Adaptive, Sensor-Based Lighting for Security Applications

Exploring Emerging Design Strategies

Prepared by the California Lighting Technology Center & Hawai'i Natural Energy Institute

Prepared for the Office of Naval Research

UCDAVIS California Lighting Technology Center

HNEI Hawaiʻi Natural Energy Institute University of Hawaiʻi at Mānoa

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INTRODUCTION

Traditional outdoor lighting technologies operate at full power throughout the night, even when areas are vacant. This extra load, energy waste and light pollution can be averted by updating the lighting system with energy-efficient light sources and lighting controls. By installing these technologies, adaptive lighting strategies can be implemented that provide the right amount of light when and where it is needed.

Lighting controls can be standalone, integrated at the light source level and inform the behavior of just that light source; or lighting controls can be deployed as a networked system allowing all sensors to inform the behavior of any light source in the network (Figure 1).

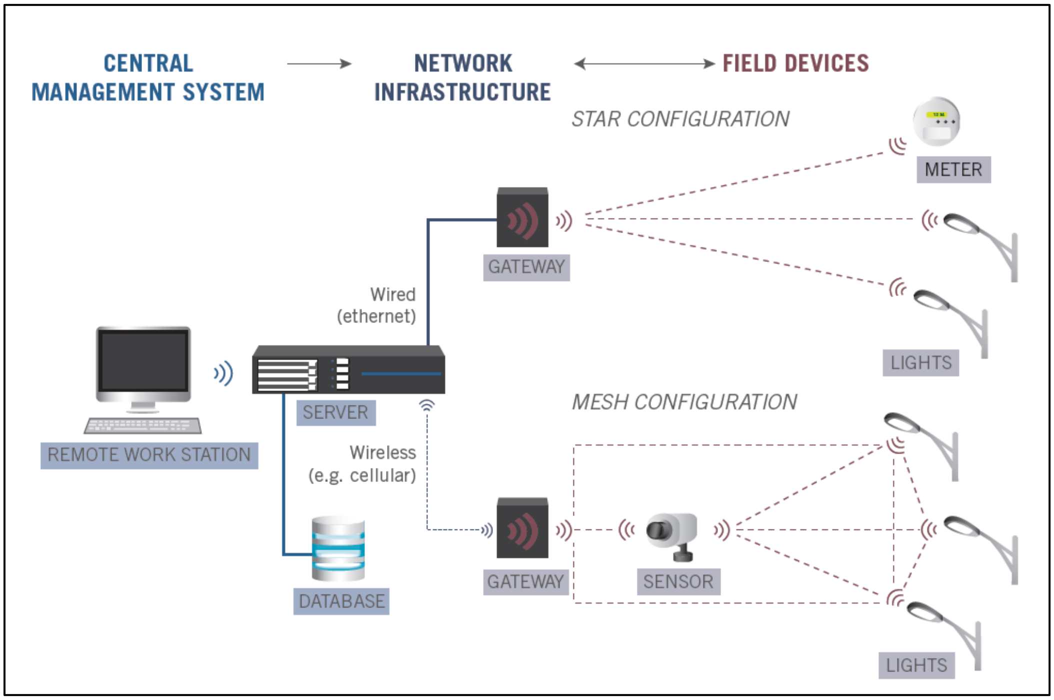

Figure 1. Example networked lighting system architecture. Photo credit: CLTC

Adaptive outdoor lighting systems utilize 1) photosensors to detect ambient daylight levels and turn on the electric light source when needed, and 2) occupancy sensors to detect when a space is occupied/vacant. The sensor sends the status signal, or 'trigger', to the lighting system and the system modifies the light levels per the settings deployed during commissioning that are appropriate for the application. Typically, lighting levels are lowered when no one is in the area, saving energy while still providing enough light to meet safety requirements for the application; and lighting levels are increased when an occupant is detected, bringing the light levels up to the recommended amount of illuminance for the application and/or task(s) being performed.

Today, adaptive lighting is considered best practice for numerous outdoor applications and has been widely adopted in building standards by many organizations, including the California Energy Commission and the United States' Department of Defense (DOD). However, most outdoor security applications remain designed with high, uniform levels of static illumination. Research conducted in 2002 shows that high, uniform light levels have little to no deterrent effect on crime, rather the elevated levels of illumination typically only increase the perception of security for people using the space.[1]

In addition to energy savings and load reduction, the project team anticipates that adaptive lighting systems implemented in security applications will increase the likelihood of guards detecting intruders by "highlighting" occupants as they trigger strategically placed occupancy sensors. For this strategy to be effective, the sensors must be configured to instantly increase light levels when triggered by an occupant, effectively serving as a visual alarm.

This effort has four key objectives:

1. The identification and testing of adaptive outdoor lighting system technologies.
2. Prototyping of an adaptive, sensor-based lighting system appropriate for use in security applications.
3. Validation of the concept through installation of the prototype system in a campus setting; and
4. Demonstration of the system in two, real-world security applications on a U.S. naval base.

The demonstration tasks address lighting system demand and energy use reductions enabled by use of adaptive lighting controls and end user feedback on the system's performance.

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[1] (Clark B. A., Outdoor Lighting and Crime, Part 1: Little or No Benefit, 2002, p. 1)

BACKGROUND

CLTC conducted a literature review to explore published security lighting guidelines and requirements; security applications appropriate for use with adaptive, sensor-based lighting systems and detectability of light level changes.

SECURITY LIGHTING GUIDELINES

CLTC conducted a literature review to understand the recommended practice and any requirements for the lighting of security applications today. Reviewed sources included the Illuminating Engineering Society and the US Department of Defense.

IES Recommended Practice

The IES publication *Guide for Security Lighting or People, Property, and Critical Infrastructure (IES G-1-16)* provides design guidance for security lighting.[2] Generally, for critical checkpoints and inspection stations such as those found on military bases, the recommended light level is the greatest of 1) 10 foot-candles at grade, or 2) twice the light level of the immediate surrounding area. Additionally, IES G-1-16 recommends that these applications have light levels of at least two foot-candles extending from the critical area towards the roadway for at least 50 feet.

US Department of Defense Facility Requirements

The US Department of Defense (DOD) publishes four documents that address security lighting at US DOD facilities.

- *Unified Facilities Criteria: Interior and Exterior Lighting Systems and Controls (UFC 3-530-01)* is the most comprehensive resource and addresses lighting and lighting control systems. Chapter 6 provides guidelines for security systems. Chapter 4 provides general requirements for outdoor lighting.[3]
- *Unified Facilities Criteria: Security Engineering: Waterfront Security (UFC 4-025-01)* addresses specific security lighting considerations for waterfronts.[4]
- *Unified Facilities Criteria: Entry Control Facilities Access Control Points (UFC 04-022-01)* addresses specific requirements for security lighting of entry control facilities and transition zones.[5]
- *Unified Facilities Criteria: Electronic Security Systems* (*UFC 4-021-02)* contains information for selecting electronic security systems.[6]
- *Unified Facilities Criteria: Cybersecurity of Facility-related Control Systems (UFC 4-010-06)* describes requirements for incorporating cybersecurity in the design of all facility-related control

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[2] (The IES Security Lighting Committee, 2016)

[3] (Department of Defnese, 2016)

[4] (Department of Defense, 2012)

[5] (Department of Defense, 2017)

[6] (Department of Defense, 2013)

systems. It requires lighting controls to be cybersecure and follow the steps outlined in the Risk Management Framework (RMF) to obtain Authority to Operate (ATO).[7]

For general exterior lighting, *UFC 3-530-01* references *ASHRAE 90.1: Energy Standard for Buildings except Low-Rise Residential Buildings.*[8] It is important to note that the current ASHRAE 90.1 standard exempts security systems from its requirements for exterior lighting controls.[9]

Additionally, *UFC 3-530-01* defines lighting requirements based on the level of protection for an application, which is determined using criteria found in *Unified Facilities Criteria: DOD Security Engineering Facilities Planning Manual (UFC 4-20-01).*[10] Protection levels are[11]:

- **Low Level of Protection (LLOP)** – Security lighting is only required for building entries and exits.[12] The lighting levels vary from 0.2 to four foot-candles based on the application and the lighting zone classification. The light levels referenced are in the horizontal plane three feet above finished grade with the uniformity of 20:1.
- **Medium Level of Protection (MLOP)** – LLOP requirements apply, with the addition of exterior wall lighting that provides 0.2 to 0.5 foot-candles measured in the horizontal plane three feet above finished grade with uniformity of 15:1.
- **High Level of Protection (HLOP)** – LLOP and MLOP requirements apply, with the addition of area lighting 30 feet around the building that provides 0.5 to 1 foot-candle measured in the horizontal plane three feet above finished grade with uniformity of 10:1.

Table 1 compiles the building lighting requirements for an unaided guard's visual assessment by application type, area, and protection level.

Table 1. US DOD Building Lighting Requirements

APPLICATION TYPE	AREA	WIDTH (FEET)	LOCATION TO LIGHT	MINIMUM LIGHT LEVEL (FC)	MAXIMUM UNIFORMITY (MAX: MIN)
PERIMETER	Inner Clear Zone	20-30	Outer edge fence	0	0:1
PERIMETER	Outer Clear Zone	30	Outer edge	0.2-0.4	10:1
PERIMETER	Isolation zone	30	Between fence lines	0.5 -1.0	6:1

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[7] (Defense, 2017)

[8] (Department of Defnese, 2016, p. 1)

[9] (ASHRAE, 2016, p. 145)

[10] (Department of Defnese, 2016, p. 134)

[11] (Department of Defnese, 2016, p. 146)

[12] (Department of Defnese, 2016, p. 146)

APPLICATION TYPE	AREA	WIDTH (FEET)	LOCATION TO LIGHT	MINIMUM LIGHT LEVEL (FC)	MAXIMUM UNIFORMITY (MAX: MIN)
BUILDING	Low Level of Protection (LLOP)	--	Building entry and exits	0.2 - 4, see *UFC 3-530-01 pp. 110-111*	20:1
BUILDING	Medium Level of Protection (MLOP)	--	Same as LLOP plus exterior walls	0.2-0.5	15:1
BUILDING	High Level of Protection (HLOP)	30	Same as MLOP and area around facility	0.5-1.0	10:1
ENTRY CONTROL FACILITY	Pedestrian	--	Entry	2-21	3:1
ENTRY CONTROL FACILITY	Vehicular	50	Pavement and sidewalk	1	4:1
ENTRY CONTROL FACILITY	ID Verification	--	Guard Station	10-100	3:1
ENTRY CONTROL FACILITY	Search Areas	--	Pavement	10-100	3:1

TARGETED SECURITY APPLICATIONS

CLTC identified four security applications typical of US DOD facilities where adaptive, sensor-based lighting systems are recommended for installation:

1. Perimeter fences
2. Building exteriors
3. Open areas/Objects
4. Entry control points

CLTC anticipates that adaptive, sensor-based lighting systems implemented in these security applications will increase the likelihood of guards detecting intruders by “highlighting” occupants as they trigger strategically placed occupancy sensors configured to increase light levels.

Perimeter Fences

Perimeter fences define borders between secured and unsecured spaces. In these applications, adaptive sensor-based security lighting installed on poles adjacent to the perimeter fence are anticipated to 1) ‘startle’ intruders approaching the fence line and 2) draw guards’ attention to these threats.

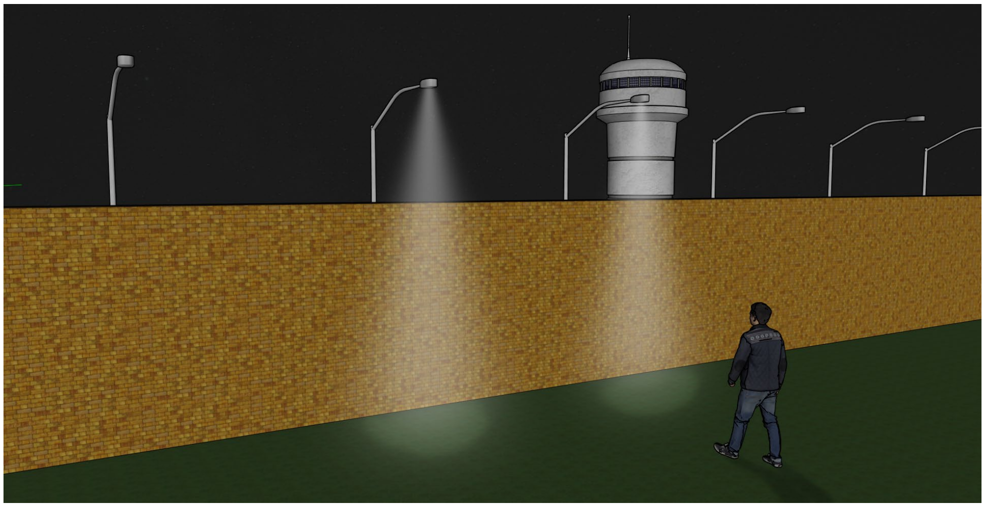

Figure 2. Example of perimeter security application with increased light levels near detected occupant

Building Exteriors

Building exteriors in military applications often require increased security. Equipping the exterior walls and adjacent spaces of these building exteriors with an adaptive, sensor-based lighting system can 1) help guards more quickly detect security threats, and 2) startle potential intruders.

