Light Emitting Plasma Outdoor Lighting Field Assessment

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LEGAL NOTICE

ABBREVIATIONS AND ACRONYMS

CIE	International Commission on Illumination
CRI	Color rendering index
HPS	High Pressure Sodium
IES	Illuminating Engineering Society
kWh	KiloWatt hours
LEP	Light Emitting Plasma
OSHA	Occupational Safety and Health Administration
PF	Power factor
PG&E	Pacific Gas and Electric Co.
RF	Radio frequency
W	Watts

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EXECUTIVE SUMMARY

PROJECT GOAL

The goal of this study was to evaluate an emerging technology for exterior lighting applications in Pacific Gas & Electric Company ("PG&E") territory. This study compared the performance of a test installation of Light Emitting Plasma (LEP) lighting and a wireless lighting control system, to an incumbent High Pressure Sodium (HPS) lighting system. The test facility was a high mast application at a study site in northern California. The study estimated power consumptions and energy savings resulting from the installation of LEP fixtures in place of the existing HPS fixtures, as well as the potential savings available from the wireless control system installed with the LEP fixtures. In addition, the study assessed illuminance levels and the visual quality provided by the LEP fixtures.

An interim report for the study (report #ET12PGE3171) was published in December 2012, and is available on the Emerging Technology Coordinating Council (ETCC) website[1]. This report supersedes report #ET12PGE3171 with updated study findings and results from a second phase of the study that was still underway when report #ET12PGE3171 was completed in 2012.

This report is intended to be read as a stand-alone document and includes all relevant project details and findings.

PROJECT DESCRIPTION

This study evaluated the performance of an installation of LEP fixtures on 80' lighting poles, with twelve fixtures per pole, at a study site in Northern California. Results of the LEP performance are compared to the performance of an existing installation of HPS lighting currently in use at the site. This report presents findings on three aspects of lighting performance:

- Energy Use
- Illuminance Levels – photopic and mesopic
- Visual Quality

The LEP fixtures were proposed to provide significant energy savings compared to HPS, according to the manufacturer. A typical HPS fixture in use at the study site uses as much as 1280 W, whereas the manufacturer projects the LEP fixtures to use 560 W. In addition, the LEP lighting was projected to provide improved visual quality with higher correlated color temperature (CCT) and higher Color Rendering Index (CRI), as well as comparable light levels.

In order to test the performance of the LEP lighting, TRC conducted field monitoring of energy use and illuminance output. The study presented in this report measured energy

[1] http://www.etcc-ca.com/sites/default/files/reports/Light%20Emitting%20Plasma%20PG%26E%20SFP%202012%20ET%20Report.pdf

use from four test LEP lighting poles and one baseline HPS lighting pole. The study also measured illuminance levels in the area impacted by the four study poles.

The overall field monitoring at the site began on August 24, 2012, and continued until June 30, 2013. Following an initial comparative analysis of the LEP and HPS lighting at full output, the study was expanded to evaluate additional LEP lighting installed at the site, as well as the energy savings potential provided by the wireless control system.

Over the course of the study, several improved versions of the LEP fixtures were installed at the site. The three fixture versions assessed in the study were referred to as "Version A," "Version B," and "Version D" ("Version C" fixtures were rejected by the study site management, and were not studied).

PROJECT FINDINGS/RESULTS

TRC monitored energy performance and illuminance output from the test LEP installations as compared to a baseline HPS installation. A baseline HPS pole chosen for the study had all lamps and ballasts replaced at the start of the study so that the HPS fixtures were at their peak output and thus provided an equivalent baseline to compare against the new LEP pole(s).

TRC assessed the energy performance and illuminance output from the test LEP installation under two control scenarios. The first control scenario dimmed all LEP fixtures to a 50% dimming signal during low activity periods at the study site. The second control scenario involved turning off half the fixtures on each pole during low activity times.

The study compared the performance of three successive versions of the LEP fixture, as incrementally improved fixtures were installed at the site over the course of the study.

