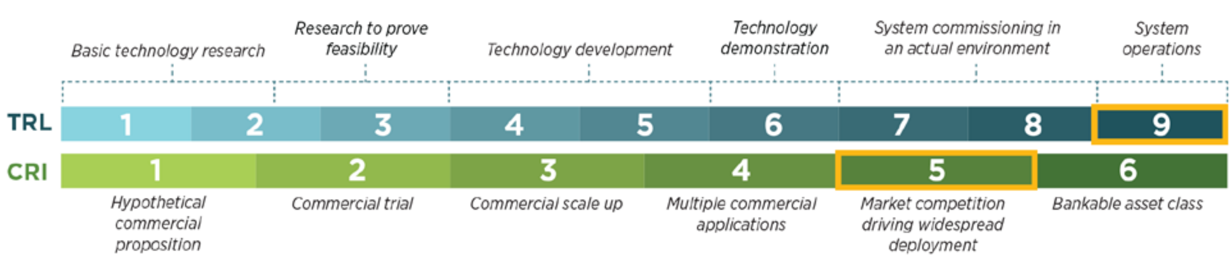
Linear LED lamps are designed to replace linear fluorescent lamps. They are available in standard T5, T8, and T12 sizes. There are three primary types of linear LED lamps, as defined by Underwriters Laboratories (UL):

- UL Type A: Linear LED lamp with internal driver that is designed to operate on a linear fluorescent lamp ballast.
- UL Type B: Linear LED lamp with internal driver that must be connected directly to line voltage for power.
- UL Type C: Linear LED lamp with external driver that is designed to replace both the linear fluorescent lamp and fluorescent lamp ballast.

Some linear LED lamp products can operate in multiple scenarios, such as (1) with a fluorescent ballast and (2) when the ballast is replaced with a compatible LED driver. These hybrid products, also called dual-mode products, are currently available in Types AB and AC.

Luminaire modifications such as changes to the wiring harness and lamp holders (e.g. socket, tombstone) are often required to install the linear LED replacement lamp products in existing linear fluorescent fixtures.

Characterization at a Glance



Product Category Characterization

Energy Benefits

Energy savings are achieved by use of LEDs, which are more efficacious and efficient as compared to fluorescent technology. Savings vary widely based on the product installed as compared to existing baselines. Additional energy savings are possible for dimmable products and when paired with lighting controls to achieve institutional tuning, scheduling, occupancy-based control, daylighting harvesting, and automated demand response.

Non-Energy Benefits

Linear LED lamps are typically offered with higher color rendering index (CRI) than traditional fluorescent lamps. The improved color accuracy and color quality characteristics of these products make them appropriate for use in retail, medical, and food preparation applications where color appearance is critical.

In California, investor-owned utilities offer incentives, or rebates, for these product types so long as they meet the criteria established through their Customized Retrofit Program.

Product Category Differentiation

Compared to traditional linear fluorescent lamps, the linear LED lamps are typically more efficacious and safer in terms of hazardous materials. Linear LED lamps may also exhibit a longer lifetime expectancy and reduced light degradation or loss in lumen output over time.

Installation Pathway and Dependencies

Linear LED lamps are most commonly installed as major renovations, retrofits, and equipment replacement projects. The installation complexity depends on the existing building infrastructure, fixture type, and lighting controls.

It is critical to select the appropriate linear LED lamp electrical architecture (i.e. UL Type A, UL Type B, UL Type C, or hybrids) for the building infrastructure. Additionally, it is important to review the interoperability and compatibility lists that manufacturers provide when pairing these products with control devices.

Small demonstrations and testing with existing equipment are often conducted prior to a large retrofit or deployment.

List of Products

Table 1: Summary of manufacturers and products for the product category.

Manufacturer	Model	Type	Differentiating Feature
Philips	various	Linear LEDs	T8 Universal works with all ballast types.
Eiko	various	Linear LEDs	Up to 80% energy savings vs. fluorescent.
Revolution Lighting	various	Linear LEDs	Industry leading warranties. Rated life up to 70,000 hours.
USHIO	various	Linear LEDs	Available coated glass tube, no yellowing.
Sylvania	various	Linear LEDs	Ballast-free T8 lamps. Minimized lumen loss due to light distribution pattern.
Hyperikon	various	Linear LEDs	Multiple color options and pack sizes. Contains no glass, mercury, or lead.
Keystone	various	Linear LEDs	Ballast compatible or direct line voltage.

Quantification of Performance

A literature search was conducted and a sample of published study results are summarized in Table 2.

Table 2: Summary of results from literature review

Location	Application	Results	Reference
Davis, California, USA	Lab Test Compared various Linear LED lamps available on the market to fluorescent baseline. Measured performance of lamps in three fixture types; troffers, wraps, and pendants. Characteristics recorded include light output, system efficacy, and power draw.	"A statewide conversion to linear LED lamps could deliver approximately a 43 percent reduction in lighting energy use and result in as much as 3.2 TWh of savings annually." System efficacy across all tested samples was better than fluorescent lamps. Efficacy varied from 99.7-135.1 lm/W with an average of 118.4 lm/W. While testing with type C LED products, results showed performance within the three types of fixtures, in terms of light output, was 10% less to 10% more compared to fluorescent. Type A and B performed worse in terms of light output compared to Type C and fluorescent baseline.	[1]
San Francisco, California, USA	Field Test Open Office Evaluated performance of Type C LED luminaires compared to existing fluorescent lighting. Measured energy use of the system with and without various control strategies.	Project savings were calculated to be 25,487 kWh/yr compared to fluorescent baseline. 5% energy savings was achieved after retrofitting existing fixtures with LED light sources and drivers. Additional energy savings up to 61% was achieved for the entire system after applying various control strategies using a lighting control system.	[2]
Davis, California, USA	Field Test Small/Mid-sized retail business Baseline was installed fluorescent lighting. Energy use of each phase of the lighting demonstration was recorded.	The LED retrofit system without the lighting control system reduced energy use by 6.9% compared to fluorescent baseline. The lighting control system paired with LED retrofits reduced the annual energy use by an additional 25.2%, from 22,035 kWh to 15,356 kWh	[3]

Location	Application	Results	Reference
Sacramento, California, USA	Lab Test Tubular LED luminaires were compared to fluorescent luminaires. Metrics gathered include lumen output, power, efficacy, and light distribution	Compared to baseline fluorescent luminaires efficacy was high 80 lm/W compared to 53 lm/W. Total system power was reduced from 83.2 Watts with fluorescents to 55.3 Watts.	[4]
California, USA	Lab Test Three different retrofit product families were tested and compared to fluorescent baseline. Compared metrics include light output quality, and power quality	Ballast compatible LED luminaires averaged 104 lm/W with average power draw of 21.5 Watts. Internal driver LEDs averaged 91 lm/W and 20.8 Watts. External driver LEDs averaged 103 lm/W and 21.8 Watts. The fluorescent lamps averaged efficacy of 79 lm/W and 25.5 Watts of power draw.	[5]

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Product Characterization Report
California Energy Product Evaluation (Cal-EPE) Hub

Technology Sector
Lighting

Product Category
Low-Voltage Direct Current (DC) Lighting

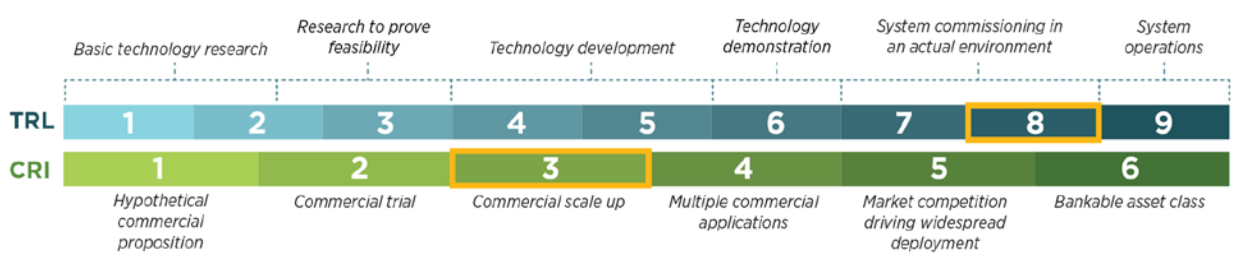
Last Updated
12/07/2018

Figure 1: Example of a low-voltage DC lighting control system. Credit: Nextek Power Hub Module [1].

Product Category Overview

Low-voltage Direct Current (LVDC) lighting uses a low-voltage (typically 24V or 48V) direct current distribution circuit, as opposed to a traditional 120V or 277V alternating current (AC) circuit. These systems reduce AC-to-DC conversion losses at each luminaire level. LVDC lighting typically comes integrated with control strategies with signals that are either modulated on the DC voltage line or on a separate wireless communication channel. The efficiency of the product prevails in a microgrid scenario where the supply power comes directly from renewable generation or energy storage, which are all native DC systems, thereby eliminating conversion losses. LVDC can be integrated with other native DC systems, but the benefits of such integrated are so far largely unrealized and unrecognized; holistic DC system design is not yet a common practice, and the systems are marketed and sold separately, which created a barrier to adopting LVDC lighting. Another notable barrier is specifiers' and contractors' unfamiliarity with DC lighting systems to procure and install the technology.

Characterization at a Glance



Product Category Characterization

Energy Benefits

The primary energy and demand savings are achieved through the use of more efficient LED light sources (which are intrinsic LVDC devices) as well as control strategies such as occupancy sensing, daylight harvesting, scheduling, granular zoning/grouping, etc. The secondary energy savings result from higher voltage conversion efficiency, avoiding AC-to-DC conversion losses at each single light point like typical AC lighting systems when energized by grid power. When fully integrated and powered directly by onsite renewable generation and storage, the systems also exhibit superior energy performance compared to AC systems because LVDC systems bypass multiple stages of DC-to-AC and AC-to-DC conversions.

Non-Energy Benefits

The low-voltage nature puts the systems in the Class 2 power circuit category of the National Electrical Code, which is subject to less stringent fire safety requirements than their AC line-voltage counterpart. Specifically, installation and maintenance of a LVDC lighting system need not be performed by a licensed electrician, and the wires do not need to run conduit, saving time, labor and material costs. The systems also demonstrate high expandability to accommodate future space (re)configuration needs because the number and location of luminaires as well as sensors are not constrained by mains wiring. In addition, LVDC lighting systems have lower embedded carbon footprints due to reduced components: the luminaires do not need extra AC-to-DC conversion circuitry or the corresponding electronic components.

Product Category Differentiation

The key difference between LVDC lighting systems and typical line-voltage lighting systems lies in the decoupling of the lighting power circuit and the AC mains circuit. The LVDC lighting circuit facilitates direct integration with onsite renewable generation and storage (which are also DC in nature) and therefore is in the best position for microgrid and nanogrid implementations.