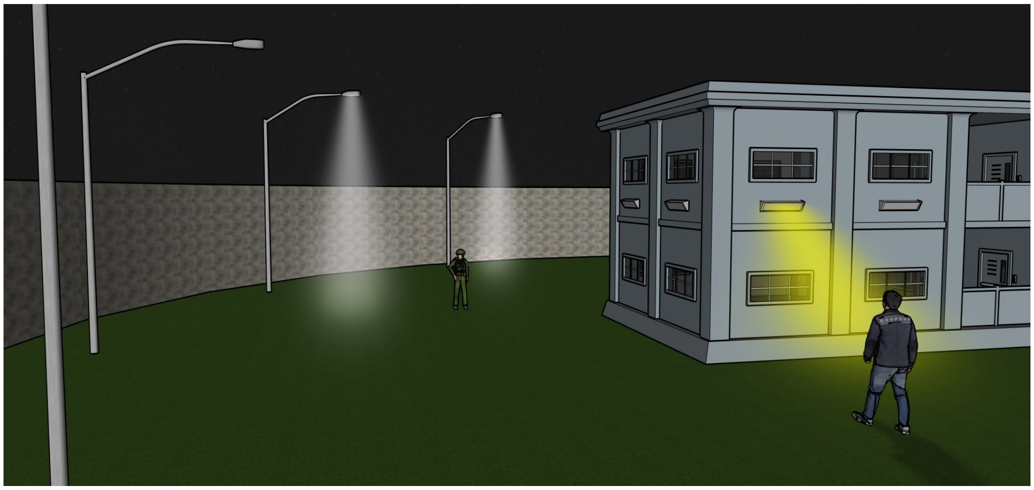

Figure 3. Example of building exterior security application with increased light levels near detected occupants.

Open Areas

Open areas, such as cargo staging yards, storage of objects such as out-of-water equipment or parking lots, often require enhanced security. In these situations, it is recommended that adaptive, sensor-based lighting systems be implemented in pole-mounted applications to help guards locate intruders.

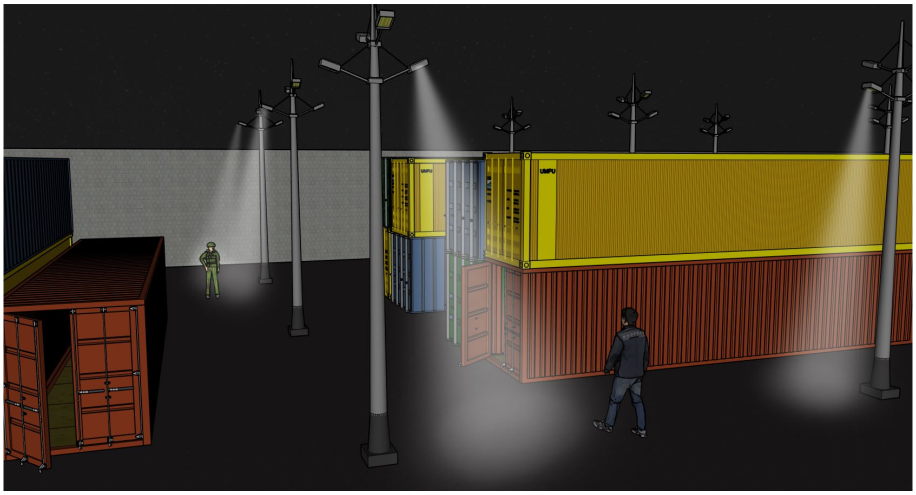

Figure 4. Example of open area security application with increased light levels near detected occupants

Entry Control Points

'Entry control points' have two purposes 1) facilitating authorized entry, and 2) deterring unauthorized intrusion. In these applications, light levels to identify faces is necessary. Adaptive, sensor-based lighting can provide enough light for efficient identification and alert guards to those approaching while also decreasing light levels and the associated load/energy use when less light is needed.

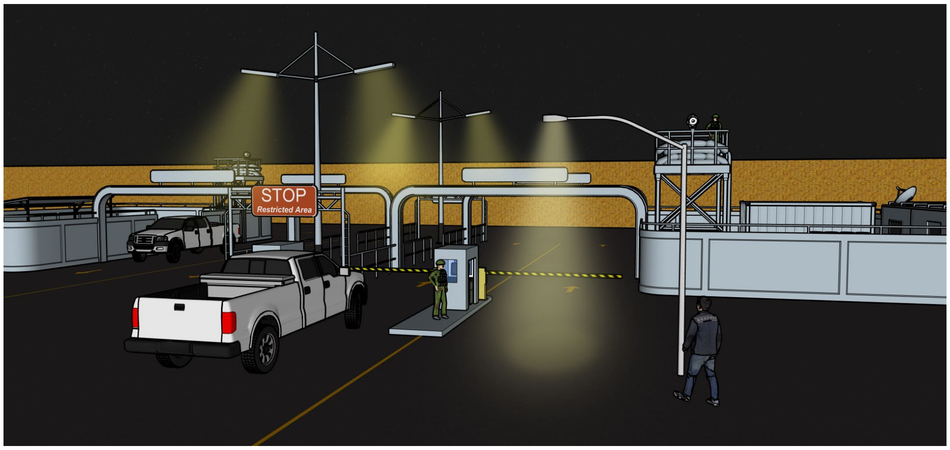

Figure 5. Example of entry control point security application

LIGHT LEVEL CHANGES

CLTC conducted a literature review to understand the detectability and acceptance of light level changes specific to human occupants. Published studies focus on indoor office environments and point to a 20 percent reduction being required for most study participants to detect a light level change. Study[13] conclusions include:

- Fifty percent of the subjects could not detect illuminance reductions less than 15 percent for the paper task and reductions less than 20 percent for the computer task, regardless of the initial illuminance or dimming function.

- Eighty percent of the subjects accepted illuminance reductions less than 30 percent for the paper task and reductions less than 40 percent for the computer task, regardless of initial illuminance or dimming function.

No studies on outdoor light levels were identified during CLTC's literature review. To address this gap in light-level studies focused on outdoor security applications, CLTC included survey questions about light level changes and acceptance by end users.

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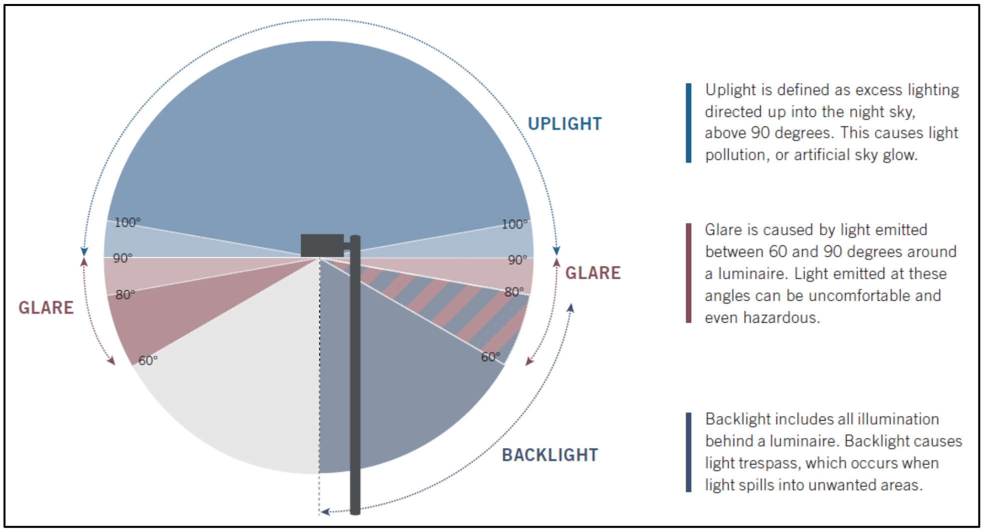
[13] Lighting Research Center. Understanding Light Levels for Load Shedding. 2003.

TECHNOLOGY OVERVIEW

Today's adaptive outdoor lighting systems require 1) dimmable light sources, 2) sensing technologies and 3) a communication platform. This section includes security-centric recommendations for each of these categories.

LIGHT SOURCES

Outdoor security luminaires are recommended to be full cutoff, meaning there is little to no light emitted above 90 degrees. This concept is defined by a score of 'U0' in IES' Backlight-Uplight-Glare (BUG) classification system.[14]



Uplight is defined as excess lighting directed up into the night sky, above 90 degrees. This causes light pollution, or artificial sky glow.

Glare is caused by light emitted between 60 and 90 degrees around a luminaire. Light emitted at these angles can be uncomfortable and even hazardous.

Backlight includes all illumination behind a luminaire. Backlight causes light trespass, which occurs when light spills into unwanted areas.

Figure 6. IES definition of Backlight, Uplight, and Glare (BUG) system for outdoor luminaires

IES recommends a Color Rendering Index (CRI) of 80 or greater in security applications where color recognition is important.[15] Since guards must accurately identify individuals either in person or by closed-circuit television (CCTV) footage, luminaires with lower CRI ratings are not appropriate for security lighting applications. The DOD limits the Correlated Color Temperature (CCT) of outdoor luminaires to 4,100 K or less.

The DesignLights Consortium Qualified Product List compiles products that adhere to their technical requirements. For wall-mounted luminaires, Appendix A provides choices for wall-mounted luminaires that are the most relevant to dynamic security lighting. Appendix B addresses relevant pole-mounted luminaires. Additionally, CLTC recommends that the luminaires chosen have ANSI 7-pin receptacles to ensure there is sufficient wiring infrastructure for all desired sensors to be mounted to the luminaire.

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[14] (Department of Defnese, 2016), (The IES Security Lighting Committee, 2016) , (Luminaire Classification Task Group, 2011)

OCCUPANCY SENSING

Occupancy sensors are typically used to automate the control of electronic loads based on the detected occupancy/vacancy of a space or area. Common loads controlled by occupancy sensors are heating, ventilation, and air conditioning (HVAC) and lighting. In bi-level security lighting applications, occupancy sensors have a dual role of 1) highlighting occupants and 2) providing energy savings. CLTC conducted a literature review to understand US DOD-recognized occupancy sensor technologies and common sensor technologies for lighting, security, and transportation industries. Common sensor technology types explored during this project included dual-technology sensors using PIR and microwave technologies, and LiDAR sensors with solid-state and mechanical components.

US DOD-Recognized Occupancy Sensor Technologies

The US DOD describes outdoor occupancy sensors for intruder detection in *Unified Facilities Criteria: Electronic Security Systems (UFC 4-021-02).* The manual categorizes the sensors as either 1) open terrain sensors or 2) perimeter/fence sensors. [16] Open terrain sensors work best on flat, cleared areas. The category includes infrared, microwave, combination (dual technology), and vibration sensors.[17] Sensors defined by the US DOD as appropriate for perimeter/fence applications are typically used in areas with well-constructed fence lines and have solid posts or gates. They include electro-mechanical systems, taut wire systems, coaxial strain-sensitive cable systems, time domain reflectometry (TDR) systems, and fiber-optic strain sensitive cable systems.[18]

The DOD also recognizes a few types of sensors that do not fall into either of the previous categories. Buried cable sensors can be used where trees and vegetation will not affect a uniform sensor depth. Fiber-optic lines can be used to monitor pipelines and manholes. *UFC 4-021-02* lists radar as its only example of a wide area sensor.[19] The manual discourages video analytics as a method of intruder detection.[20]

Dual-Technology

Combination, or dual-technology, sensors incorporate two detection technologies. The sensor evaluated during this phase of the project combined PIR and microwave. When combined, the dual-technology PIR and microwave sensor can increase the probability of detection or decrease the likelihood of false alarms, depending on whether they are configured in an “or” or “and” design.[21] “And” configured PIR and

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[16] (Department of Defense, 2013, p. 66)

[17] (Department of Defense, 2013, p. 66)

[18] (Department of Defense, 2013, pp. 71-73)

[19] (Department of Defense, 2013, p. 73)

[20] (Department of Defense, 2013, p. 75)

[21] (Department of Defense, 2013, pp. 71, 75)

microwave combination sensors can reduce energy consumption because the microwave sensor, which uses much more energy, can be configured to activate only after the PIR is triggered.[22]

Passive Infrared

Infrared sensing is a common technology used for occupancy detection within the lighting industry and is by far the most used by lighting manufacturers. Passive infrared (PIR) utilizes a pyroelectric sensor to detect infrared light within its field of view (FOV), which is observed as a voltage output. Occupants that enter the FOV create a shift in the perceived infrared light via body temperature, which causes the voltage to change. The sensor translates the change as detection. PIR is a reliable and cost-effective solution, but PIR detection loses reliability during extreme temperature shifts.

Microwave

Microwave detection works by emitting pulsed microwave signals and calculating the time it takes for the signal to bounce and return to the sensor, often referred to as the time of flight. The frequency of these waves creates the baseline environment for the sensor. When an occupant enters the sensor's FOV it creates a Doppler shift, which is a change in frequency of the waves based on the observer, in this case the sensor. The sensor will interpret this change as detection and respond. Microwave motion sensors have been mainly utilized in street lighting applications due to their long detection range in narrow fields of view. Although they are less prominent on the market than PIR sensors, they are promising for long-distance motion sensing.