This section provides energy savings results as measured on site from version D of the LEP fixture – the most recent version of LEP fixture tested for this study and one that is proposed to be the most energy efficient version.

Energy Savings:

Overall, LEP lighting represents a significant reduction in power consumption over HPS in high-mast applications. As shown in Table 1 and Table 2, the LEP lighting at full power uses less than half the power of the HPS lighting at full output. However, the LEP fixtures draw a small amount of power when the fixtures are turned off, shown in the tables below as "standby power." In addition, when light levels are reduced during low activity nights at the site, the combination of the LEP lighting and wireless control system provides an energy savings of 67% compared to the incumbent HPS. The controls also provide 32% savings over the LEP fixtures without controls.

TABLE 1: POWER CONSUMPTION SUMMARY

	POWER AT FULL OUTPUT (W)	POWER AT LOW ACTIVITY TIMES (W)	STANDBY POWER (W)	AVERAGE DAILY ENERGY USE (KWH)
HPS Pole	12944	12944	0	155
LEP Pole, no controls	6232	6232	43	75
LEP Pole, half-on half-off control for low activity	6232	3099	43	51

Table 2: Energy Savings Summary

	Power Savings at Full Output W (%)	Power Savings at Low Activity Times W (%)	Standby Power (W)	Average Daily Energy Savings kWh (%)
Savings, LEP without controls vs. HPS	6712 (52%)	6712 (52%)	+43	80 (52%)
Savings, LEP with controls vs HPS	6712 (52%)	9845 (76%)	+43	104 (67%)
Savings, LEP with controls vs LEP without controls	0	3133 (50%)	0	24 (32%)

Illuminance Results:

TRC used calculated mesopic illuminance to evaluate light levels at the study site because mesopic illuminance more accurately describes visual performance in exterior night time conditions than traditional photopic illuminance. Mesopic illuminance was calculated based on measured photopic and scotopic illuminance values (see "Photopic, Scotopic, and Mesopic vision"). Results show that LEP lighting provides less illuminance than the existing HPS fixtures. Despite the lower light levels at the site, most employees at the site surveyed for the study reported that the LEP lighting appears brighter than the existing HPS lighting.

Table 3, summarizes the calculated mesopic illuminance conditions at the site for the baseline HPS lighting, and the most current LEP fixture tested in the study ("Version D"). For the area most directly impacted by the LEP pole -- up to 120' between the poles, and up to 120' toward the water line from the last row of poles -- the average mesopic illuminance is 51 lux, which is slightly less than the minimum average of 54 lux required by the Occupational Safety and Health Administration (OSHA). However, note that the Version D pole measured for the study was surrounded by older LEP fixtures with lower output, and some poles with only eight fixtures instead of twelve. TRC believes that a full installation of Version D LEP fixtures at the study site would meet the minimum light level requirements.

Table 3. Calculated Mesopic Illuminance Measurements

	Average (lux)	Maximum (lux)	Minimum (lux)	Max:Min	Avg:Min
HPS	77	125	24	5.20:1	3.20:1
LEP v.D	51	127	14	9.36:1	3.73:1

Project Recommendations

Based on the results of this study, TRC presents the following strengths and weaknesses of the LEP lighting and wireless lighting controls assessed in this study. TRC recommends that PG&E consider these strengths and weaknesses in deciding whether to adopt LEP lighting and wireless lighting controls into the Energy Efficiency ("EE") program.

Strengths:

- **LEP lighting provides significant power savings compared to HPS** – At full output the LEP lighting resulted in a 52% energy use savings compared to the incumbent HPS lighting at the study site.

- **LEP lighting provides greatly improved visual quality compared to HPS** – Surveys of port staff indicated that most respondents found the LEP lighting to appear brighter and improve visibility compared to the HPS lighting at the study site.
- **LEP fixtures did not experience significant lumen depreciation** – The results of the study indicate that the LEP fixtures did not experience any significant lumen depreciation over the ten month duration of the study.
- **Wireless lighting controls provide significant energy savings** – The wireless control system installed with the LEP lighting at the site has the potential to provide a combined 67% energy savings compared to the incumbent HPS lighting at the study site, and up 32% energy savings compared to the LEP lighting without active controls.
- **Wireless lighting controls provide greatly improved control flexibility** – In addition to the energy savings, the wireless lighting controls allow for much greater flexibility than existing timer controls. Improved flexibility includes the ability to establish multiple zones, the ability to specify control zoning down to the individual fixture level, and the ability to change zones and control scenarios as the needs of the site change.