Installation Pathway and Dependencies

The installation pathway is either new construction or retrofit. There are no particular installation or support dependencies.

List of Products

Table 1: Summary of manufacturers and products for the product category.

Manufacturer	Model	Type	Differentiating Feature
Audacy	LVDC Ceiling Grid System	Audacy LVDC power system, wireless sensors and controls, and partner luminaires	Compatible with Armstrong ceilings.
Eaton	DLVP (Distributed Low-Voltage Power) System	Eaton DLVP system hardware and LED luminaires	Uses standard CAT 5/6 Ethernet cable with proprietary connectors. Out-of-the-box code compliant (ASHRAE 90.1 and CA Title 24).
LumaStream	LumaStream System	LumaStream Trinity power supply and LumaStream low-voltage luminaires	Supports LumaStream partner control software and hardware.
LumaNext	LumaNext Open Power Platform	LumaNext power system, Bluetooth Mesh wireless sensors and controls, and LumaNext low-voltage luminaires	Includes battery packs in the product offering.
Nextek	Power Hub Driver (PhD) & Power Server Module	Nextek DC power system, wireless sensors and controls, and Nextek or eMerge Alliance partner luminaires	Partner of the eMerge Alliance ecosystem.
Sigma Luminous	Sigma Smart IoT System	Sigma Smart Controller, EnOcean wireless sensors and switches, and Sigma Luminous low-voltage luminaires	Multi-protocol (BACnet/IP, LonWorks) controller available for BMS/HVAC integration and control.

Quantification of Performance

A literature search was conducted and a sample of published study results are summarized in Table 2.

Table 2: Summary of results from literature review

Location	Application	Results	Reference
Michigan, USA	Estimated energy usage from a general open-space office and kitchen areas within an office building that is retrofitted with a low-voltage DC lighting system with LED luminaires. Baseline is a 34W T8 fluorescent lighting system.	61% energy savings. Lighting energy consumption reduced from 195.85 kWh per month to 76.8 kWh per month.	[2]
Fairfax, Virginia, USA	Projected energy savings from an energy audit performed by a professional energy auditor for a chain restaurant that is retrofitted with a low-voltage DC lighting system with LED luminaires. Baseline is a mix of incandescent and fluorescent lighting.	80% annual energy savings (54,361 kWh reduced to 11,140 kWh). 82% annual maintenance savings ($3091 reduced to $561). 80% overall annual operational savings (energy plus maintenance). 80% GHG reduction (85,070 lb reduced to 17,433 lb).	[3] [4]
St. Petersburg, Florida, USA	Projected energy savings from a detailed energy analysis performed by a professional energy consultant on a 26,948 ft^2 2-story assisted living facility that is retrofitted with a low-voltage DC lighting system with LED luminaires. Baseline is a new AC lighting system (likely with LED luminaires but not mentioned in the literature).	48% annual energy savings (66,443 kWh reduced to 34,514 kWh). $400-800 cooling savings (simulated using eQuest).	[5] [6]
Cleveland, Ohio, USA	Estimated energy savings from a 3,500 ft^2 space within a 333,500 ft^2 data center building that is retrofitted with a low-voltage DC lighting system with LED luminaires. Baseline is the conventional fluorescent lighting system.	Up to 70% energy savings.	[7]

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Technology Sector
Lighting

Product Category
Luminaires with Embedded Sensors and Self-Contained Controls

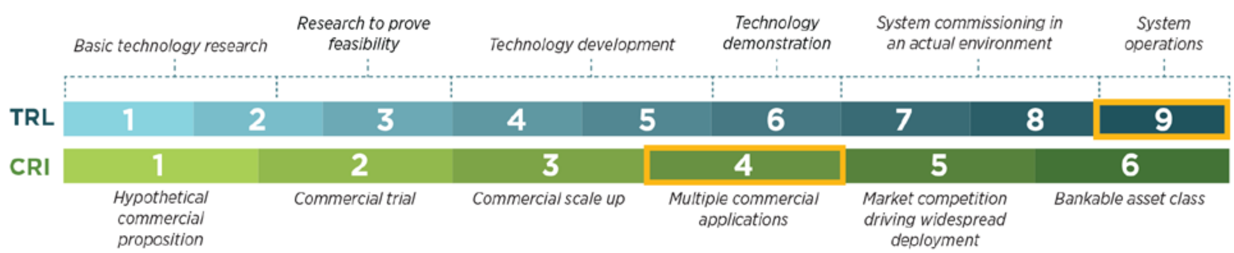
Last Updated
11/29/2018

Figure 1: Picture of luminaire-embedded sensors and controls [1] [2].

Product Category Overview

Luminaire-embedded sensors are an integral part of the luminaire, enabling control strategies including occupancy sensing and daylight harvesting. Each luminaire has native computing and processing power to autonomously make local control decisions. The basic form of this product does not require any connectivity or wiring to external sensors or controllers to provide illumination service and control strategies. These sensors are one of the simplest ways to implement basic lighting controls in LED conversion retrofit projects to capture energy savings associated with lighting controls. Some manufacturers may offer as a default or optional product feature additional connectivity for communication and coordination with nearby luminaires or with a central controller. The luminaire may optionally have a built-in IR near field communication (NFC), Bluetooth receiver, or both for advanced commissioning such as grouping or light level trimming. It may also use a handheld remote controller, smartphone app, or both.

Characterization at a Glance



Product Category Characterization

Energy Benefits

Energy savings for this product category are achieved through both high efficiency LED light source and basic lighting control strategies. Common lighting control strategies include occupancy sensing, daylight harvesting, high-end trim, personal control, scheduling, load shedding, color tuning, and scene control, among which occupancy sensing and daylight harvesting combined often account for more than half of the energy savings potential. The LED light source reduces the energy consumption bottomline compared to more traditional light sources such as fluorsecent lamps and high intensity discharge lamps. The luminaire generates energy savings through occupancy sensing by autonomously turning the light off or fading to a low background light level when no human activity is detected by the occupancy sensor. The luminaire also generates energy savings through daylight harvesting by dimming the light to supplement available daylight at the task plane based on what the embedded photosensor "sees." The operator can adjust (typically lower, a.k.a high-end trim) the maximum light level of most luminaires in this product category during the commissioning process to better meet the space's actual lighting needs, thereby further reducing the energy consumption bottomline and resulting in additional energy savings. In general, the potential energy savings for this product category are about 50-60% [3].

Non-Energy Benefits

Due to the autonomous controls and embedded sensors, this product category provides a way to meet both the lighting power density requirements and controls provisions in the building energy codes without installing more complex networked lighting controls systems. Installation time and cost is low since each luminaire only needs to be dropped into the cell grid (or mounted on the ceiling) and connected to the main wires without other low-voltage wiring for controls. This product category also reduces maintenance effort since the entire assembly can easily be swapped out without touching external wiring or affecting the operation of other luminaires and sensors. Additionally the expertise and effort required for commissioning this product category is low compared to a fully networked lighting control system because commissioning typically involves only pushing buttons on a handheld remote device or using a simple app on the smartphone; IT skillsets are not required. The light level of each luminaire is controlled individually based on what the embedded photosensor "sees," thus preventing the light in part of an area from dimming too low (in contrast with what could happen when the entire zone is controlled by a single sensor). This flexibility will ensure an occupant's lighting needs, and hence productivity, is not jeopardized due to daylight dimming control.

Product Category Differentiation

This product category differentiates from similar lighting product categories (with comparable features and savings potentials) in that its commissioning is simple and its sensors and control logics are embedded in the luminaire package. It provides one of the most economical ways to dress the ceiling with a new luminaire appearance that creates a better illumination environment and has all the essential energy savings controls in place.

Installation Pathway and Dependencies

The most effective installation pathway is retrofit with the products in the form of luminaire retrofit kits. In the case of ceiling recessed troffers, the installation dependency is the existing luminaire size. The retrofit kits need to fit inside the existing luminaire enclosure, and the product has to be selected in accordance with the existing luminaire dimension: 2'-by-2', 2'-by-4' or 1'-by-4'. New construction and major renovation where new luminaires are installed are other possible installation pathways for both grid ceiling and high bay applications. There is no installation dependency in these cases; however, the product category will be competing against other sophisticated networked lighting options which may be more advantageous in generating energy and non-energy benefits.

List of Products

Table 1: Summary of manufacturers and products for the product category.

Manufacturer	Model	Type	Differentiating Feature
Acuity	nLight Air	Luminaire	Can expand to a fully networked lighting control system.
Digital Lumens (Osram)	CLE	Luminaire	Support high bay fixtures for high bay commercial and industrial applications. Support onboard energy, fault and temperature monitoring and data logging. Can expand to a fully networked lighting control system.
Digital Lumens (Osram)	ILE	Luminaire	Support high bay fixtures for high bay commercial and industrial applications. Support onboard energy and fault monitoring and data logging. Adjustable luminaire optics. Can expand to a fully networked lighting control system.
Digital Lumens (Osram)	LLE	Luminaire	Support high bay fixtures for high bay commercial and industrial applications. Can expand to a fully networked lighting control system. Support onboard energy monitoring and data logging.
Eaton	WaveLinx	Luminaire	Support both indoor and outdoor luminaires. Can expand to a fully networked lighting control system, which also support receptacle control.
Eaton	LumaWatt Pro	Luminaire	Support both indoor and outdoor luminaires. Can expand to a fully networked lighting control system, which also support receptacle control.
Leviton	Intellect	Luminaire	Can expand to room-level control system with wireless keypads.
Magnum	OPUS-CLMLD	Luminaire	Support luminaire grouping. Support onboard energy reporting.
Philips Lighting (Signify)	SpaceWise	Luminaire	Works for industrial (high bay) application. Works with a list of compatible wireless switches. Support occupancy sharing/coordination with neighboring luminaires. Support grouping/zoning.

Manufacturer	Model	Type	Differentiating Feature
Philips Lighting (Signify)	SpaceWise DT	Luminaire	Works with a list of compatible wireless switches. Support occupancy sharing/coordination with neighboring luminaires.
Philips Lighting (Signify)	SNS 200	Luminaire or retrofit kit	Works with a list of compatible wireless switches. Support occupancy sharing/coordination with neighboring luminaires.
Philips Lighting (Signify)	SNS 102	Luminaire or retrofit kit	Works with a list of compatible wireless switches.
Xeleum	Xi-Fi	Luminaire	Support high bay fixtures for high bay commercial and industrial applications. Can expand to a fully networked lighting control system.

Quantification of Performance

A literature search was conducted and a sample of published study results are summarized in Table *2*.