LiDAR

The operating principle of Light Detection and Ranging (LiDAR) is Time of Flight (ToF), which refers to the time it takes for IR radiation at specific wavelengths to be sensed at its emission location after it is backscattered by surfaces. Using the constant speed of light, the ToF is converted to the distance of the surfaces that reflected the radiation. During vacancy, the LiDAR signals remain constant. Changes in the LiDAR signals indicate moving objects in the covered area.

Particularly utilized in security applications, LiDAR technologies are available with solid-state and mechanical scanning sensing. Solid-state LiDAR technologies do not contain any mechanical components, whereas mechanical scanning LiDAR technologies contain moving components that increase detection coverage area without needing to increase the number of sensors used.

NETWORKED LIGHTING CONTROL SYSTEMS

Networked lighting control systems can control select groups of luminaires or lighting for whole buildings, facilities, or campuses. There are centralized, panel-based wired systems and distributed intelligence systems which are available in both wired and wireless forms. The number of lighting control networks and systems on the market has increased in recent years, with interfaces becoming increasingly user-friendly. These systems can integrate daylight sensing, advanced scheduling, occupancy-based control, demand response and data monitoring. Lighting also can be controlled as part of a computerized building

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[22] (SimpliSafe, 2013)

management system (BMS) or energy management control system (EMCS) that can address HVAC and other systems in addition to lighting.

LABORATORY EVALUATION

CLTC conducted a laboratory evaluation of outdoor occupancy sensors and outdoor networked lighting control systems to understand the benefits and limitations of each approach. Evaluation results informed a prototype system for the field research phase of the project.

OUTDOOR OCCUPANCY SENSORS

CLTC tested a cross-section of outdoor occupancy sensing technologies (Table 2). The dual technology sensor selected for testing was approximately one-eighth of the cost of the second most affordable sensor that was tested. Test Sensor 2 is a solid-state LiDAR sensor. This model offers a wider field of view (90 degrees) compared to other models using this technology. Two mechanical LiDAR sensors were tested. Test Sensor 3 has a 190-degree field of detection. Test Sensor 4, from the same brand as Test Sensor 3, offered similar features to those of the larger unit, but with a 95-degree field of view, more compact housing, and lower cost.

Table 2. Reference names for sensors selected for testing.

Sensor ID	Technology
Test sensor 1	Passive Infrared plus Microwave
Test sensor 2	Solid State LiDAR
Test sensor 3	Mechanical LiDAR
Test sensor 4	Mechanical LiDAR

Figure 7. Dual Technology Sensor – Test Sensor 1 (left), Solid State LiDAR Sensor – Test Sensor 2 (middle left), mechanical LIDAR sensor – Test Sensor 3 (middle right), mechanical LIDAR sensor – Test Sensor 4 (right)

Methodology

To determine the detection range of each sensor, CLTC conducted a test to determine the perimeter of the sensor's coverage pattern in all directions. The first step of the test procedure was to define the test grid. A 45-meter radius was established to account for the possibility that detection could exceed manufacturer specifications. The test area was defined by grid squares of one-meter-by-one-meter. The sensors were mounted at 1.22-meters (or four-feet) from the ground, which falls within the manufacturer mounting height specifications for all the sensors.

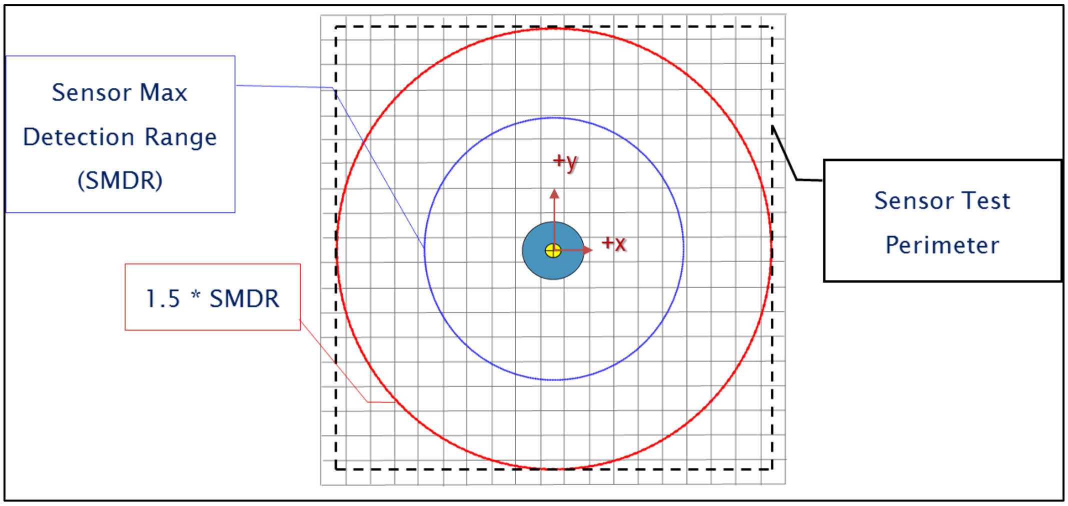

Figure 8. Test grid showing the sensor's maximum detection distance (SMDR) claimed by the manufacturer (blue circle) and the maximum distance used for testing (red circle)

To characterize the spatial sensitivity of motion-sensing technologies, the moving object needs to approach the sensor along different directional paths. To accomplish this, the test grid was rotated, and the sensor evaluated for motion along multiple paths in several discrete rotations. Two approaches address the issue of large testing area requirements and the rotation of the grid, as described below.

1) **Rotate the sensor instead of the test grid:** Rotating the whole test grid for multiple angles of interest is difficult and time-consuming. Rotating the sensor is a less labor-intensive approach to achieving the same goal.

2) **Using half (or a quarter) of the total test grid:** The sensor rotation can address all directional paths using half of the complete test grid, consisting of all unit cells in the positive x quadrants. To evaluate the motion sensor spatial sensitivity, the movement of the moving object starts from the bottom of the first column, towards the sensor and then away from it in the same direction until the object exits the test grid. This process is repeated for every column to cover the mapped test grid (Figure 9, left). The testing area can be further reduced to a quarter of the total grid, which will require the moving object to return to the movement origin after it reaches the top of the quadrant (Figure 9, right). Then, the sensor is rotated by a discrete angle and the object-movement process is repeated until all moving directions are covered (Figure 10).

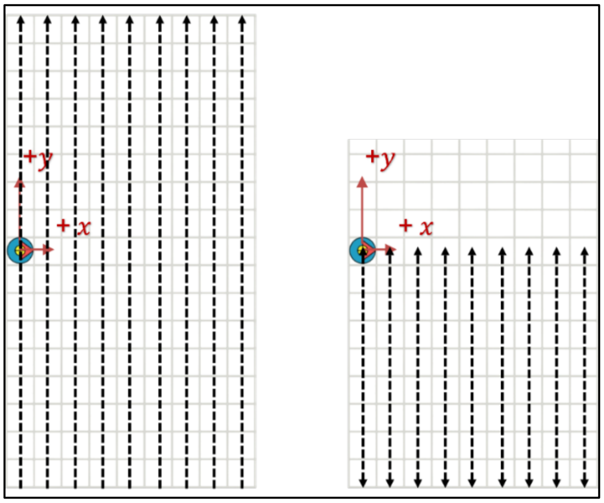

Figure 9. Directional paths of moving object relative to rotating sensor, considering unidirectional movement that requires half of the complete test area (left) and bidirectional movement, which requires a quarter of the complete test area (right)

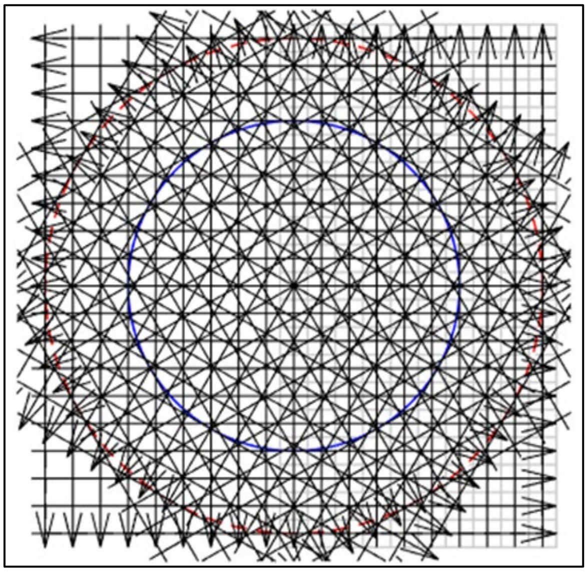

Figure 10. Compilation of all directional paths of the moving object relative to the sensor, for complete characterization of the motion-sensing area

Figure 10 shows the pattern that is created through rotating the object's path at 30-degree increments over 360 degrees. This pattern indicates all directional paths that the moving object should take relative to the sensor. This method allows for a full characterization of the sensor's detection area. For the perimeter-coverage characterization, the test of interest for this study, only the maximum detection distance was recorded.

Results

In general, both LiDAR sensors performed more consistently than the dual technology sensor in terms of coverage pattern and detection reliability. Furthermore, the mechanically scanning LiDAR sensors outperformed the solid-state LiDAR in terms of reliability by more consistently detecting occupants over time and under various conditions. For these reasons, Test Sensor 3 and Test Sensor 4 were selected for use in the Field Research systems. Summary results for each tested sensor are provided in the following sections.

Dual Technology (Test Sensor 1)

CLTC evaluated the perimeter coverage of the Passive Infrared plus Microwave Sensor. Test Sensor 1 results offered several sensitivity adjustments options, although it had fewer features and adjustment options than the other sensors tested. The data shows that this sensor's detection perimeter is erratic. The sensor also missed detection seven of 48 tests, for a failure rate of 15 percent.

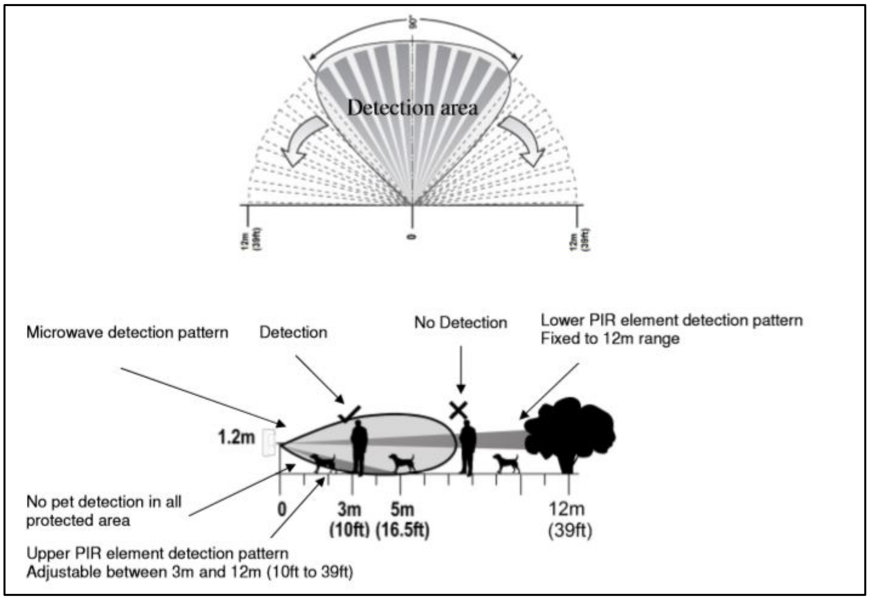

Figure 11. Manufacturer diagram for Test Sensor 1

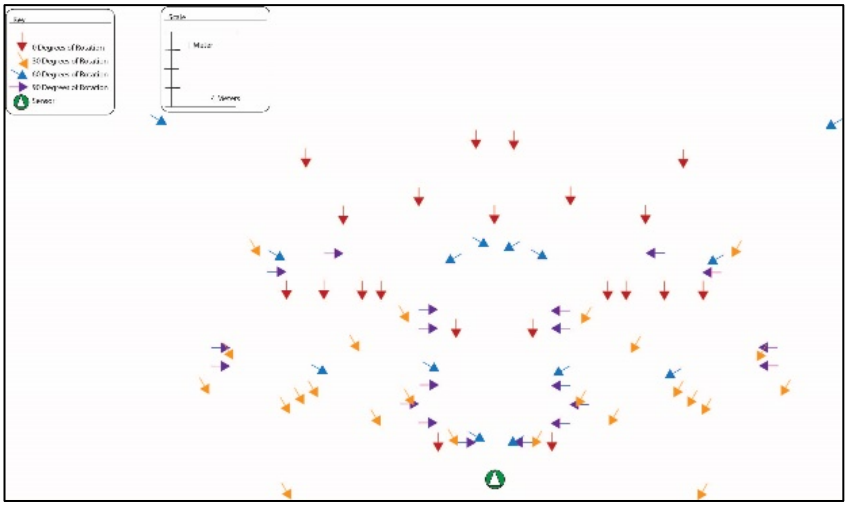

Figure 12. Tested sensor perimeter diagram for Test Sensor 1

Solid State LiDAR Sensor (Test Sensor 2)

Test Sensor 2 connects to a computer and can be monitored through a user interface. Because of the design of the interface, however, it was difficult to identify detection events. The data shows that this sensor's detection perimeter is relatively like the manufacturer's diagram. The sensor missed detection in seven of 48 tests, for a failure rate of 15 percent.

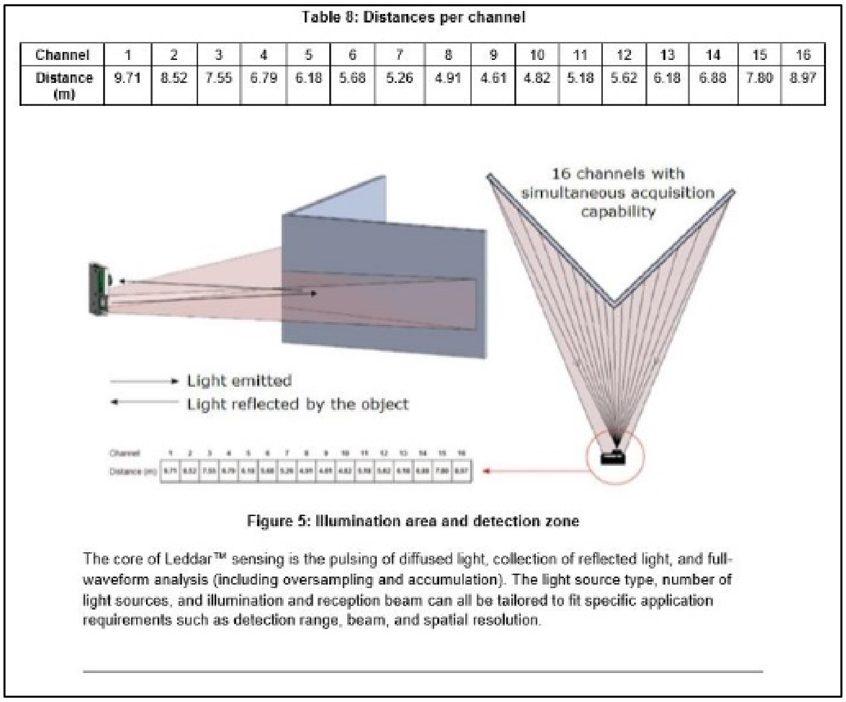

Table 8: Distances per channel

Channel	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Distance (m)	9.71	8.52	7.55	6.79	6.18	5.68	5.26	4.91	4.61	4.82	5.18	5.62	6.18	6.88	7.80	8.97

Figure 5: Illumination area and detection zone

The core of Leddar™ sensing is the pulsing of diffused light, collection of reflected light, and full-waveform analysis (including oversampling and accumulation). The light source type, number of light sources, and illumination and reception beam can all be tailored to fit specific application requirements such as detection range, beam, and spatial resolution.

Figure 13. Manufacturer diagram for Test Sensor 2

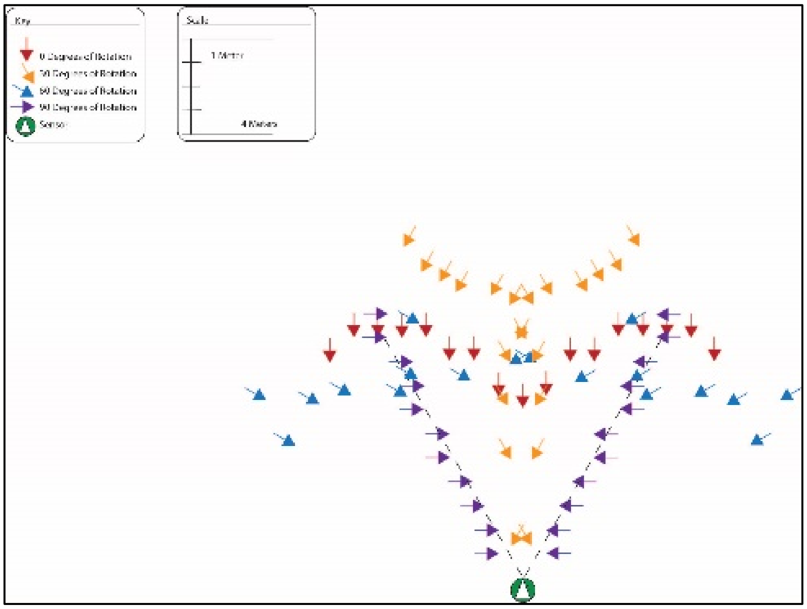

Figure 14. Tested sensor perimeter diagram for Test Sensor 2

Mechanical LiDAR Sensor (Test Sensor 3)

Test Sensor 4 has sensitivity, range, and output options, and this sensor is able to integrate well with other components. The user interface of Test Sensor 4 is easy to read. The data shows that this sensor's detection perimeter is regular and like the manufacturer's diagram. The sensor did not miss any detections.

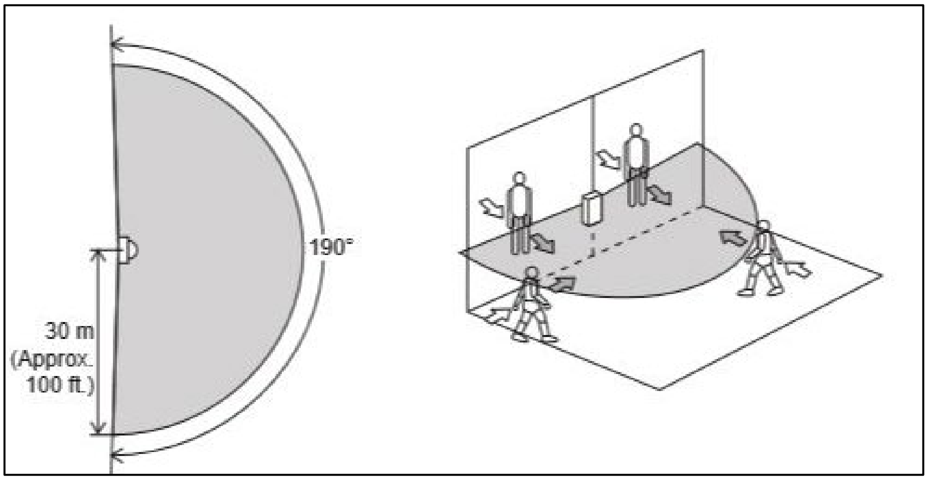

Figure 15. Manufacturer diagram for Test Sensor 3

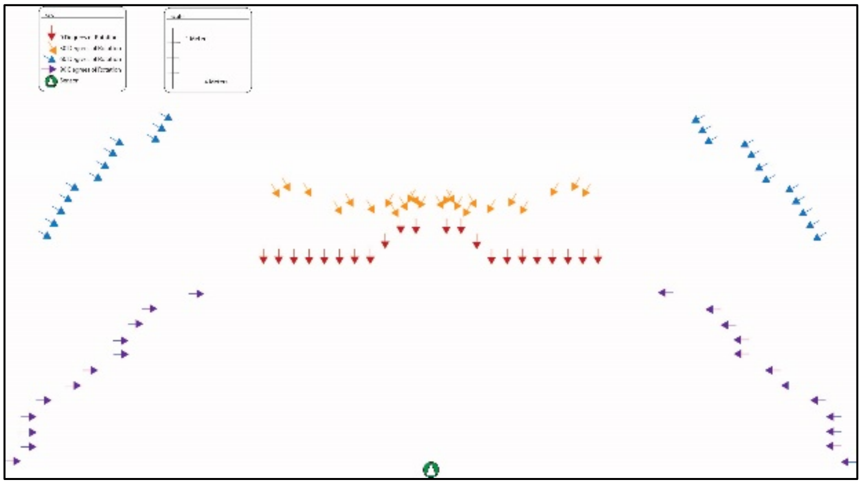

Figure 16. Tested sensor perimeter diagram for Test Sensor

Mechanical LiDAR Sensor (Test Sensor 4)

Test Sensor 4 has sensitivity, range, and output options, and this sensor is able to integrate with other components. The user interface for Test Sensor 4 is easy to read, has a smaller form factor than other similar sensors, and was close to half of the cost at the time of this study. The data shows that this sensor's detection perimeter is regular and like the manufacturer's diagram. The sensor did not miss any detections.

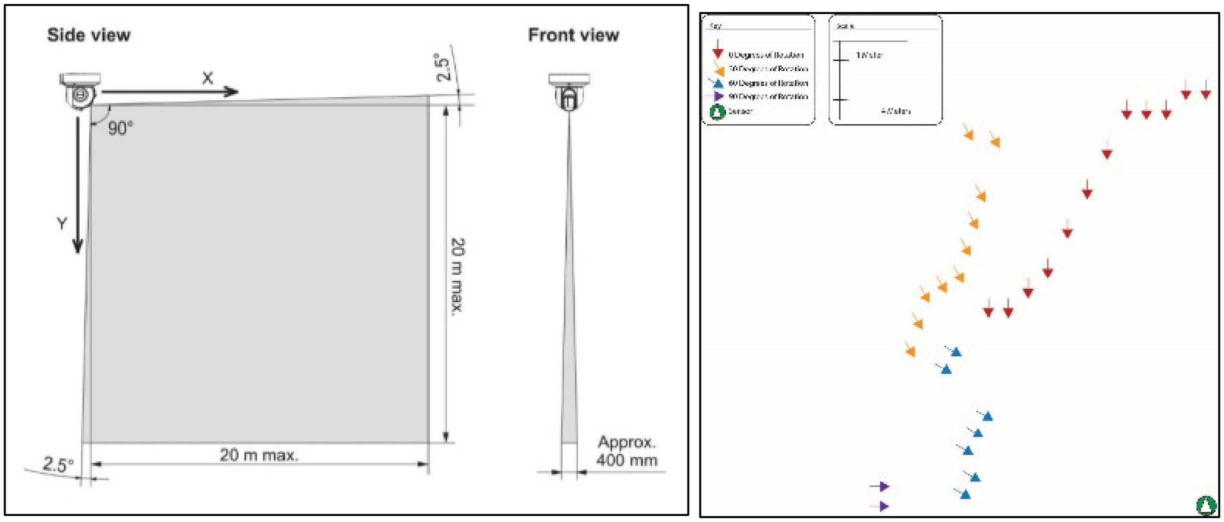

Figure 17. Manufacturer diagram for Test Sensor 4 (left) and tested sensor perimeter diagram (right)

OUTDOOR NETWORKED LIGHTING CONTROL SYSTEMS

Outdoor networked lighting control systems are necessary to implement the *Adaptive, Sensor-Based Lighting* strategy. CLTC identified the necessary features to make the strategy function, procured samples of systems claiming to meet the selection criteria and tested the systems in the laboratory. Results from this testing informed the field research activities.

Selection Criteria

CLTC defined the system operation as follows:

- On at dusk (low mode)
- High mode triggered by external occupancy sensor input (motion) for site-specified amount of time.
- Off at dawn

To achieve this, the system requires the following features:

- Bi-level dimming via 0 – 10 V wires
- External sensor input
- Photocell or scheduling capabilities (i.e., 7-pin)
- Standalone operation mode (cyber security requirement)

Market Assessment

CLTC conducted a market assessment of commercially available outdoor networked control systems. Nine systems were compiled and compared to the selection criteria (Table 3).

Table 3. Outdoor Networked Control Systems

Manufacturer ID	External Sensor Input	Photocell/ Scheduling	0-10 V/ Bi-Level Output	Node Pin Type	Standalone vs. Networked
Manufacturer 1	No	Photocell	Yes	7-pin	-
Manufacturer 2	No	Scheduling	Yes	7-pin	-
Manufacturer 3	No	Scheduling	Yes	7-pin	-
Manufacturer 4	No	Scheduling	Yes	5-pin	-
Manufacturer 5	Yes	Photocell	Yes	7-pin	Both
Manufacturer 6	Yes	Photocell	Yes	7-pin	Both

Manufacturer ID	External Sensor Input	Photocell/ Scheduling	0-10 V/ Bi-Level Output	Node Pin Type	Standalone vs. Networked
Manufacturer 7	Yes	Scheduling	Yes	7-pin	Networked Only
Manufacturer 8	Yes	Scheduling	Yes	7-pin	No Response
Manufacturer 9	Yes	Photocell	Yes	7-pin	Both

Results

Three of the nine systems compiled during the market assessment met the selection criteria for testing (Table 4). CLTC procured systems from Manufacturer 5, Manufacturer 6, and Manufacturer 9. To evaluate the systems, each product was installed, commissioned, and programmed with dimmable LED lights at the laboratory. Summary results from the testing are provided in Table 5.

Table 4. Outdoor networked control systems that met the selection criteria

Manufacturer ID	External Sensor Input	Photocell/ Scheduling	0-10 V/ Bi-Level Output	Node Pin Type	Standalone vs. Networked
Manufacturer 5	Yes	Photocell	Yes	7-pin	Both
Manufacturer 6	Yes	Photocell	Yes	7-pin	Both
Manufacturer 9	Yes	Photocell	Yes	7-pin	Both

Table 5. Results from Installation and Commissioning of Control Systems in Laboratory

Manufacturer	Network Requirements	Ease of Programming	Ease of Commissioning	Manufacturer Documentation	Technical Support
Manufacturer 5	GPS	N/A	Very Bad	Bad	Bad
Manufacturer 6	Standalone or Gateway	Good	Good	Bad	Great
Manufacturer 9	Gateway	Great	Neutral	Bad	Neutral

Scale: Very Bad (1), Bad (2), Neutral (3), Good (4), Great (5)

Manufacturer 5 nodes were the most complex to commission and required manufacturer activation after installation. Additionally, the system required a radio frequency (RF) sticker to be placed on the 7-pin receptacle on the fixture so that each node corresponds to one fixture. This commissioning approach meant that nodes could not be interchanged for troubleshooting or replacement. Each node functioned independent of the others and required no gateway or internet access. However, GPS was required for the commissioning. Due to the complexity of the commissioning, nodes were not programmed in the laboratory.