Table 2: Summary of results from literature review

Location	Application	Results	Reference
Chicago, Illinois, USA	Field measurement of a 19,750 ft^2 office space comprising a large open office area, 6 private offices, 6 conference rooms, 2 break rooms and 2 copy rooms. Baseline is the existing condition consisting of 254 2-lamp 2x4 parabolic troffers and 5 2x2 parabolic troffers. Measurements include true RMS voltage, current, power and energy usage were metered at 5-minute intervals.	62% energy savings (0.98 kWh/ft^2/yr), where 16% savings were from LED conversion and 46% savings were from controls. The baseline is 2.56 kWh/ft^2/yr. 61% reduction in GHG emissions (0.47 kg CO_2/ft^2/yr). The baseline is 1.22 kg CO_2/ft^2/yr.	[4]
Atlanta, Georgia, USA	Field measurement of a 12,900 ft^2 office space comprising a large open office area, 2 private offices, 2 conference rooms and 1 break room. Baseline is the existing condition consisting of 131 2-lamp 2x4 troffers and 6 2-lamp 2x2 troffers. Measurements include true RMS voltage, current, power and energy usage were metered at 5-minute intervals.	40% energy savings (1.06 kWh/ft^2/yr), where 21% savings were from LED conversion, and 19% savings were from controls. The baseline is 1.78 kWh/ft^2/yr. 41% reduction in GHG emissions (0.51 kg CO_2/ft^2/yr). The baseline is 0.86 kg CO_2/ft^2/yr.	[4]

Location	Application	Results	Reference
Seattle, Washington, USA	Field measurement of a 20,000 ft^2 office space with a mix of private and open offices. Baseline is the as-is existing condition adjusted for the new dimming ballast. The as-is condition includes 180 2-lamp (T5HO) 1-ballast recessed center-basket luminaires. Measurements include power reading at 15-minute intervals.	41% energy savings on default settings (32,625 kWh/yr or 1.63 $kWh/ft^2/yr$). 59% energy savings when adjusted for user preference (22,366 kWh/yr or 1.12 $kWh/ft^2/yr$). Adjusted baseline is 57,847 kWh/yr or 2.89 $kWh/ft^2/yr$. 21% peak demand reduction on default settings (0.71 W/ft^2 compared to 0.90 W/ft^2 adjusted baseline). 46% peak demand reduction when adjusted for user preference (0.49 W/ft^2). The study does not include savings from LED conversion.	[5]
Kent, Washington, USA	Field measurement of a 15,000 ft^2 office space with predominately open offices. Baseline is the as-is existing condition adjusted for the new dimming ballast. The as-is condition includes 138 3-lamp (T8) 1-ballast recessed parabolic luminaires. Measurements include power reading at 15-minute intervals.	35% energy savings on default settings (30,100 kWh/yr or 2.0 $kWh/ft^2/yr$). 35% energy savings when configured per designer specification (30,700 kWh/yr or 2.0 $kWh/ft^2/yr$). 39% energy savings when adjusted for user preference (28,100 kWh/yr or 1.9 $kWh/ft^2/yr$). Adjusted baseline is 46,800 kWh/yr or 3.1 $kWh/ft^2/yr$. No peak demand reduction on default settings (0.69 W/ft^2 compared to 0.69 W/ft^2 adjusted baseline). 12% peak demand reduction when configured per designer specification (0.61 W/ft^2). 15% peak demand reduction when adjusted for user preference (0.59 W/ft^2). The study does not include savings from LED conversion.	[5]

Location	Application	Results	Reference
Portland, Oregon, USA	Field measurement of a 5,418 ft^2 office space with half of the space being private offices, 2 conference rooms and a small open office area. Baseline is the as-is existing condition. The as-is condition includes 73 3-lamp (T8) 2-ballast paracube troffers and 2 2-lamp (T8U) 1-ballast paracube troffers. Measurements include power reading at 15-minute intervals.	32% energy savings on default settings (9,504 kWh/yr or 1.66 $kWh/ft^2/yr$). 37% energy savings when configured per designer specification (8,813 kWh/yr or 1.54 $kWh/ft^2/yr$). 36% energy savings when adjusted for user preference (8,977 kWh/yr or 1.57 $kWh/ft^2/yr$). Adjusted baseline is 14,029 kWh/yr or 2.45 $kWh/ft^2/yr$. 15% peak demand reduction on default settings (0.66 W/ft^2 compared to 0.78 W/ft^2 adjusted baseline). 31% peak demand reduction when configured per designer specification (0.54 W/ft^2). 31% peak demand reduction when adjusted for user preference (0.54 W/ft^2). The study does not include savings from LED conversion.	[5]
Albany, New York, USA	21 simulations across products in this product category using field measurements in an open office. Baseline is manual light switches operated by occupants. Measurements include PIR motion sensor readings.	43% average energy savings across standard and possible variations, including occupancy sensor field of view, occupancy timeout, grouping, vacancy light level. 40% energy savings in a typical configuration, i.e. wide field of view occupancy sensor, 20-minute occupancy timeout, no luminaire grouping, no vacancy light level). This study only assessed the energy savings potential of occupancy sensing control, not including savings from LED conversion, daylight harvesting and high-end trim.	[6]

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Technology Sector
Lighting

Product Category
Networked Lighting Controls (Wired and Wireless)

Last Updated
01/07/2019

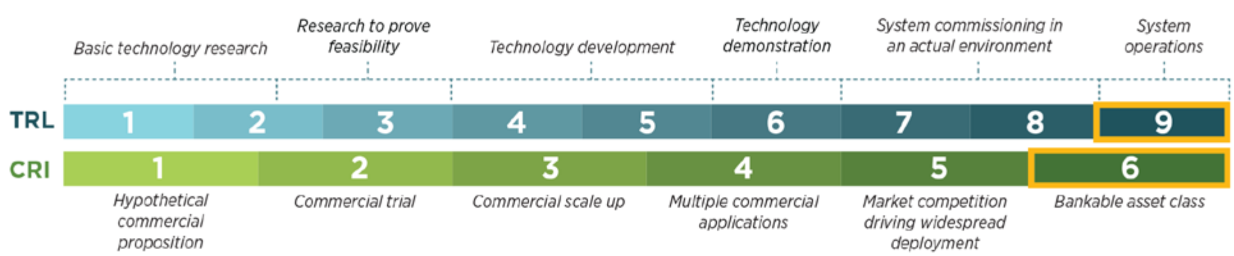
Figure 1: Example Wired Enterprise Networked Lighting Control System. (DLM by WattStopper.) Photo Credit: WattStopper

Product Category Overview

Networked lighting controls establish a control network via dedicated cables or wireless communication protocols (e.g. Bluetooth, ZigBee) between the luminaire drivers, sensors, switches/user interfaces (UIs), and the main lighting controller. Often, the lighting controller is capable of connecting to the cloud or building management system (BMS) for additional functionality and integration with other building systems.

The network created by the lighting control products allows individual and group control of connected devices to enable multiple control strategies including area control, dimming, scheduling, occupancy sensing, daylight harvesting, institutional tuning, and automated demand response.

Characterization at a Glance



Product Category Characterization

Energy Benefits

Energy and demand savings can be achieved through a combination of lighting control strategies, including area control, dimming, scheduling, occupancy sensing, daylight harvesting, institutional tuning, and, if equipped with the necessary hardware configuration, automated demand response (ADR).

Networked lighting control products are most efficient and offer the most benefit when connected to dimmable light sources. Use of dimmable sources and a room-level lighting control system are often the only way to enable certain lighting control strategies such as personal dimming, institutional tuning, and automated demand response. Because of this, wireless room-level lighting control systems are typically installed with dimmable LED luminaires. This creates a one-time, permanent load reduction (often conversion from fluorescent to LED sources) and generates additional savings beyond that achieved by the controls themselves.

Certain lighting control systems enable a building to participate in automated demand response (ADR) programs. When the ADR feature is provided and the building owner enrolls in a utility ADR program, additional demand reduction savings during critical events are created by reducing the power of preselected lighting fixtures in response to an automated signal from the utility. ADR is not designed as an energy savings strategy. It is focused on short-term, demand reduction, however energy is saved during demand response events. Facilities that participate in the ADR program and reduce their load in response to these events typically receive reduced energy pricing and/or alternate incentives such as rebates.

Non-Energy Benefits

Most networked lighting control systems are easily expanded. For most products, commissioning a lighting device only requires energizing the device and connecting it to the control network. Then the device can be “discovered” by the lighting controller. This ease-of-installation feature of the products reduces the amount of labor required to commission the additional fixtures compared to similar systems without this feature.

Networked lighting control systems software solutions typically offer a manufacturer-specific energy monitoring and control tool. Most control software allows for additional features such as remote monitoring, smart device connectivity, and automated system updates, which can further reduce maintenance and operating costs.

Product Category Differentiation

Today’s commercially-available lighting control systems can be differentiated based on their communication platform architecture (wired vs. wireless) and their intended application (enterprise vs. room-level).

Wired vs. Wireless

Wired control systems are networked via dedicated cables. Because of this, wired control systems often require increased planning and installation efforts to properly route and install high- and low-voltage cables. Wireless control systems are networked by using a proprietary communication method (i.e., bluetooth, zigbee) or internet connectivity (i.e., WiFi). Because of this, installation is typically less labor intensive than wired systems and fixtures can allow for fixtures to be mounted in locations where wiring to the lighting controller is not possible and or is very difficult and adds significant cost.

Enterprise vs. Room-level

Enterprise lighting control systems are designed to control whole buildings and often have a high device limit. Room-level lighting control systems typically have a smaller number of individually addressable devices. Products from both system categories are easy to expand and provide equivalent control features. Room-level controllers are not intended for direct connection to and participation in utility automated demand response programs. Additional equipment, often offered by a third-party, is required to enable automated demand response in these controllers.

Installation Pathway and Dependencies

For networked lighting control systems, the most common installation pathways are new construction and major renovations of existing buildings. Equipment replacements and retrofits are other viable installation pathways, as wireless network lighting controls do not require additional wiring. Networked lighting control systems require internet connectivity to allow for automatic system updates and remote monitoring. The products can function without internet connectivity with limited features.

Due to the increased complexity of installation associated with lighting controls as opposed to traditional wiring, training programs such as the California Advanced Lighting Controls Training Program (CALCTP) have been developed to train contractors and electricians. As such, a CALCTP-Certified Installation Contractor may be needed for installation. Note, beginning July 1, 2019, lighting control projects receiving $2,000 or more in utility program incentives will be required to utilize CALCTP-certified installation teams.

List of Products

Table 1: Summary of manufacturers and products for the product category.