Manufacturer 6 provided responsive technical support to troubleshoot issues with initial system components and through the project durations. To commission the system, devices required additional communication steps. After commissioning process and user interface was understood, the control system offers a large range of options for customization.

Manufacturer 9 controls were easy to program but the technical support lacked accessibility and breadth. Additionally, the system did not provide the manufacturer-claimed functionality. Nodes required a gateway connected to the internet via Wi-Fi or cellular. This contradicted the system specifications given to CLTC staff by the manufacturer representative.

Based on these results, CLTC selected the networked version of Manufacturer 6 for the field research installation at the proof-of-concept demonstration site; and CLTC selected standalone version of Manufacturer 6 with no networking at the military demonstration to fulfill cybersecurity requirements of the site.

FIELD RESEARCH

The field research was conducted in two phases: 1) proof-of-concept demonstration and 2) two security application demonstrations. An overview of the site, installation, commissioning, energy savings and end user feedback is provided for each demonstration. Site selection and technology installation activities were coordinated and led by Hawai'i Natural Energy Institute (HNEI).

PROOF-OF-CONCEPT DEMONSTRATION

HNEI identified the Zero Net Energy Research Platform Facility (also referred to as FROGs) at the University of Hawaii at Mānoa's campus as an appropriate demonstration site for the proof-of-concept evaluation. The FROGs consist of two buildings, referred to as FROG Building 1 and FROG Building 2. The proof-of-concept system installed at FROG buildings was informed by the outcomes from the laboratory evaluation.

Site Plan

The project team analyzed the UHM FROGs building site to determine the best placement of sensors for total coverage using Test Sensor 3 and Test Sensor 4.

Figure 18. FROG buildings at University of Hawaii, Mānoa

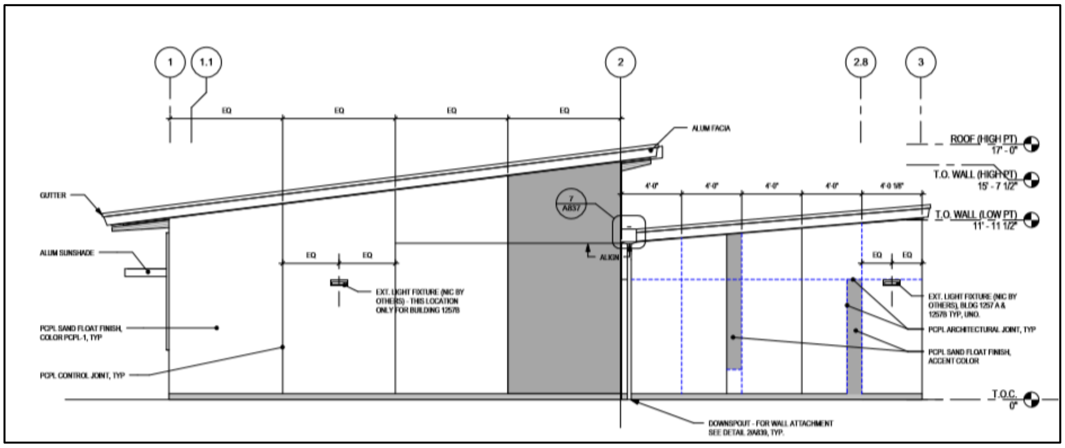

Figure 19. Elevation view of FROG buildings at University of Hawaii, Mānoa

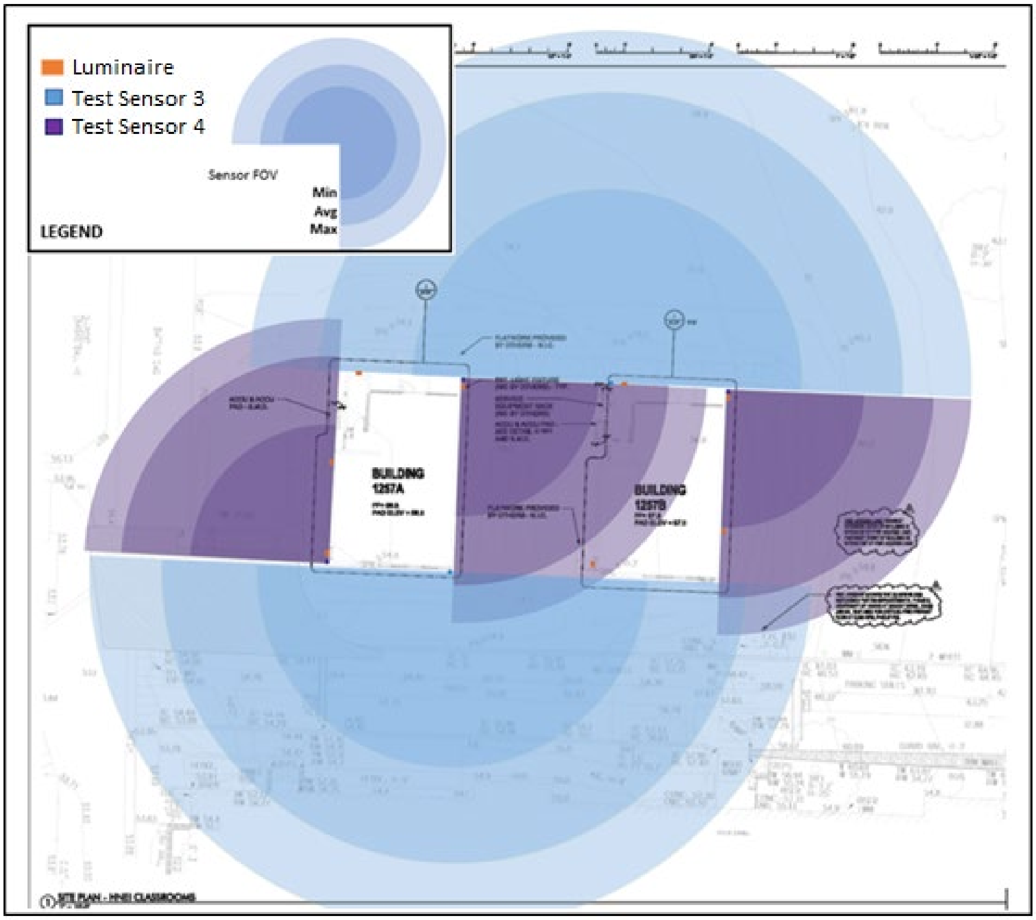

Figure 20. Sensor coverage layout at FROG. buildings

Installation & Commissioning

UHM facility staff installed dimmable LED wallpacks, occupancy sensors identified during the laboratory evaluation, and networked control system based on an installation guidance from the project team (Appendix E). The wallpack and its dimming curve are provided in Figure 21.

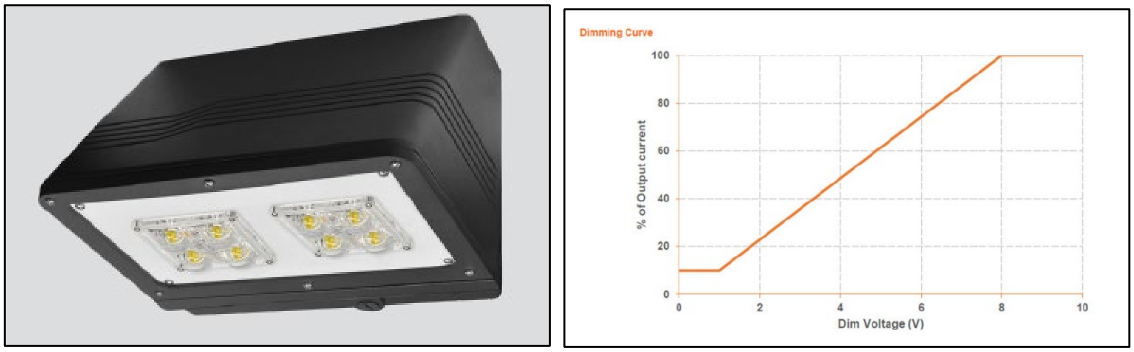

Figure 21. Dimmable LED wallpack (left) and dimming curve for luminaires installed on UHM FROG buildings

CLTC programmed the control system and sensors to operate per the following parameters:

- High mode: 10 V, 100% light output
- Low mode: 3 V, approximately 35% light output
- Ramp rate: Immediate/1 second
- Time out: 5 minutes

Energy Savings

CLTC installed metering and verification (M&V) equipment to monitor the load over time of both the pre-existing and retrofit lighting systems at the FROG buildings. The M&V equipment was installed September 18, 2019, to collect baseline energy use data. The retrofit system was installed October 1, 2019 but was not fully commissioned until December 19, 2019. Data was collected for the fully commissioned retrofit system through July 30, 2020. This resulted in 13 days of the LED-only with the manufacturer supplied PIR occupancy sensor and photocell; 79 days of data for the LED-only lighting system with photocell; and 223 days of data for the retrofit lighting system, or approximately seven months. Based on this collected data, data reduction analysis was conducted to determine average daily energy use and annual energy use for lighting systems after normalizing the load data for length-of-day.

M&V Equipment

Revenue grade metering equipment for 120 V electrical service was selected to monitor power and energy use of the lighting circuits at the outdoor lighting applications. The accuracy of the equipment meets the requirements of the ANSI C12.1 standard when used with Continental Control System current transformers rated for IEEE C57.13 class 0.6 accuracy.

Table 6 lists the specified equipment. Specifications with wiring diagrams are provided in Appendix C. The equipment was configured to collect lighting power and energy use data in one-minute intervals.

Table 6. Energy monitoring equipment used at UHM FROG buildings

Monitoring Equipment Type	Model
Current Transformers	CCS ACT-0750-20
Data Logger	Ezesystem ezeio

Results

Data collected at two FROG buildings for the following scenarios was analyzed to determine the energy savings achieved by the fully commissioned retrofit system:

- Baseline: LED wallpacks with manufacturer supplied PIR/Photocell sensor
- Pre-commissioned: LED wallpacks with networked controls and photocell
- Post-retrofit: LED wallpacks with network controls, photocell, and LiDAR occupancy sensor

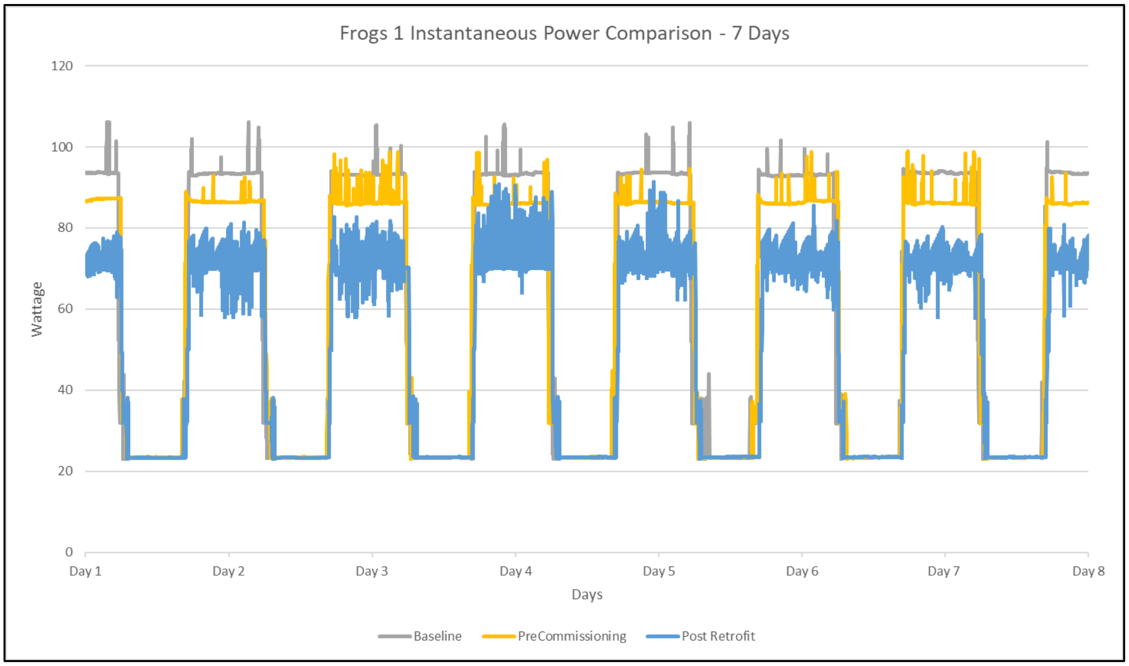

Figure 22. Instantaneous Power for FROG Building 1 – Seven Day Comparison

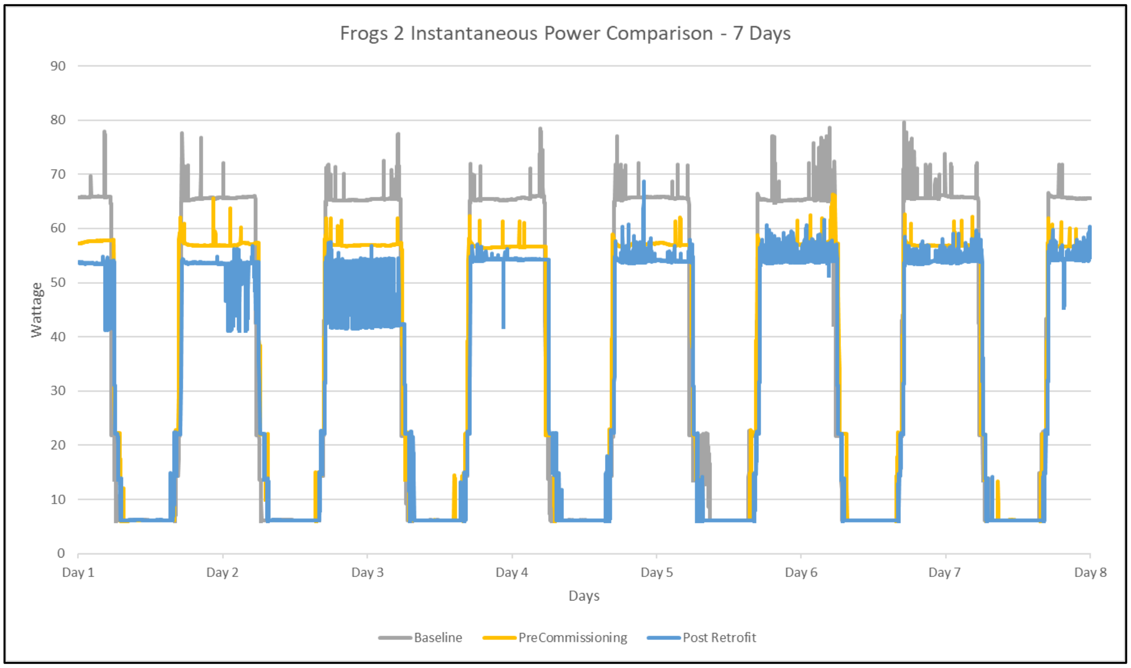

Figure 23. Instantaneous Power for FROG Building 2 – Seven Day Comparison

Historic data associated with the daily sunrise and sunset times for the area over the monitoring period was gathered through publicly available weather monitoring sites.[23] Each associated nightly length and recorded nightly energy use was then scaled and averaged over the recorded period for each phase. Then using the average of those scaled values an approximate yearly energy use curve was created to extrapolate the estimated annual energy savings during each stage. Graphs of annual extrapolated savings for baseline, precommisioned and fully commissioned systems at both demonstration sites is provided in Figure 24 and Figure 25.

Based on the normalized data collected at FROG Buildings 1 and 2, annual energy savings achieved by adding the LiDAR occupancy sensor to an LED wallpack with a photocell is estimated at approximately 16.0 to 16.8 percent. This is an additional 4.3 to 8.7 percent energy savings as compared to the LED wallpack paired with only a photocell at the same installation. Complete energy and savings information for both demonstrations are provided in Table 7.

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[23] https://www.timeanddate.com/ and https://sunrise-sunset.org/

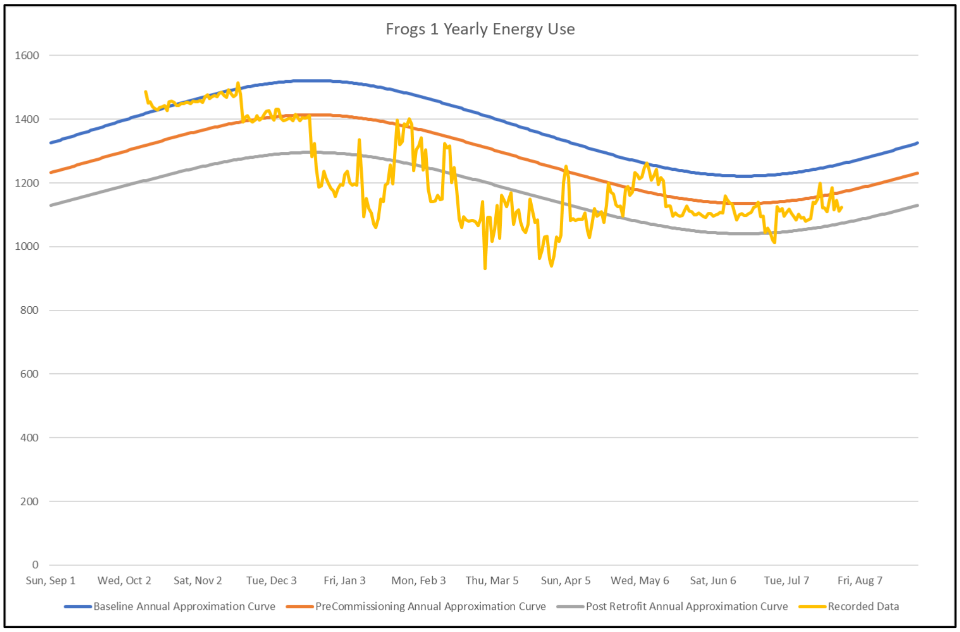


Figure 24. Annual Energy Use Extrapolation Based on Varying Length of Day – FROG Building 1

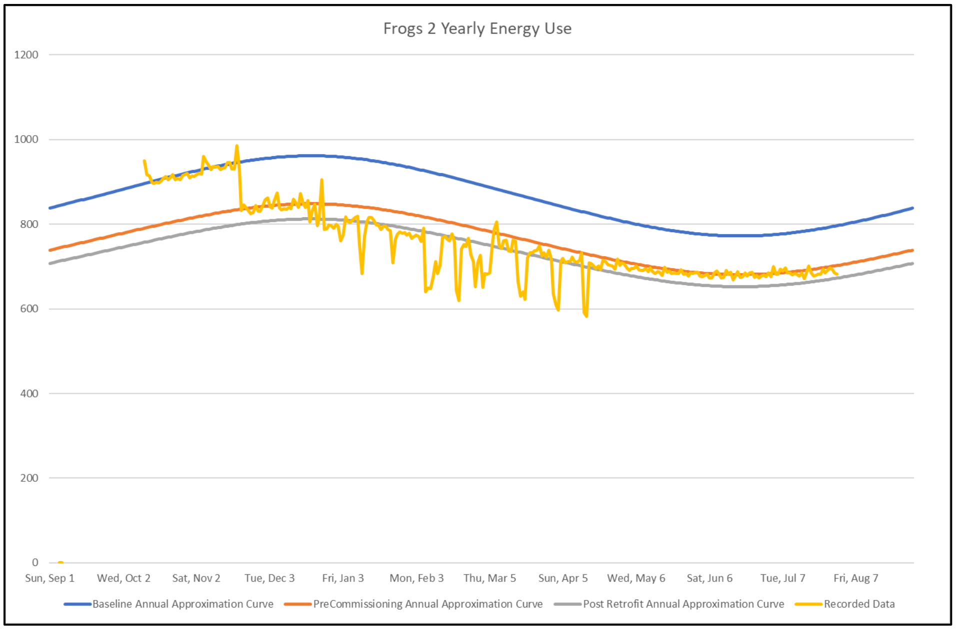


Figure 25. Annual Energy Use Extrapolation Based on Varying Length of Day – FROG Building 2

Table 7. Energy Use Savings for FROG Buildings 1 and 2

	FROG 1			FROG 2		
Scenario	*LED + PIR/Photocell Sensor*	*LED + Photocell*	*LED + Photocell + LiDAR*	*LED + PIR/Photocell Sensor*	*LED + Photocell*	*LED + Photocell + LiDAR*
Number of Days Monitored	*13*	*79*	*223*	*13*	*79*	*223*
Total Energy Use for Monitored Period (kWh)	61.3	40.8	255.7	37.8	23.6	161.4
Length-of-Day Adjusted Average Daily Energy Use (kWh)	1.37	1.28	1.17	0.87	0.77	0.73
Length-of-Day-Adjusted Annual Energy Use (kWh)	501.4	466.0	427.0	316.9	279.5	267.7
Calculated Annual Energy Savings vs. LED Wallpack (%)	**-**	**7.3%**	**16.0%**	**-**	**12.5%**	**16.8%**

End User Feedback

CLTC completed a survey of the University of Hawaii Mānoa teaching staff that utilize the FROG buildings. Of the five staff members who participated, three reported entering or exiting the FROG buildings when the outdoor electric lights were on (i.e., before sunrise, after sunset). These three staff members cited their impression of the updated outdoor lighting at the FROG buildings as being positive (one staff) or neutral (two staff). Only one staff member was aware of the lighting system changes that took place in December 2019. No one noticed the light level changes.

CLTC asked the five UHM staff their general opinion about increased light levels and improved safety. All five responded that they believed the increase in light level improved safety of the outdoor area. Additionally, CLTC asked if increased light level reduce criminal activity and all five staff members responded yes.

SECURITY APPLICATION DEMONSTRATION

HNEI identified and coordinated the demonstration of the *Adaptive Sensor-Based Lighting System* with the Naval Facilities Engineering Systems Command Hawaii (NAVFAC). Outcomes from the market assessment, laboratory evaluation, and proof-of-concept design phase were used to inform the system installed at the two NAVFAC secure military applications. This installation was used to evaluate user response and energy benefits of the strategy. The adaptive security lighting was installed at two NAVFAC locations 1) the MP3 building and 2) South Guard Shack.

Site Plan

Based on entry points and typical occupancy patterns, the project team analyzed the MP3 and South Guard Shack sites to determine the best placement of sensors for total coverage using Test Sensor 3 and Test Sensor 4.

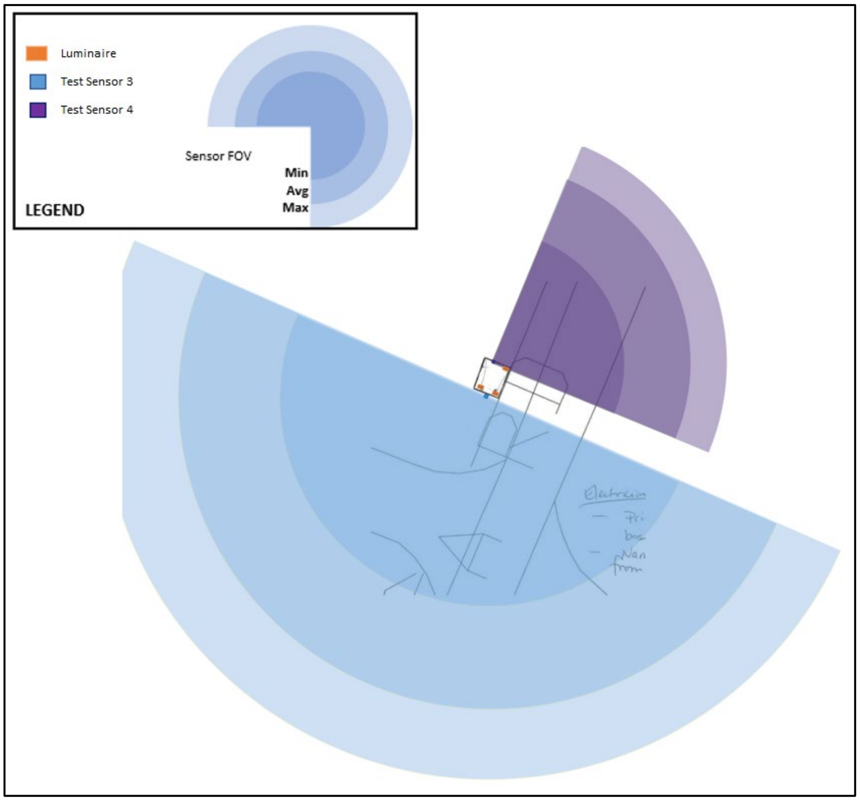


Figure 26. Sensor coverage layout at South Guard Shack

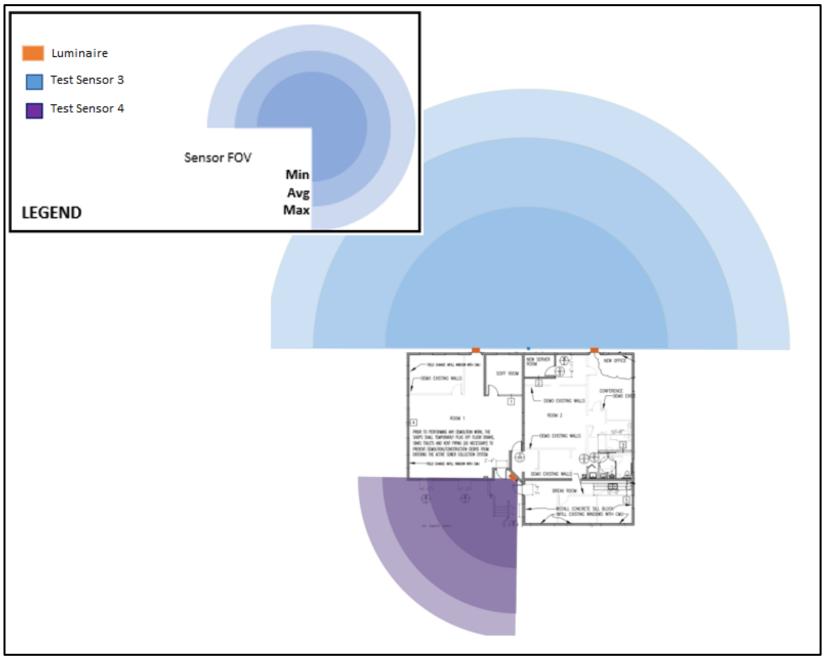


Figure 27. Sensor coverage layout at MP3 building

Installation & Commissioning

A licensed electrical contractor installed dimmable LED wallpacks, sensors (Test Sensors 3 and 4) and control nodes based on installation guidance provided by the project team (Appendix F). Note, the control nodes were configured to be standalone to meet cybersecurity requirements of the military sites.