Manufacturer	**Model**	**Type**	**Differentiating Feature**
Acuity Controls	nECY System Controller	Wired Enterprise Lighting Control System	Native BACnet. ENVYSION graphic interface Integrate with BMS.
Enlighted	Energy Manager	Wired Enterprise Lighting Control System	Direct Power Metering. BACnet Support. Security Encryption available.
Lutron	Quantum	Wired Enterprise Lighting Control System	Additional Shade Control. Additional Window Control . Promotes third party integration.
Lutron	GRAFIK Eye 4000	Wired Enterprise Lighting Control System	Promotes third party integration.
Osram	Encelium Extend LMS	Wired Enterprise Lighting Control System	IoT Connectivity.
Philips	Dynalite	Wired Enterprise Lighting Control System	Compatible with DALI solutions DyNet network control.
Wattstopper	DLM	Wired Enterprise Lighting Control System	Low Voltage connections to control devices.
Hubbell	NX Distributed Intelligence	Wired Enterprise Lighting Control System	Utilizes a distributed network architecture.
Acuity Controls	Xpoint Wireless	Wireless Enterprise Lighting Controller	For high bay and parking garage applications.
Autani	Autani Manager	Wireless Enterprise Lighting Controller	Can integrate with environment sensors and metering devices.
California Eastern Laboratories	Cortet	Wireless Enterprise Lighting Controller	IoT enabled device. Certified device list.
Cree	Smartcast Wireless	Wireless Enterprise Lighting Controller	IoT enabled device. Allows PoE lighting with IoT.
Creston	Zum	Wireless Enterprise Lighting Controller	Pair and Play connectivity.
Current by GE	Controlscope Manager	Wireless Enterprise Lighting Controller	Lighting, HVAC, plug loads, and fan controller. ADR compatibility.

Manufacturer	Model	Type	Differentiating Feature
Douglas Lighting Controls	Dialog Room Controller	Wired Room-level Lighting Controller	"Plug 'N Control" feature BACnet and DR Ready.
Eaton	Room Controller	Wired Room-level Lighting Controller	"Click & Go" ready using RJ45 wiring. Integrated connections for Greengate Patient Control Station.
ETC	Unison Echo Room Controller	Wired Room-level Lighting Controller	A/V integration.
Wattstopper	Room Controller	Wired Room-level Lighting Controller	Cat 5e cables for connection 2-3 Relays to switch up to 20 amps of load.
Lutron	Homeworks QS	Wired Room-level Lighting Controller	Allows control with IR remotes. Integrated shade control.
EnOcean	EasyFit	Wireless Room-level Lighting Controller	Self-powered sensors Integration with BMS.
Leviton	LuminaRF	Wireless Room-level Lighting Controller	Zigbee Enabled Uses RF communications to lamps.
Acuity	nLight Air	Wireless Room-level Lighting Controller	Five-tier security architecture BACnet compatible.
Lutron	GRAFIK Eye QS	Wireless Room-level Lighting Controller	Shade control. Integrated EcoSystem.

Quantification of Performance

A literature search was conducted and a sample of published study results are summarized in Table 2.

Table 2: Summary of results from literature review

Location	Application	Results	Reference
Berkeley, California, USA	Meta-Analysis 88 Papers and Case Studies focusing on energy saving control strategies. LBNL facility	"Based on the meta-analysis, the best estimates of energy savings potential are 24% for occupancy, 28% for daylighting, 31% for personal tuning, 36% for institutional tuning, and 38% for multiple approaches."	[1]
Ontario, Canada	Field Test College campus (Classrooms, Corridors, & Offices) Baseline was theoretical power calculation from luminaries with only scheduling and high-end trim implemented as control strategies. Luminaire's ballast load was recorded during test.	"Rooms that were occupied sporadically during the day, such as classrooms, benefited the greatest from installation of manual wall switches and occupancy sensors." In classroom settings savings of 9.8% were achieved from implementation of a photosensor and 4.0% were achieved from implementation of scene settings compared to baseline. In corridors 25.1% savings were achieved from photosensor and scene implementation. In offices 21.7% savings were achieved from photosensor and scene implementation.	[2]

Location	Application	Results	Reference
San Diego, CA	Field Test Hotel (Guest rooms & Bathrooms) Baseline is hotel with no occupancy lighting controls. Measured occupancy status of area during periods were lights were on. Recorded energy use of bathroom lighting.	From the implementation of room level controls, potential energy savings of system was estimated to average 214 kWh per room with incandescent lighting and 53 kWh per room with CFL lighting annually. On average 53% of energy used by lighting during baseline testing were during periods were the area was unoccupied. From the implementation of bathroom lighting controls, a power reduction of 44% was recorded, savings were extrapolated to be 56 kWh per bathroom annually.	[3]
La Jolla, CA	Field Test Veterans Administration Medical Center (Open Office Area): 2640 square feet Baseline system used no control strategies Power data was logged before, during, and after energy efficiency test.	Baseline used 3.5 kW of energy daily from two months of data. Personal tuning of light fixtures resulted in 29% energy savings from baseline. Daylight harvesting implementation of the same area saved an additional 21% energy savings. Resulting in on average 50% energy savings per day.	[4]
Davis, CA	Field Test Small/Mid-sized retail business Baseline was fluorescent lighting with no control strategies. Energy use of each phase of the lighting demonstration was recorded.	The LED retrofit system without the lighting control system reduced energy use by 6.9% compared to fluorescent baseline. The lighting control system paired with LED retrofits reduced the annual energy use by an additional 25.2%, from 22,035 kWh to 15,356 kWh.	[5]
Davis, CA	Lab Test Tested monitoring features and accuracy of various lighting control systems under 3 different load dim levels (100%, 50%, 10%). Recorded and compared various lighting control system power measurements to actual power analyzer measurements.	Advance Lighting Control System (ALCS) overestimated energy use on average by 7.73% with a maximum of 13.4% between the three load levels. ALCS 2 overestimated energy use on average by 62% with high of 76%. ALCS 3 employed the best monitoring features, only overestimating energy use on average by 1.2% with max of 2.1% All three ALCS struggled the most with monitoring low (10% dimmed) loads.	[6]

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Technology Sector
Lighting

Product Category
Networked Lighting Controls using Powerline Communication (PLC)

Last Updated
12/05/2018

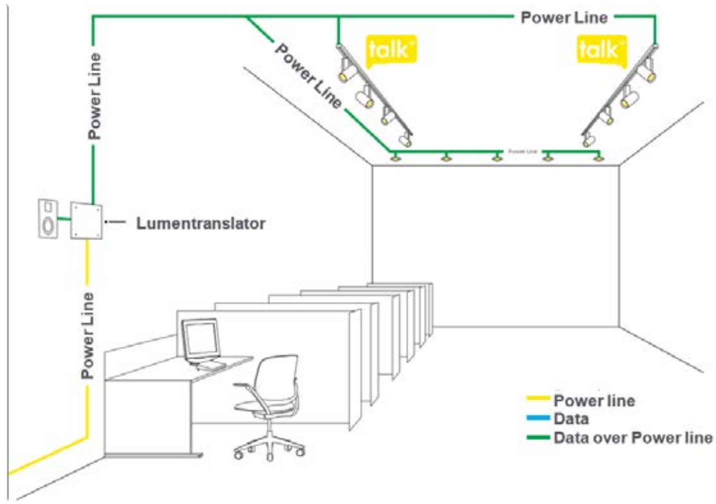
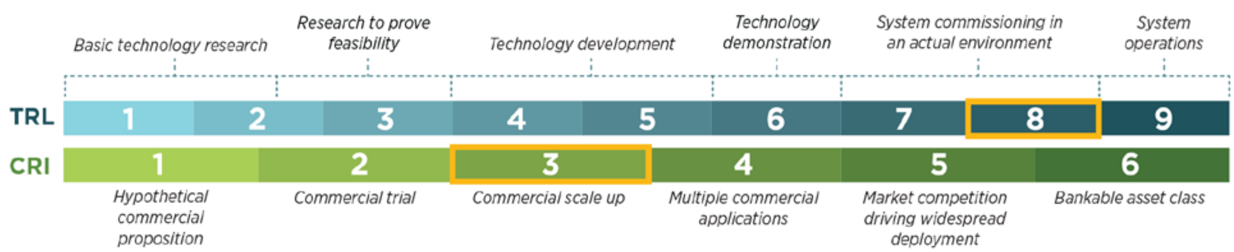


Figure 1: Example of a networked lighting system utilizing powerline communication. Credit: edModus Wattwave [1]

Product Category Overview

Networked lighting controls using powerline communication (PLC) to establish a control network that modulates data and control signals over the same wires supplying line voltage to the devices. PLC systems create individual addressability of network devices (luminaires, sensors, etc.) without the need for separate control or data wirings, thus reducing both material and labor costs for retrofit projects. Products with PLC technology exist on the market for both indoor and outdoor applications. The product contributes to energy savings by leveraging device individual addressability to implement various lighting control strategies. PLC lighting systems also create the possibility to include and control other assets on the same electric power circuit that support the same PLC protocol.

Characterization at a Glance



Product Category Characterization

Energy Benefits

Energy and demand savings are achieved primarily through granular dimming and switching of light points. These abilities are made possible by PLC's individual addressability, including grouping/zoning, scheduling, and high-end trim. Optional sensors can generate further savings via advanced control strategies, such as occupancy/motion sensing and daylight harvesting. PLC systems can be added to existing lighting systems without disruption or equipment replacement; LED conversion typically happens at the same time during the retrofit, thereby creating additional savings through permanent load reduction from efficient LED light sources. Another energy savings opportunity lies in the ability to include and control other plug loads on the same electrical circuit if they also support the same PLC protocol.

Non-Energy Benefits

PLC lighting systems provide an immediate non-energy benefit by incurring lower initial costs in both material and labor compared to other wired networked lighting controls; PLC lighting systems also require minimum additional wiring or rewiring. The systems are easily expandable to support future needs as long as the electrical circuit can accommodate the additional loads. Sitting on the same electrical circuit as many other power-consuming building equipment, PLC systems have superior integration potential if the equipment supports the same PLC protocol. This would increase facility asset management effectiveness and operational efficiency through integrated remote monitoring, data analytics, and control of a large inter-system network.

Product Category Differentiation

The key differentiation of PLC lighting systems is the simplcity of their network architecture, which requires minimal alteration to the existing wiring and lighting devices. The system also requires fewer additional devices—such as gateways for wireless systems or load controllers for other wired systems—to establish the control network. This simplicity historically came at the expense of communication quality, as the power carried on the same line can introduce significant noise to the control signals; however, such issues have been largely mitigated as the technology matures. Another important differentiation is the system's unique potential of including other power-consuming assets in the same control network leveraging the same electrical circuit, provided that those assets also support the same PLC protocol.

Installation Pathway and Dependencies

The primary installation pathway is retrofit, and in many cases it can be considered an add-on if LED conversion is not happening at the same time. There is no notable installation dependency.

List of Products

Table 1: Summary of manufacturers and products for the product category.

Manufacturer	Model	Type	Differentiating Feature
Lumenpulse	Lumentalk	Lumentalk system hardware and software with Lumentalk LED luminaires	Supports most popular standardized control protocols, including DMX, DALI, 0-10V dimming and TRIAC.
enModus	Wattwave	enModus system hardware, software and luminaires with integrated sensors	Supports 1-10V dimming, DALI, Modbus and Bluetooth. Provides cloud connectivity for IoT applications.

Manufacturer	**Model**	**Type**	**Differentiating Feature**
Echelon	Lumewave	Lumewave PLC system hardware and software with embedded outdoor lighting controllers (add-on for existing luminaires)	Provides hybrid solution integrating PLC and RF communication tailored to specific project needs. Provides cloud connectivity.
SWARCO FUTURIT	FUTURLUX	FUTURLUX PLC system hardware, software and streetlight luminaires	Possibility to connect environmental sensors.
Power Control Systems (PCS)	GreenWorx	PCS PLC system hardware, software, luminaires and sensors	Specialize in high-bay applications and parking structures.
iLumTech	DALI PLC	iLumTech DALI PLC hardware and software with any DALI luminaires	Specifically for DALI luminaires.

Quantification of Performance

A literature search was conducted and a sample of published study results are summarized in Table 2.

Table 2: Summary of results from literature review

Location	**Application**	**Results**	**Reference**
United Kingdom	Measured energy usage from a warehouse. Baseline is the existing lighting system with 4-lamp (80W each), T5 high bay luminaires.	96% energy savings, consisting of 88% savings from efficient LED light sources and additional 66% energy savings from controls on top of the new LED baseline. CO2 savings of 14,604 kg.	[2]
United Kingdom	Measured energy usage from a warehouse. Baseline is the existing lighting system with 400W sodium high bay luminaires.	98% energy savings, consisting of 76% savings from efficient LED light sources and 94% energy savings from using controls on top of the new LED baseline. CO2 savings of 6,548 kg.	[3]
United Kingdom	Measured energy usage from a multi-shift manufacturing (printing) facility. Baseline is the existing lighting system with 400W sodium high bay luminaires.	81% energy savings, consisting of 68% savings from efficient LED light sources and 41% energy savings from controls on top of the new LED baseline. CO2 savings of 27,944 kg.	[4]

Location	**Application**	**Results**	**Reference**
United Kingdom	Measured energy usage from a 24-hour-shift (weekdays) manufacturing facility. Baseline is the existing lighting system with 250W metal halide and sodium high bay luminaires.	89% energy savings, consisting of 79% savings from efficient LED light sources and 51% energy savings from controls on top of the new LED baseline. CO2 savings of 27,944 kg.	[5]
United Kingdom	Measured energy usage from a data center. Baseline is the existing fluorescent lighting system.	99% energy, consisting of 49% savings from efficient LED light sources and 98% energy savings from controls on top of the new LED baseline. CO2 savings of 2,445 kg.	[6]
New York, New York, USA	Estimated energy usage of a classroom within a new educational center in Manhattan. Baseline is a T5HO fluorescent lighting system. The energy savings were only estimated for LED conversion, not including savings from controls.	25% energy savings.	[7]

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Technology Sector
Lighting

Product Category
Off-Grid LED Lighting Systems

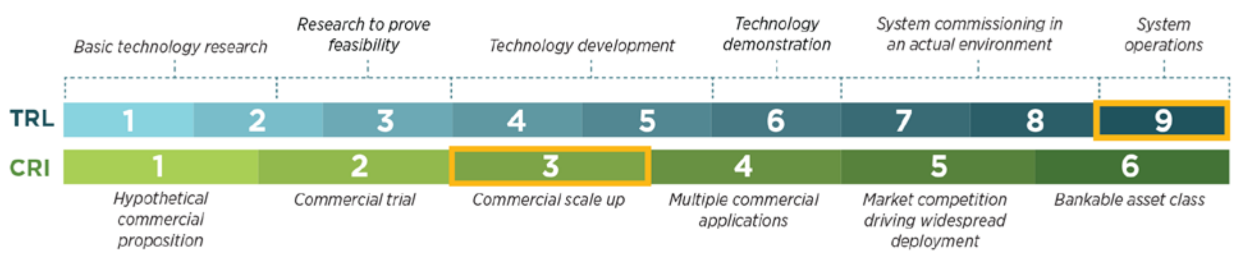
Last Updated
12/11/2018

Figure 1: Solar Charge Controller and LED Constant Current Driver

Product Category Overview

LED lighting powered by local direct-current (DC) renewable resources (e.g. photovoltaic (PV) solar arrays) allow for off-grid lighting systems. An off-grid lighting system is one that is not connected to the electricity grid and relies on local generation and energy storage only for power. This system requires the use of specialized controllers and drivers to directly power LED lighting, eliminating the need for AC-to-DC converters. This reduces conversion losses as compared to traditional AC powered lighting systems that convert the AC power from the grid to the DC power used by the LED lighting device.

Characterization at a Glance



Product Category Characterization

Energy Benefits

When compared to a grid-connected equivalent system, energy savings for off-grid lighting systems are 100%. However, higher initial costs are typical of this type of implementation as the energy generation components must be purchased and installed as part of the system. Additionally, the system has improved efficiency by eliminating AC-to-DC conversions when compared to a grid-connected equivalent system.

Non-Energy Benefits

Because no grid connection is needed, lighting can be provided in secluded and undeveloped areas. Off-grid lighting systems can be used for temporary buildings/camps where connection to grid is not possible or too involved for short term use.

Since the system operates off-grid, the devices powered by the renewable resources are not impacted by grid power outages and fluctuations from grid peak demand. Assuming the off-grid storage capacity is large enough, this increases the reliability to the system.

Product Category Differentiation

Off-grid LED lighting systems do not depend on the grid for generation or storage. The device stops generating and storing power when connected needs and energy storage capacity are met. This is different than a microgrid application of DC lighting, where the system may deliver excess power back to the grid after local needs are met and all energy storage capacity is achieved.

Installation Pathway and Dependencies

Off-grid systems are most typical in new construction projects. Major renovations of an existing building are also feasible where cost of existing lighting system replacement and reconnection to the electricity grid is exceptionally high. Additionally, small scale off-grid lighting systems can be used as additions to add lighting functionality to existing facilities when costs for grid-connected systems place them out of reach.

List of Products

Table 1: Summary of manufacturers and products for the product category.

Manufacturer	Model	Type	Differentiating Feature
Morningstar	SunLight Charge Controller	Charge Controller	Allows dynamic lighting scheduling based on outdoor day and night cycles.
Clear Blue	Lighting Controls	Lighting Controller	Allows dynamic lighting scheduling based on outdoor day and night cycles. Create time/length based profiles with adjustable dimmability.
Epever	Landstar GPLI series	Solar Charge Controller and LED Driver	Integrated Charge controller and driver. Allows adjustment of LED rated current and current percentage. IR communication.
WattWorks	DC LED Lighting & Solar PV Power Station	DC lights, Battery Bank, and Solar PV Panels	Kits that provides all components to assemble off grid lighting.

Quantification of Performance

A literature search was conducted and a sample of published study results are summarized in Table 2.

Table 2: Summary of results from literature review

Location	Application	Results	Reference
Berkeley, California, USA	Case Study Analyzes potential for small off-grid lighting systems, typically seen in Africa and Asia, to be used in larger household-scale solar home systems.	By using super-efficient appliances with a higher up-front cost to standard appliances, components of the solar home systems, such as battery and PV modules, can be reduced. This overall results in a retail price reduction compared to the standard appliance equivalent system. “Falling LED prices and increases in efficacy have helped enable rapid sales growth for pico-solar products that provide basic lighting and, often, mobile charging services for off-grid use”	[1]

Location	Application	Results	Reference
Berkeley, California, USA	Technology and Market Assessment Summarizes feasibility, cost effectiveness, market barriers, customer needs, and savings potential for DC or Hybrid DC-AC systems to power zero net energy buildings.	Compared to a baseline building with AC distribution both residential and commercial buildings have electricity saving potential ranging from 2-14% from modeling data and 2-8% from experimental data. Research shows that AC-DC converters average peak efficiencies of 87.6% for low wattage and 93.7% for high wattages, while DC-DC converters average 90.6% (0-1 kW systems) and 97.5% (1-5 kW systems). Efficiencies in both categories are expected to improve but due to the lesser number of conversions in DC systems there is high energy saving potential.	[2]
Fugar City, Nigeria	Case Study: Four different solutions were analyzed in order to generate power for street lighting; Diesel generator, grid electricity, On-site solar, Off-site solar. Solutions were compared in terms of technical feasibility, financial feasibility, and environmental impact.	On-Site solar was looked to be technically, economically feasible and environmentally friendly compared to diesel generators and unreliable grid electricity.	[3]
Sub-Saharan Africa	Field Study Explores life cycle energy performance in the market for modern off-grid lighting products in Sub-Saharan Africa. Calculates energy payback period for Off-grid Lighting Products. Calculates energy return on investment for Off-Grid Lighting products.	"Off-grid LED lighting has a surprisingly fast energy payback periods compared with other solar applications. Both grid and solar-charged LED products appear to have substantially faster energy payback than kilowatt-scale, grid-connected solar photovoltaic systems."	[4]

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Product Characterization Report
California Energy Product Evaluation (Cal-EPE) Hub

Technology Sector
Lighting

Product Category
Power over Ethernet (PoE) Lighting

Last Updated
12/04/2018

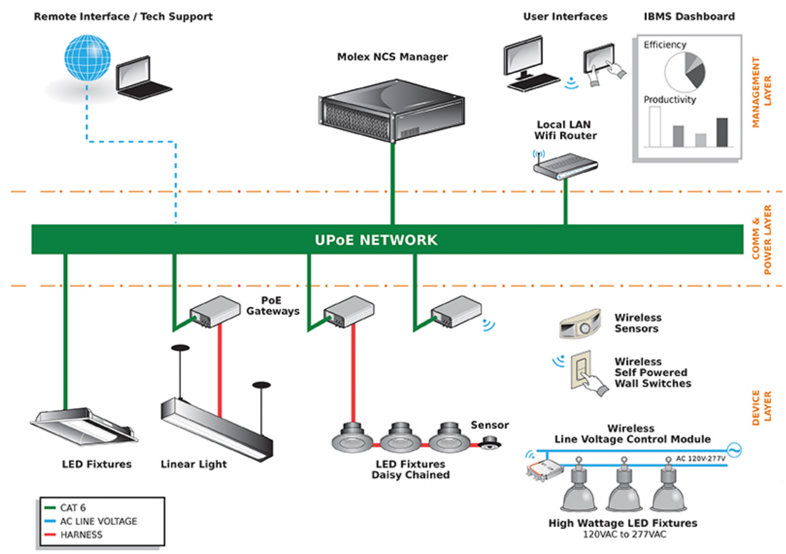
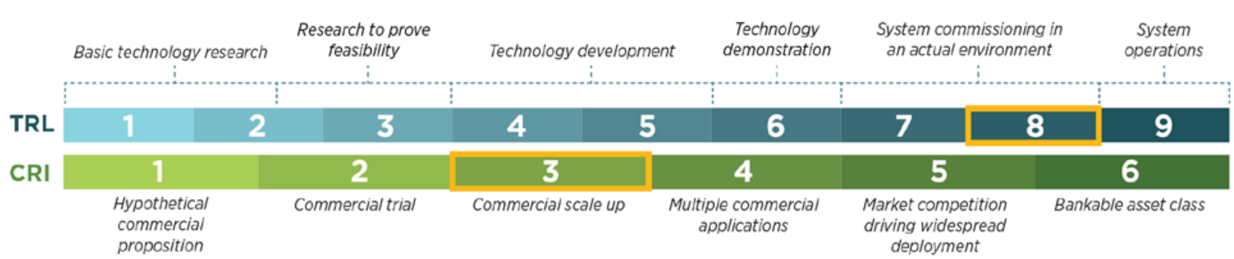