MP3 Building

CLTC programmed the control system and sensors at MP3 to operate per the following parameters:

- High mode: 10 V, 100% light output
- Low mode: 3 V, approximately 35% light output
- Ramp rate: Immediate/1 second
- Time out: 15 minutes

The wallpack installed at MP3, including the manufacturer-provided dimming curve for the wallpack is shown in Figure 28.

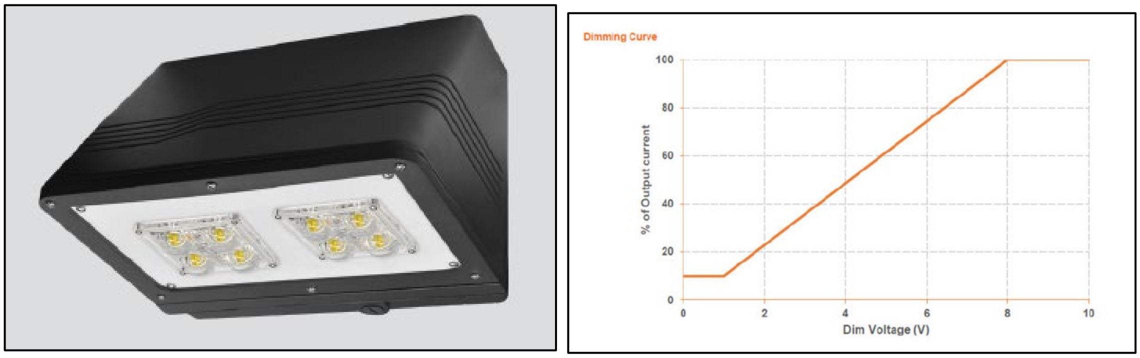


Figure 28. Dimmable LED wallpack and dimming curve for LED fixtures installed on MP3 buildings.

South Guard Shack

CLTC programmed the control system and sensors at the South Guard Shack to operate per the following parameters:

- High mode: 10 V, 100% light output
- Low mode: 3 V, approximately 30% light output
- Ramp rate: Immediate/1 second
- Time out: 15 minutes

The floodlights installed at the South Guard Shack are shown in Figure 29 along with the manufacturer-provided dimming curve.

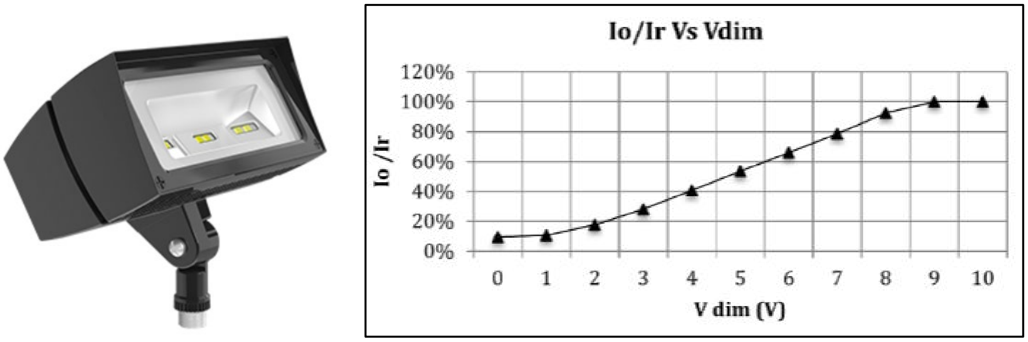


Figure 29. Dimmable LED floodlights and Manufacturer-provided dimming curve for LED fixtures installed on South Guard Shack

Energy Savings

The project team installed metering and verification (M&V) equipment to monitor the load over time of both the pre-existing and retrofit lighting systems at the MP3 and South Guard Shack buildings. The M&V equipment was installed September 18, 2019, to collect baseline energy use data. The retrofit system was installed between December 16, 2019, and December 19, 2019. The equipment at MP3 was commissioned during this period but the South Guard Shack was not fully commissioned until January 23, 2021, due to the need of additional wiring. Data was collected for both the fully commissioned retrofit systems through July 30, 2020. This resulted in 90 days of the pre-retrofit systems, or approximately three months. With 224 days of data for the retrofit lighting system for MP3 and 190 days of data for the retrofit lighting system for the Guard Shack, or approximately seven and six months, respectively. Based on this collected data, data reduction analysis was conducted to determine average daily energy use and annual energy use for lighting systems after normalizing the load data for length-of-day.

M&V Equipment

Revenue grade metering equipment for 120 V electrical service was selected to monitor power and energy use of the lighting circuits at the outdoor lighting applications. The accuracy of the equipment meets the requirements of the ANSI C12.1 standard when used with Continental Control System current transformers rated for IEEE C57.13 class 0.6 accuracy.

Table 8 lists the specified equipment. Specifications with wiring diagrams are provided in Appendix D. The equipment, shown in Table 8, was configured to collect lighting power and energy use data in one-minute intervals.

Table 8. Energy monitoring equipment for security application demonstration

Monitoring Equipment Type	Model
AC Power Measurement Device	WattNode RWNB-3Y-208-P
Current Transformers	CCS ACT-075-020
Data Logger	HOBO UX120-017M

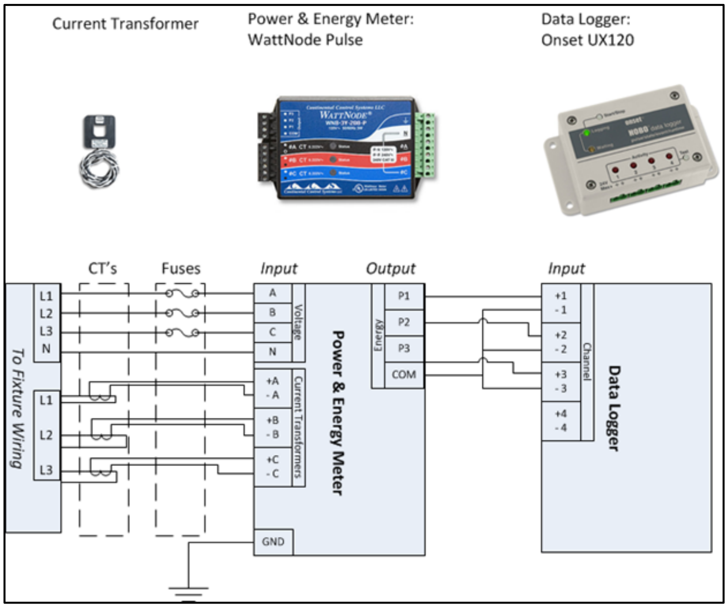


Figure 30. Photographs (Top) of technologies used for energy and power measurements; Diagram (bottom) showing the wiring connections for the system.

Results

Data collected at the MP3 and South Guard Shack was analyzed to determine the energy savings achieved by the fully commissioned retrofit system. Two periods were analyzed:

- Baseline: September 18, 2019, to December 16, 2019, with existing LED luminaires operating based on photocell
- Post-retrofit: December 20, 2019, to July 30, 2020, with new LED luminaires, photocell, and LiDAR occupancy sensors

Seven-day load profile comparisons of the baseline lighting systems versus the post-retrofit lighting systems are provided in Figure 31 and Figure 32. Like the FROG buildings, an approximate energy use curve was created for each building utilizing historic sunrise and sunset times during the recorded period to extrapolate the estimated annual energy savings of the retrofit system.

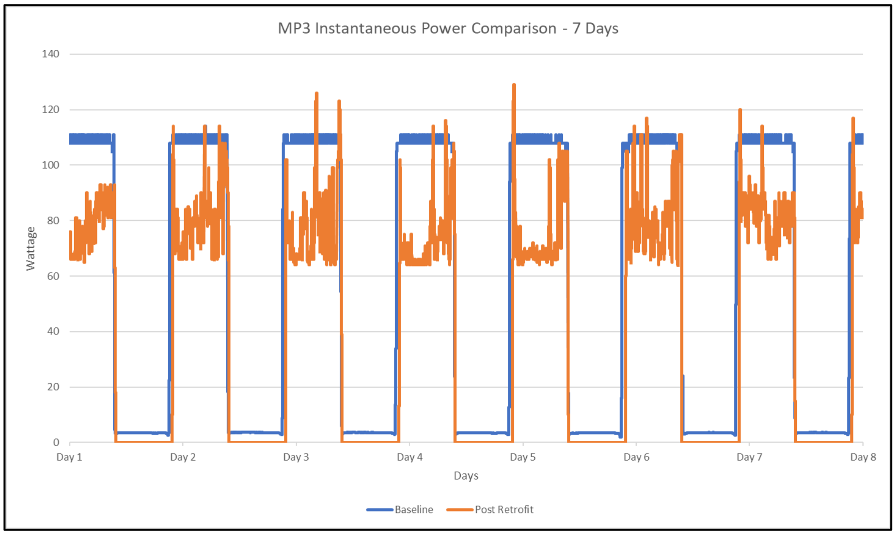


Figure 31. Instantaneous Power for MP3 Building – Seven Day Comparison

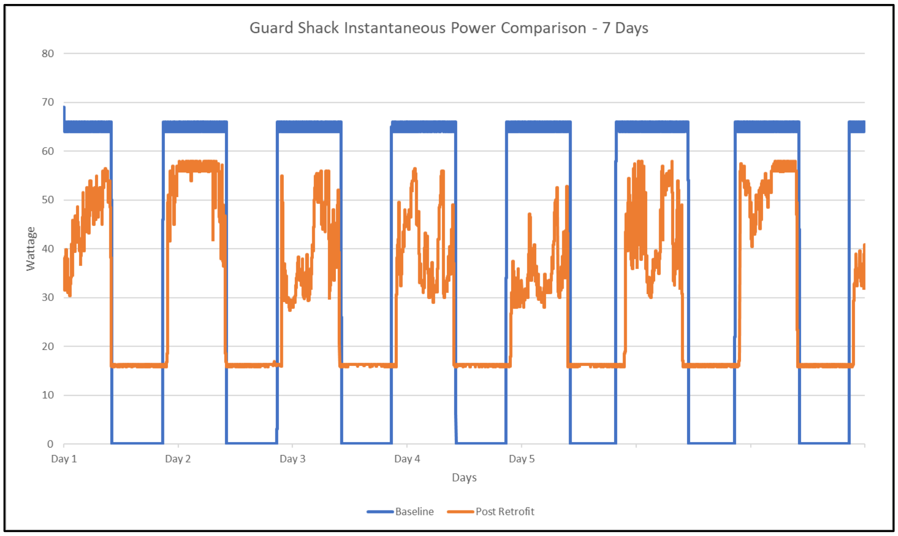


Figure 32. Instantaneous Power for South Guard Shack – Seven Day Comparison

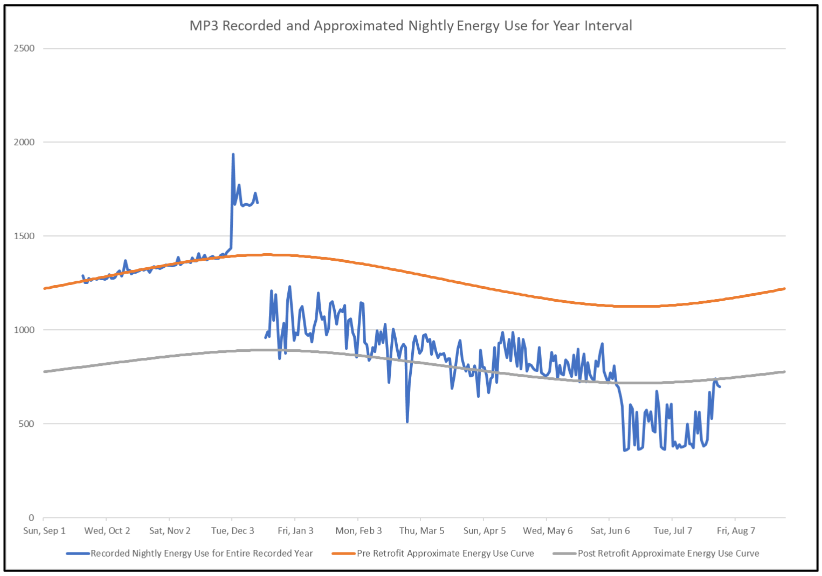


Figure 33. Annual Energy Use Extrapolation Based on Varying Length of Day – MP3 Building

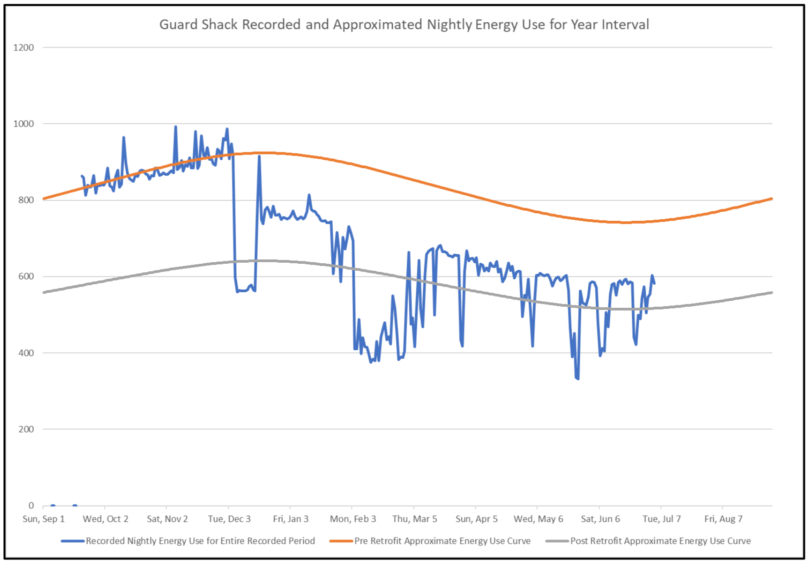


Figure 34. Annual Energy Use Extrapolation Based on Varying Length of Day – South Guard Shack

Based on the normalized data collected at MP3 Building and the South Guard Shack, annual energy savings achieved by adding the standalone LiDAR occupancy sensor to an LED wallpack in military applications is estimated to range between 36.1 to 44.3 percent.