Figure 1: Example of a Power over Ethernet lighting system architecture. Credit: Deco Lighting [1]

Product Category Overview

Power over Ethernet (PoE) lighting uses Cat5/6 Ethernet cables to enable singular connection for both communications and power, conforming to the protocol defined in the Institute of Electrical and Electronics Engineers (IEEE) 802.3 Standards. The product has the same reliability of a traditional wired system without using typical 120V or 277V line-voltage wires and separate control signal wires. Energy savings are achieved using lighting control strategies like other wired and wireless lighting control systems, such as occupancy sensing, daylight harvesting, etc. While the PoE lighting system is largely separate from the building's main IT network in current implementations, it is expected to eventually become an integral part of the IT infrastructure as the technology matures, reducing asset management and maintenance overhead. More importantly, PoE will facilitate better and easier integration of lighting with other building systems in the PoE ecosystem, creating more energy benefits and possibly more high-value non-energy benefits as well. The barriers for PoE lighting include high first cost, lack of familiarity to specify and install it, and the ambiguity on how the organization’s operational technology (OT) and IT teams and policies should coordinate to properly manage the technology.

Characterization at a Glance



Product Category Characterization

Energy Benefits

Energy and demand savings for PoE systems are achieved through a combination of lighting control strategies, including occupancy sensing, daylight harvesting, scheduling, proper zoning, and high-end trim. The PoE system is intrinsically digital and works best with LED lighting. Therefore, savings are also generated through permanent load reduction of efficient LED light sources. Deeper energy savings may be further achieved through better integration with other building systems in the PoE ecosystem.

Persistent energy savings can be realized through near-real-time energy reporting, monitoring, and diagnosis, which have been built into many PoE lighting systems and are one of the major selling points. Continuous energy savings are achieved because of the ability and ease to recommission the system, such as regrouping luminaires to form new control zones or modifying control schedules, as space use or tenants change.

Demand flexibility may be created through the automated demand response capability of the PoE lighting system. The product is capable of producing load "shed" for traditional demand response events as well as performing "shimmy" type of load control to provide advanced grid services when the energy market matures in the future.

Non-Energy Benefits

PoE lighting systems are future-proof due to the standardized Ethernet network architecture, which allows easy system upgrade and expansion such as adding or replacing power sourcing equipment (i.e. power supplies or network switches), luminaires, and sensors to accommodate future needs without disrupting the existing setup or altering the mains wiring. The Ethernet-based system further enables seamless system integration to other Ethernet-based systems, including the IT network infrastructure, building management system and Li-Fi (visible light communication). Maintenance cost and effort are lower compared to line-voltage systems as the Class 2 low-voltage PoE systems do not require a licensed electrician to perform maintenance tasks nor do they subject to the same stringent fire safety requirements. High-speed and high-bandwidth networking capability enables the PoE systems for many advanced Internet of Things (IoT) applications, including space utilization optimization, indoor positioning, asset tracking, etc., that can generate far higher business value than energy benefits.

Product Category Differentiation

PoE lighting systems differentiate from similar networked lighting controls (NLCs) in that they implement standardized power and network protocol conforming to the IEEE 802.3 standards. This facilitates interoperability within the Ethernet ecosystem and allows the lighting systems to be integrated and managed as part of the IT assets. PoE lighting systems also possess the highest network speed and bandwidth among all NLCs, which makes it capable of carrying large volume of data and playing a key role in the intelligent building IoT ecosystem.

Installation Pathway and Dependencies

The installation pathways are new construction or major renovation, with the new construction pathway currently makes most economic sense. An installation dependency is the location planning for network switches (which typically are also the power sourcing equipment) of the PoE lighting system, especially when co-locating them with other IT network equipment in the server room or wiring closet. A support dependency is conformance to the organization’s IT policy when the PoE lighting system is managed as part of the IT assets and shares the same IT infrastructure.

List of Products

Table 1: Summary of manufacturers and products for the product category.

Manufacturer	Model	Type	Differentiating Feature
Cree	SmartCast PoE	Cree PoE network system and PoE luminaires	Partner of the Cisco Digital Building ecosystem.
Deco Lighting	VECTOR series (PoE-enabled luminaires) powered by Molex Transcend	Deco PoE luminaires with Molex PoE network system	Molex is a partner of the Cisco Digital Building ecosystem.
Eaton	Power over Ethernet	Eaton PoE network system and PoE luminaires	Partner of the Cisco Digital Building ecosystem.
H.E. Williams	Power over Ethernet	H.E. Williams PoE luminaires with Igor's PoE network system	Allows daisy-chain of devices.
Hubbell Lighting	PowerHUBB	Hubbell PoE network system and PoE luminaires	Allows daisy-chain of devices.
Igor	Nexos Platform	Igor PoE network system with partner PoE luminaires	Partner of the Cisco Digital Building ecosystem.
Philips Lighting (Signify)	InterAct Office PoE	Philips PoE network system and PoE luminaires	Partner of the Cisco Digital Building ecosystem.
Innovative Lighting	GENISYS PoE Lighting Systems	Innovative Lighting PoE network system and PoE luminaires	Proprietary Intellidrive can expand one PoE switch port to support multiple devices.

Quantification of Performance

A literature search was conducted and a sample of published study results are summarized in Table 2.

Table 2: Summary of results from literature review

Location	Application	Results	Reference
Toronto, Canada	Estimated energy use for a 30-story LEED Platinum office and retail development. The PoE lighting Installation includes 1,400 LED luminaires. Baseline is theoretical traditional fluorescent lighting.	80% energy savings (177,000 kWh savings) after PoE installation, including 50% savings from efficient LED light sources.	[2]

Location	Application	Results	Reference
Iowa, USA	Calculated energy use for a 3-story housing complex. The incumbent lighting system was replaced with a PoE system with new LED luminaires and sensors. Baseline is the existing T8 fluorescent lighting systems.	86% energy savings (annual energy consumption of 6304 kWh compared to the 45,722 kWh baseline), composed of 62% savings from efficient LED light sources and 24% savings from controls and analytics. $1700 total maintenance cost savings per year. 53% appreciation in property values.	[3] [4]
Amsterdam, the Netherlands	New construction project Estimated energy savings from a 15-story 430,500 ft^2 multi-tenant office building consisting of about 6,500 connected LED luminaires. Baseline for estimating savings is a "would-be" case using a typical lighting system (baseline not specified in the literature).	$115,000 annual energy cost savings. $4.2 million space utilization cost savings through space optimization using occupancy sensor data. Lower annual cost per employee by over $2,100.	[5]

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Product Characterization Report
California Energy Product Evaluation (Cal-EPE) Hub

Technology Sector
Lighting

Product Category
Task Oriented Lighting

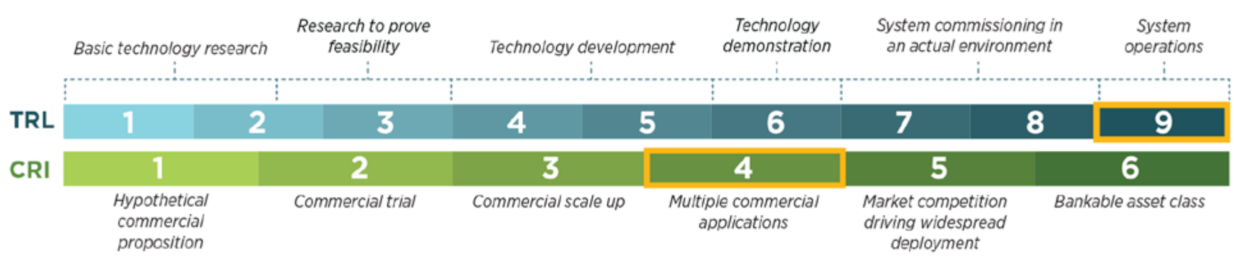
Last Updated
12/3/2018

Figure 1: Typical task light used for typing and reading.

Product Category Overview

Task lighting systems provide focused, elevated light levels in areas where users need it most. Task lighting may be coupled with reduced general (overhead) lighting as appropriate. When both task lighting and reduced levels of general lighting are combined in an integrated design, the system is often referred to as task-ambient lighting. In these systems, the general lighting is lower than and complementary to the task lighting. Task lighting is also often dimmable and can be adjusted by the user to allow for the right amount of illumination for the specified task. Modern task light systems use LED sources combined with some form of local user control.

Characterization at a Glance



Product Category Characterization

Energy Benefits

Energy savings are achieved by coupling energy-efficient task lighting with low-level general overhead lighting. Compared to overhead lights, task lights typically require less power for equivalent brightness due to the proximity of the task light to the task plane. Assuming the design is based on modern lighting power densities and use of LEDs, savings often range from 10% to 25% in common applications. When task lighting or task-ambient lighting is used to replace legacy fluorescent systems, savings may be higher.

Non-Energy Benefits

Users can use individual lighting control to adjust light levels as they see fit to give them the best visual comfort level. Through this mechanism task lighting may increase productivity for such individuals [2].

Product Category Differentiation

Compared to typical overhead lighting, task lighting is in closer proximity to the task plane, allowing it to appropriately illuminate the task area while consuming less power than overhead lighting consumes to achieve comparative illumination. Most luminaires can be considered task-oriented lighting if they supplement a general, overhead lighting system and are placed appropriately to achieve proper illumination and comfort for the user. Systems that include both a task and ambient component are typically installed with furniture at workstations.

Installation Pathway and Dependencies

Task lighting systems are commonly a plug load device in task-specific areas such as work benches and desks. In some environments, task light systems are hardwired and integrated with commercial furniture, which can decrease the likelihood of energy savings. In these cases, the general overhead lighting is not specified in combination with the task lighting. The base electrical construction phase that includes the overhead lighting often occurs well in advance of or completely independent from specification and installation of furniture and interior finishes. Similarly, in an owner-tenant relationship, building owners must provide a minimal level of lighting, whereas tenants are responsible for providing task lighting for their work areas and employees. An integrated design is rarely achieved.

List of Products

Table 1: Summary of manufacturers and products for the product category.

Manufacturer	**Model**	**Type**	**Differentiating Feature**
Verilux	Various	Task-Oriented Luminaire	Full Spectrum Lighting. Color Temp adjustable. Light output adjustable.
Brightech	Various	Task-Oriented Luminaire	No dust designs. No construction needed.
Phive	Various	Task-Oriented Luminaire	Color Temp adjustable. Light output adjustable.
Koncept	Various	Task-Oriented Luminaire	Slim Lamp Design. Light output adjustable.
Tambient	Various	Task-Ambient System	Task and ambient lighting system with integrated monitor mounts.

Quantification of Performance

A literature search was conducted and a sample of published study results are summarized in Table 2.

Table 2: Summary of results from literature review.

Location	Application	Results	Reference
Oakland, California, USA	Case Study Six private offices and 44 open cubicle spaces. Baseline included fluorescent pendants and fluorescent and incandescent desk lamps. California's 2008 Building Energy Efficiency Standard reduced the allowed lighting power density by 25% to 0.9 W/ft^2. Measured lighting power density of space of baseline and LED IOLS retrofit.	Annual energy savings at demonstration sites was 44%. "Significant energy savings ranging from 25-60% with lighting power densities as low as 0.6 W/ft^2." Annual savings of 43,503 kWh compared to baseline.	[1]
Berkeley, California, USA	System Program Manual Lab Test Detailed technical information for implementing an incentive program for task-ambient and occupancy-based plug load control.	Energy Savings for Specified Technology Packages versus DOE Reference Buildings ranged from 12-16% in large buildings and 16-20% in small buildings.	[2]
Davis, California, USA	Case Study: Office Building Baseline included fluorescent troffers and fluorescent and incandescent desk lamps. California's 2008 Building Energy Efficiency Standard reduced the allowed lighting power density by 25% to 0.85 W/ft^2. Photometric measurements along with energy usage was recorded.	Study reported energy savings, typically 40-50%. System used 45% less energy than the baseline system. Estimated total life-cycle savings of more than $20,000. Annual combined savings of 13,996 kWh compared to baseline.	[3]

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Technology Sector
Lighting

Product Category
Wireless Networked Lighting Controls for Exterior/Smart City Applications

Last Updated
12/18/2018

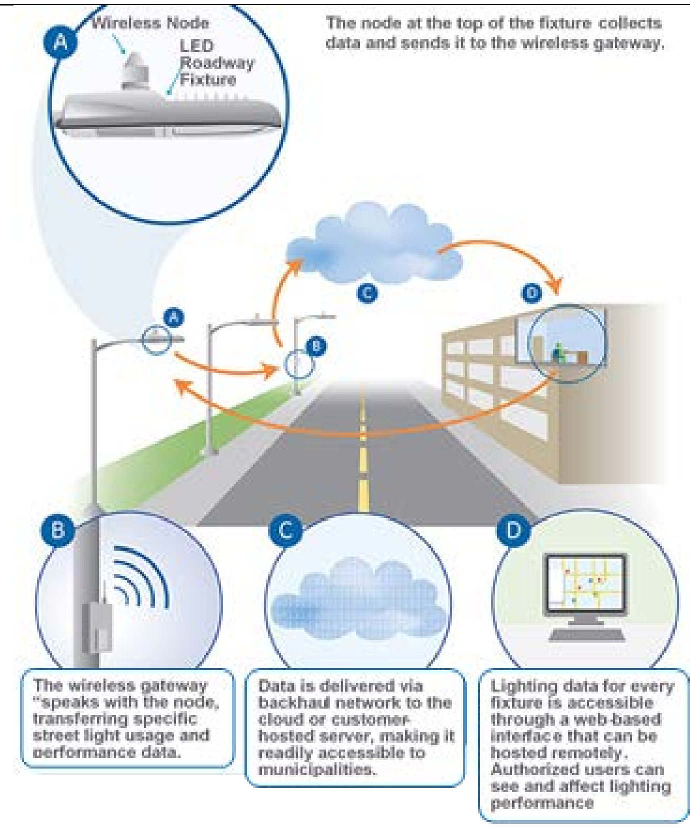
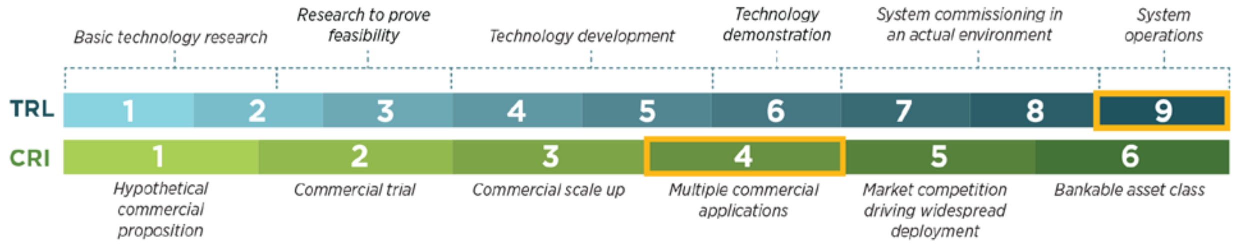


Figure 1: Example of a wireless networked lighting control system. Credit: Current by GE (modified for better readability) [1]

Product Category Overview

Wireless outdoor lighting management systems establish a control network for street, roadway, or area lighting through a wireless node. The node is either locked-in on top of an LED luminaire via a standardized socket (commonly known as a NEMA socket) or embedded in a luminaire. The node typically has a photosensor or astronomical clock that can autonomously turn the lights on at nighttime and off during daytime. It can also be equipped with metering capabilities to provide an accurate account of energy usage. The wireless node communicates with a central management system (CMS) that provides a platform for remote monitoring, diagnostics, and control capabilities. In addition, various smart city integration is possible through the platform, such as air quality monitoring, acoustic analytics for gunshot or crash detection, and video analytics for license plate recognition. Auxiliary power and communication enables other smart city services, leveraging its communication infrastructure. Energy savings are achieved through conversion to efficient LED light and through reducing or eliminating lighting during times when it is not needed (i.e. during daylight hours, or when no pedestrian or vehicle traffic is detected).

Characterization at a Glance



Product Category Characterization

Energy Benefits

Energy benefits result from deployment of efficient light sources as well as autonomous and flexible controls. The system is typically put in place at the time of replacing incumbent fixtures that have high intensity discharge (HID) light sources—including mercury vapor, high pressure sodium (HPS), low pressure sodium, and metal halide lamps—with LED luminaires. Therefore, the primary energy savings come from LED conversion. Additional savings also result from autonomous and flexible controls to reduce light level in the several ways: (1) The photosensor or astronomical clock built in to each light point ensures lights are automatically turned off during daytime; (2) the light points can be scheduled to dim to different levels based on the expected traffic volume at different hours; and (3) the integrated motion sensor, if equipped, can reduce light level when no vehicle or pedestrian traffic is detected (also known as lighting on demand).

While not in practice today, street and area lighting may be used to participate in demand response events and other grid services when the grid peak shifts towards evening hours in the future, thereby generating dynamic demand savings.

Non-Energy Benefits

Increased maintenance efficiency is the immediate non-energy benefit. The network control system can identify failures (either reported by the light point or through trending of the light point's operating characteristics, such as energy usage) and accurately locate the faulty light point (via built-in GPS) for the maintenance crew to take corrective actions during daytime hours. Many systems provide the ability to integrate with or have built-in work order management systems, which would further streamline the maintenance workflow. Improved quality and versatility of public space and roadway is another non-energy benefit, especially when integrated with other smart city systems and services. This may be in the form of increased safety, reduced crime rate, and faster first responder response time due to better lighting and acoustic/image analytics for incident identification. Smart city integration also opens opportunities for improved city services, such as waste and drainage management leveraging the lighting network's communication infrastructure.

Product Category Differentiation

This product category differentiate itself from simple street and area LED lighting retrofit in that it provides much more advanced control, monitoring, and management capabilities to allow cities and municipalities to centrally operate the lighting system as an asset.

Installation Pathway and Dependencies

The installation pathways are new construction, major renovation, or retrofit. There are no installation or support dependencies for this product category.

List of Products

Table 1: Summary of manufacturers and products for the product category.

Manufacturer	Model	Type	Differentiating Feature
Acuity	ROAM	ROAM network and control system with Acuity Brands luminaires	Proprietary mesh network.
Current by GE	LightGrid	LightGrid network management and control system with GE luminaires	Proprietary mesh network.
DimOnOff	Smart City Management System	DimOnOff sensor, network and control systems with any fixtures with NEMA sockets	Optional CitySound ambient sound analytic solution and ALPR automatic license plate recognition technology. Proprietary mesh network among control nodes.
Echelon	LumInsight & Lumeeave	LumInsight central management system, Lumewave network components with any fixtures with NEMA sockets	Offers a hybrid solution of wireless and wired (powerline communication) control network.
Flashnet	intelliLIGHT	intelliLight StreetLight Control software and hardware with any fixtures	Communication technology agnostic, supporting LonWorks PLC, LoRaWAN, NB-IoT, Sigfox and LTE-M.
Hubbell	wiSCAPE	wiSCAPE control network software and hardware with wiSCAPE enabled luminaires	Proprietary mesh network.
Philips Lighting (Signify)	CityTouch	CityTouch platform, including network software and hardware with CityTouch Ready luminaires	Luminaires produced by manufactures in the CityTouch Ready partner program offer plug-and-play capability Cellular network with star topology.
Telematics	T-Light	T-Light network control software and hardware with any fixtures with NEMA sockets	Proprietary mesh network.
Telensa	Planet	Planet network control software and hardware with any fixtures with NEMA sockets	Supports smart city applications including traffic analytics, drainage monitoring, waste analytics, and air quality monitoring. Proprietary ultra-narrow band (UNB) network.

Quantification of Performance

A literature search was conducted and a sample of published study results are summarized in Table 2.