Table 9. Energy Use Savings for Military Applications (MP3 Building and South Guard Shack)

	MP3 Building		**South Guard Shack**	
Scenario	*Existing LED + Photocell Only*	*New LED + Photocell + LiDAR*	*Existing LED Only*	*New LED + Photocell + LiDAR*
Number of Days Monitored	*90*	*224*	*90*	*224*
Total Energy Use for Monitored Period (kWh)	119.3	180.3	66.1	90.8
Length-of-Day Adjusted Average Daily Energy Use (kWh)	1.26	0.81	0.83	0.58
Length-of-Day-Adjusted Annual Energy Use (kWh)	461.6	294.3	304.4	211.3
Calculated Annual Energy Savings vs. LED Wallpack (%)	-	**44.3%**	-	**36.1%**

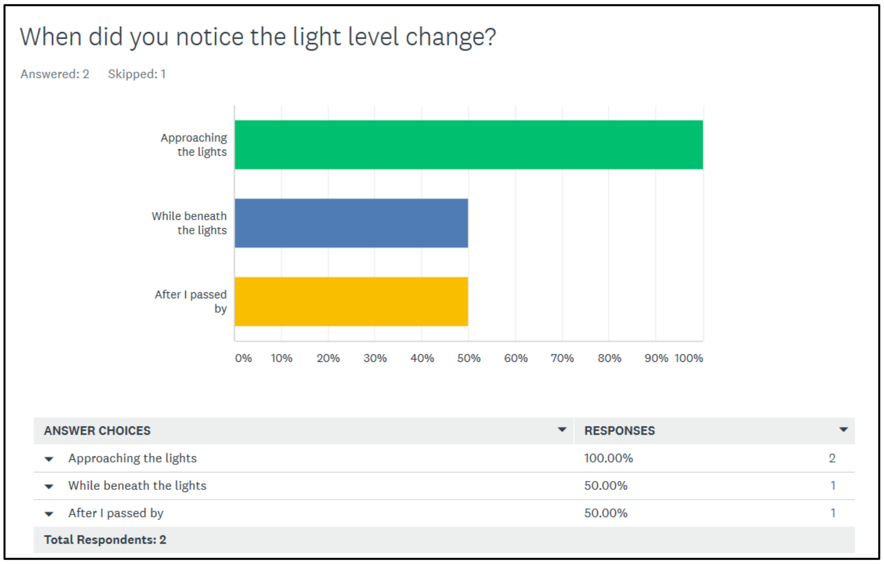
End User Feedback

CLTC disseminated a survey to the users of the MP3 and South Guard Shack buildings.

MP3 Building

Three MP3 staff took the survey. Of the three staff, two reported entering or exiting the MP3 building when the outdoor electric lights were on (i.e., before sunrise, after sunset). These two staff members cited their impression of the updated outdoor lighting at the MP3 building as being positive. Two responded that they were aware of the lighting system changes that took place in December 2019/January 2020.

Two responded that they noticed the light level changes. CLTC asked the two respondents when they noticed the light levels change. Both responded that they noticed the light levels change approaching the lights. In addition, one responded that they noticed the light levels change while beneath the lights and one responded that they noticed the light levels change after they passed by the lights, as shown in Figure 35.


When did you notice the light level change?

Answered: 2 Skipped: 1

ANSWER CHOICES	RESPONSES	
Approaching the lights	100.00%	2
While beneath the lights	50.00%	1
After I passed by	50.00%	1
Total Respondents: 2		

Figure 35. MP3 staff response to question, "When did you notice the light level change?"

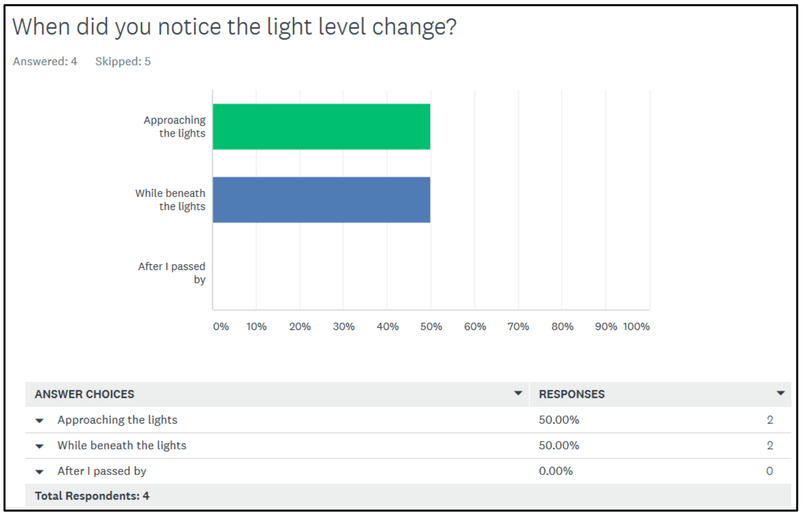
When asked if the light level was sufficient for their tasks (i.e., detect others, walk, jog, ride your bicycle, interact with others) as they approached the MP3 building two of the respondents replied yes. When asked if the light level was sufficient for their tasks (i.e., detect others, walk, jog, ride your bicycle, interact with others) when they were near the MP3 building two of the respondents replied yes.

CLTC asked the three MP3 staff their general opinion about if increased light levels improve safety. All three responded yes. Additionally, CLTC asked if increased light level reduce criminal activity. Two responded yes and one responded that the "light levels change gradually it is hardly noticeable".

South Guard Shack

Nine staff took the survey, all of which reported entering or exiting the Guard Shack when the outdoor electric lights were on (i.e., before sunrise, after sunset). Of the nine, five staff members cited their impression of the updated outdoor lighting at the Guard Shack as being positive and four cited theirs as being neutral. Five of the nine responded that they were aware of the lighting system changes that took place in December 2019/January 2020.

Four of the nine responded that they noticed the light level changes. CLTC asked the four respondents when they noticed the light levels change. Two responded that they noticed the light levels change approaching the lights, and two responded that they noticed the light levels change while beneath the lights, as shown in Figure 36.



When did you notice the light level change?

Answered: 4 Skipped: 5

ANSWER CHOICES	RESPONSES	
Approaching the lights	50.00%	2
While beneath the lights	50.00%	2
After I passed by	0.00%	0
Total Respondents: 4		

Figure 36. Guard Shack staff response to question, “When did you notice the light level change?”

When asked if the light level was sufficient for their tasks (i.e., detect others, walk, jog, ride your bicycle, interact with others) as they approached the Guard Shack seven of the respondents replied yes. Four of the respondents requested that the light levels be brighter as they approached the Guard Shack. When asked if the light level was sufficient for their tasks (i.e., detect others, walk, jog, ride your bicycle, interact with others) when they were near the Guard Shack eight of the respondents replied yes. Two of the respondents requested that the light levels be brighter while they were near the Guard Shack.

CLTC asked the Guard Shack to staff if the real-time change in light level helped to identify when and where others were in the near vicinity. All nine staff responded yes. CLTC also asked the nine Guard Shack staff their general opinion about if increased light levels improve safety. All nine responded yes. Additionally, CLTC asked if increased light level reduce criminal activity. All responded yes.

RECOMMENDATIONS

Based on outcomes from this research, CLTC developed lighting recommendations for both general and high security exterior lighting applications.

GENERAL SECURITY EXTERIOR LIGHTING SPECIFICATION

The general exterior lighting specification establishes best practices for adaptive lighting systems in outdoor security applications. Additional guidance is provided to ensure lighting control systems are selected based on feature availability and cyber security considerations. The summary of the recommendations is provided in Table 10.

Table 10. General Security Exterior Lighting System Specification Summary

Criteria	Recommendation
Light Distribution	Full cutoff, or U0 in the BUG classification system
Dimmability	0-10V to enable bi-level functionality
Color Rendering Index	80 or greater
Correlated Color Temperature	3,000 K or less
Connection Type	ANSI 7-pin
Lighting Level	Meet DOD criteria for location's specified level of protection
Occupancy Sensor	Compatible with lighting system controls; reliable detection of occupants
Dusk-to-Dawn Operation	Photocell or timeclock schedule
Cybersecurity	Comply with site networking requirements to ensure cybersecure system; standalone systems with no networking components are compliant at most DOD sites.

Outdoor security luminaires are recommended to be full cutoff, meaning there is little to no light emitted above 90 degrees. This concept is defined by a score of 'U0' in IES' Backlight-Uplight-Glare (BUG) classification system.[24] CLTC recommends that the luminaire be equipped with 0-10V dimming to enable bi-level light levels. IES recommends a Color Rendering Index (CRI) of 80 or greater in security applications where color recognition is important.[25] Since guards must accurately identify individuals either in person or by CCTV footage, luminaires with lower CRI ratings are not appropriate for security lighting applications. The DOD limits the Correlated Color Temperature (CCT) of outdoor luminaires to 4,100 K or less. CLTC recommends CCT of 3,000 K or less to align with guidelines to minimize potential harmful human and environmental effects of light at night.[26]

CLTC recommends that the luminaires chosen have ANSI 7-pin receptacles to ensure there is sufficient wiring infrastructure for all desired sensors to be mounted to the luminaire. To enable bi-level operation

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[24] (Department of Defnese, 2016), (The IES Security Lighting Committee, 2016) , (Luminaire Classification Task Group, 2011)

[26] American Medical Association. AMA adopts guidance to reduce harm from high intensity street lights. June 2016.

based on occupancy, CLTC recommends the use of occupancy sensors such as those evaluated in this project. CLTC recommends that the occupancy sensor selection criteria be based on the reliability of occupant detection, as well as the compatibility with the lighting control system. The system should be equipped with the ability to automatically operate from dusk to dawn, either via the use of a photocell or a time clock.

Additionally, all cyber security requirements for DOD sites must be approved by the facility and/or IT groups. Standalone systems that do not have networked components typically comply with the cyber security requirements at military sites.

For military sites, the Department of Defense defines security lighting in terms of each application's 'level of protection':

- **Low Level of Protection (LLOP)** – Security lighting is only required for building entries and exits.[27] The lighting levels vary from 0.2 to four foot-candles based on the application and the lighting zone classification. The light levels referenced are in the horizontal plane three feet above finished grade with the uniformity of 20:1.
- **Medium Level of Protection (MLOP)** – LLOP requirements apply, with the addition of exterior wall lighting that provides 0.2 to 0.5 foot-candles measured in the horizontal plane three feet above finished grade with uniformity of 15:1.
- **High Level of Protection (HLOP)** – LLOP and MLOP requirements apply, with the addition of area lighting 30 feet around the building that provides 0.5 to 1 foot-candle measured in the horizontal plane three feet above finished grade with uniformity of 10:1.

HIGH SECURITY APPLICATIONS SPECIFICATION

The specification for high security applications expands the general specification by adding specific light level requirements to increase the ability of guards to detect occupants based on 'highlighting' them with the light level change. The high security specification is focused on four applications identified in this report:

1. Perimeter fences
2. Building exteriors
3. Open areas/objects
4. Entry control points

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[27] (Department of Defnese, 2016, p. 146)

For these high security applications, CLTC recommends that the lighting equipment meet the general security recommendations and be capable of delivering light levels that align with ‘High Level of Protection (HLOP)’ requirements. HLOP light level requirements include low- and medium- level of protection requirements with the addition of area lighting 30 feet around the building that provides 0.5 to 1 foot-candle measured in the horizontal plane three feet above finished grade with uniformity of 10:1.

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