Table 2: Summary of results from literature review

Location	Application	Results	Reference
Fort Sill, Oklahoma, USA	Measured energy usage from a networked lighting system with 40 LED luminaires deployed on a major roadway on an army base. The baseline is the incumbent system of 250W HPS luminaires.	59% energy savings over a one-year operation, a reduction from 579.1 kWh to 235.8 kWh per light point.	[2]
Montreal, Quebec, Canada	Estimated savings from the initial phase of the city's street lighting infrastructure improvement project replacing HPS lighting with connected LED systems. The baseline is the incumbent system of 132,000 HPS fixtures.	35% energy savings. 55% maintenance savings. 123 tons annual GHG savings. CAD219M savings over 20 years.	[3]
Mississauga, Ontario, Canada	Estimated savings from the city's street lighting infrastructure improvement project converting HPS lighting to connected LED systems. The baseline is the incumbent system of 49,000 HPS fixtures.	55% energy savings ($3,355,000 CAD annual savings). 50% maintenance savings (CAD1, 150,000 annual savings).	[4]
Shawinigan, Quebec, Canada	Estimated savings from the city's street lighting infrastructure improvement project converting HPS lighting to connected LED systems. The baseline is the incumbent system of 6,141 HPS fixtures.	68.9% energy savings ($305,378 CAD annual savings). 35% maintenance savings (CAD176,515 annual savings).	[5]
Bellingham, Washington, USA	Estimated savings from retrofitting 3,600 city-owned streetlights and lighting infrastructure with a networked control system and LED luminaires. The baseline is existing HPS fixtures.	70% energy savings (1.8M kWh) by 2020 $240,000 annual energy cost savings. 2 million pounds annual carbon emission reduction.	[6]
Cambridge, Massachusetts, USA	Estimated savings from retrofitting 7,000 streetlights to connected LEDs, including 4,900 cobra fixtures and 2,100 decorative fixtures. The baseline is existing HPS fixtures.	80% energy savings. $500,000 annual energy cost savings.	[7]
Clemson, South Carolina, USA	Estimated savings from a campus parking lot that is retrofitted with LED luminaires managed by a networked control system. The baseline is a lighting system with 400W metal halide fixtures.	40% energy cost savings.	[8]
Mecca, Saudi Arabia	Energy savings from 25,000 streetlights that are converted to LEDs and managed by a networked control system. (The literature does not specify whether the energy usage is measured or estimated). The baseline is existing 250W HPS fixtures.	24% savings (reduction from 42,398 MWh to 32,222 MWh.	[9]

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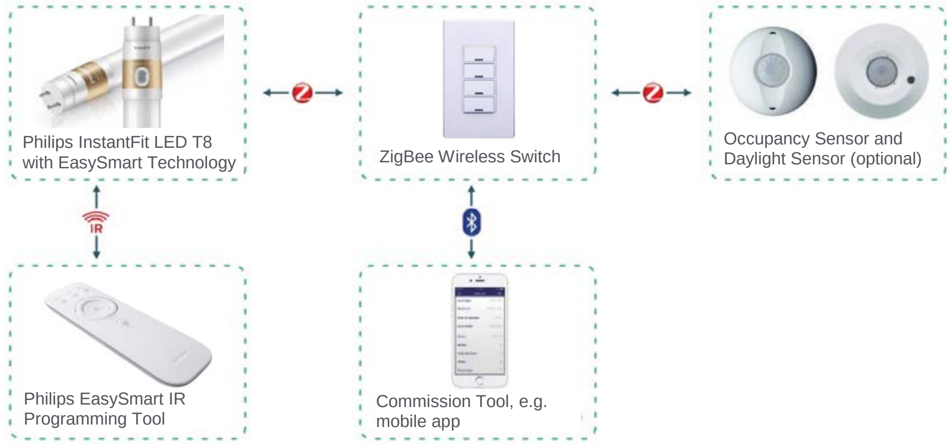
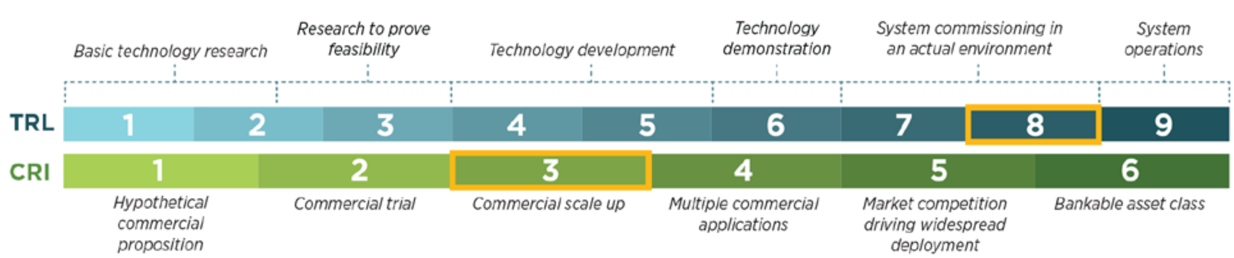
Technology Sector Wireless Tubular LEDs (TLEDs) Product Category Wireless Tubular Light Emitting Diode Lamps Last Updated 11/29/2018	 *Figure 1: Wireless TLEDs and wireless communication/control ecosystem* [1] [2].

Product Category Overview

Wireless Tubular Light Emitting Diode (TLED) lamps are a replacement for tubular fluorescent lamps and can be dropped into existing linear fluorescent fixtures. TLED lamps connect to other devices—such as dimmer switches or sensors—through a wireless communication protocol. The connectivity allows multiple TLEDs to be strategically assigned as a group and controlled together without having to modify the physical wiring. This provides the most cost-effective way to capture energy savings through more appropriate zoning or grouping. Energy savings may also result from occupancy sensing or daylight harvesting in the cases where TLEDs are connected to and controlled by a wireless occupancy sensor or photo sensor.

Characterization at a Glance



Product Category Characterization

Energy Benefits

TLEDs save on energy and demand through high efficiency LED light sources and appropriate zoning or grouping of fixtures where the lights are switched or dimmed at a more granular level based on the usage of the space. Manual dimming via wireless switches, dimmers, or an app may contribute to additional savings. Certain product variations in this product category allow the wireless TLEDs to be controlled by wireless sensors to achieve deeper savings through more advanced control strategies, including occupancy sensing and daylight harvesting.

Non-Energy Benefits

Compared to other lighting system upgrades (e.g. full luminaire change outs with networked controls), TLEDs incur lower upfront costs in both material and labor for making incremental improvements to the existing lighting system. Wireless TLEDs are intended for low commissioning effort as commissioning is localized (within the coverage of a local control device, such as a switch or a sensor) and typically only involves assigning lamps to the local control device, which does not rely on extensive product knowledge or specialized software skills.

Product Category Differentiation

This product category differs from similar lighting product categories in that it reduces the time and cost on lighting improvement to a level comparable to typical lamp replacement, offering the most basic form of connected lighting. It provides an economical way to add a layer of control sophistication to the existing lighting system: namely flexible zoning/grouping and control strategies like occupancy sensing and daylight harvesting for certain variations in this product category.

Installation Pathway and Dependencies

The installation pathway for this product category is retrofit. The wireless TLEDs currently come in the same form factor as 4-foot linear fluorescent lamps and therefore can only be installed in fixtures that originally house 4-foot linear fluorescent lamps, such as 1’-by-4’ or 2’-by-4’ troffers, wraparound lights, and strip lights. As with their non-connected counterparts, product selection may depend on the compatibility with the type of ballasts (electromagnetic or electronic, instant start or rapid start, etc.) that are currently in place.

List of Products

Table 1: Summary of manufacturers and products for the product category.

Manufacturer	Model	Type	Differentiating Feature
Philips Lighting (Signify)	InstantFit EasySmart	Linear fluorescent tube replacement	Works with control devices, (switches, occupancy sensors and daylight sensors), from vendors in the EasySmart ecosystem. Can support occupancy sensing, daylight harvesting, continuous dimming, personal control and task tuning.
Ledvance	SubstiTUBE Connected	Linear fluorescent tube replacement	Controlled by Ledvance SubstiTUBE Connected Sensor. Can support occupancy sensing control.
Lunera	Lunera Smart T8	Linear fluorescent tube replacement	Controlled by devices, (switches and occupancy sensors), in the Lunera Smart Lamp ecosystem for the Lunera Ambient Compute IoT Platform. Can support occupancy sensing and energy reporting.
ChessWise	MyriaMesh Smart T8 LED Tube	Linear fluorescent tube replacement	Works with control devices, (switches, multisensors and driver interface), in the MyriaMesh product line. Compatible with magnetic ballasts (only).

Quantification of Performance

A literature search was conducted and a sample of published study results are summarized in Table 2. Due to the relatively short time on the market, literature specifically evaluating energy benefits of wireless TLEDs is not yet publicly available. The literature provided below documents only energy savings of non-connected regular TLEDs, which do not capture additional savings from flexible and improved grouping/zoning, dimming, or other possible control strategies such as occupancy sensing and daylight harvesting. In other words, the savings figures presented in the table should be treated as the lower bound of the possible energy savings from wireless TLEDs.

Table 2: Summary of results from literature review

Location	Application	Results	Reference
Washington, DC, USA	Field measurement (in sampled spaces) of a 1,700,000 ft^2 space comprising 35,000 troffers. Baseline is the existing condition. Each of the 35,000 troffers contained one 32 W linear fluorescent lamps with a system wattage of 29.4 W. The reported savings were exclusively from reduced wattage of TLEDs. Savings from the granular lamp grouping/zoning capability of wireless TLEDs were not accounted for.	50% energy savings (2,100,000 kWh/yr or 1.24 kWh/ft^2/yr). The pre-retrofit baseline is 4,200,000 kWh/yr or 2.47 kWh/ft^2/yr.	[3] [4]
Auburn, Washington, USA	Field measurement of two discrete open office spaces on the first floor of a 100,000 ft^2 building. The measurements were spot measurements of instantaneous luminaire power consumption (in W). Baseline is the existing condition consisting of 2'-by-4' 2-lamp (T8) recessed troffers with electronic ballasts. Existing lighting controls were on/off switches. The savings were exclusively from reduced wattage of TLEDs. Savings from the granular lamp grouping/zoning capability of wireless TLEDs were not accounted for.	34% energy savings reduction. Projected post-retrofit energy consumption is 129.2 kWh/yr. Baseline is 240.0 kWh/yr.	[5]

Location	Application	Results	Reference
Dallas, Texas, USA	Field measurement of two office sections on the seventh floor on a 16-story 1,000,000 ft^2 building comprising open and private offices, common areas and corridors. The measurements were spot measurements of instantaneous luminaire power consumption (in W). Baseline is the existing condition consisting of 2'-by-4' recessed troffers in either 2- or 3-lamp (T8) configuration with electronic ballasts. Existing lighting controls were on/off switches. The savings were exclusively from reduced wattage of TLEDs. Savings from the granular lamp grouping/zoning capability of wireless TLEDs were not accounted for.	28.5% energy savings. Projected post-retrofit energy consumption is 171.6 kWh/yr. Baseline is 240.0 kWh/yr.	[5]
Logan, Utah, USA	Estimated energy savings from replacing linear fluorescent lamps to TLEDs on the retail sales floor area. Baseline is a comparable store with similar footprint and temperature but uses traditional light sources. The savings were exclusively from reduced wattage of TLEDs. Savings from the granular lamp grouping/zoning capability of wireless TLEDs were not accounted for.	57% monthly energy savings (45,993 kWh). The comparable baseline energy consumption is approximately 107,000 kWh. 381 MT/yr carbon dioxide reduction.	[6]
Madrid, Spain	Calculated energy savings aggregated across more than 120 sites replacing more than 20,000 linear fluorescent lamps with TLEDs. Baseline is the existing 36W linear fluorescent lamps installed in the troffers. The savings were exclusively from reduced wattage of TLEDs. Savings from the granular lamp grouping/zoning capability of wireless TLEDs were not accounted for.	55% energy savings.	[7]

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