Weaknesses:

- **LEP light levels were significantly lower than HPS** – At full output, the Version D fixtures provided an average mesopic illuminance of 51 lux, compared to 77 lux from the incumbent HPS lighting.
- **LEP dimming results in low light output with high power consumption –** The results of the control scenario tests found that dimming the LEP fixtures to a control signal of 50% provided only 43% of the illuminance compared to full output, but with 70% power consumption compared to full output settings. Other dimming levels exhibited similar results. These results indicated that dimming the LEP fixtures provide only minimal power savings compared to the reduction in light levels.
- **LEP fixtures had high failure rate –** A total of eight LEP fixtures experienced failures over the course of the study (7% of the fixtures installed for the study, not including the fixture failure attributed to human error). Failures occurred across all three fixture versions studied. Some of this failure could be partly due to the fact that the product was actively under development though quality control and failure issues need to be addressed if LEP is to scale in the market.
- **Wireless lighting controls experienced functionality problems** – Over the course of the study the wireless control system experience several problems. Problems included failures communicating with fixtures, and problems automatically updating the schedules to match changes in sunrise and sunset times. Similar to the recommendation above, these control system glitches need to be evaluated and fixed in order for a more robust installation and operation of future LEP fixtures.

INTRODUCTION

This study originated from a PG&E Contract Work Authorization for the Heschong Mahone Group, Inc., a TRC Company (hereinafter "TRC"). This study evaluates the performance of an installation of Light Emitting Plasma (LEP) lighting and wireless lighting controls as an alternative to the existing High Pressure Sodium (HPS) in a high-mast application at a study site in northern California. The LEP lighting provides the potential for energy savings, more dynamic control capability, and improved visual quality over HPS lighting.

STUDY SCOPE

This study was conducted in two phases: an initial study, published in an interim report in December 2012,[2] and an expanded study, presented here. The expanded study builds on the findings of the initial study, with longer term field monitoring and a wider variety of test conditions.

INITIAL STUDY

The initial study was primarily focused on the direct comparison of the performance of a single LEP pole with a single HPS pole at full output. Energy monitoring for this initial study was conducted between August 24 and October 1, 2012. Illuminance measurements for the initial study were taken on September 20 and October 18, 2012.

EXPANDED STUDY

The expanded study includes energy monitoring of three additional LEP poles but without the baseline HPS pole (the baseline HPS pole was retrofitted to LEP on November 15, 2012). TRC continued to measure illuminance levels at the study site using similar protocols as the initial study. The expanded study also evaluated capabilities of the wireless control system installed with the LEP lighting. Field monitoring for the expanded study was completed on June 30, 2013.

This expanded study updated the initial findings and examined additional performance aspects, as follows:

- Long term LEP lighting performance, such as lumen depreciation, over approximately 10 months
- Illuminance and visual quality performance of three successive generations of the LEP fixture product
- Energy and performance implications of the wireless control system, including dimming performance, and separately controlling individual fixtures on a single pole.

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[2] Report #ET12PGE3171. http://www.etcc-ca.com/sites/default/files/reports/Light%20Emitting%20Plasma%20PG%26E%20SFP%202012%20ET%20Report.pdf

This report presents combined results from both the initial study and the expanded study.

STUDY SITE

This study was carried out at Ports America Outer Harbor Terminal, LLC (hereinafter referred to as "the study site"), a privately operated port terminal facility within the Port of Oakland in Oakland, CA. The terminal facility is used to load and unload cargo from large cargo container ships. The facility is capable of processing over 487,000 cargo containers per year. Ships arrive and depart at all times of day and night, so nighttime lighting is crucial to the operations of the facility.

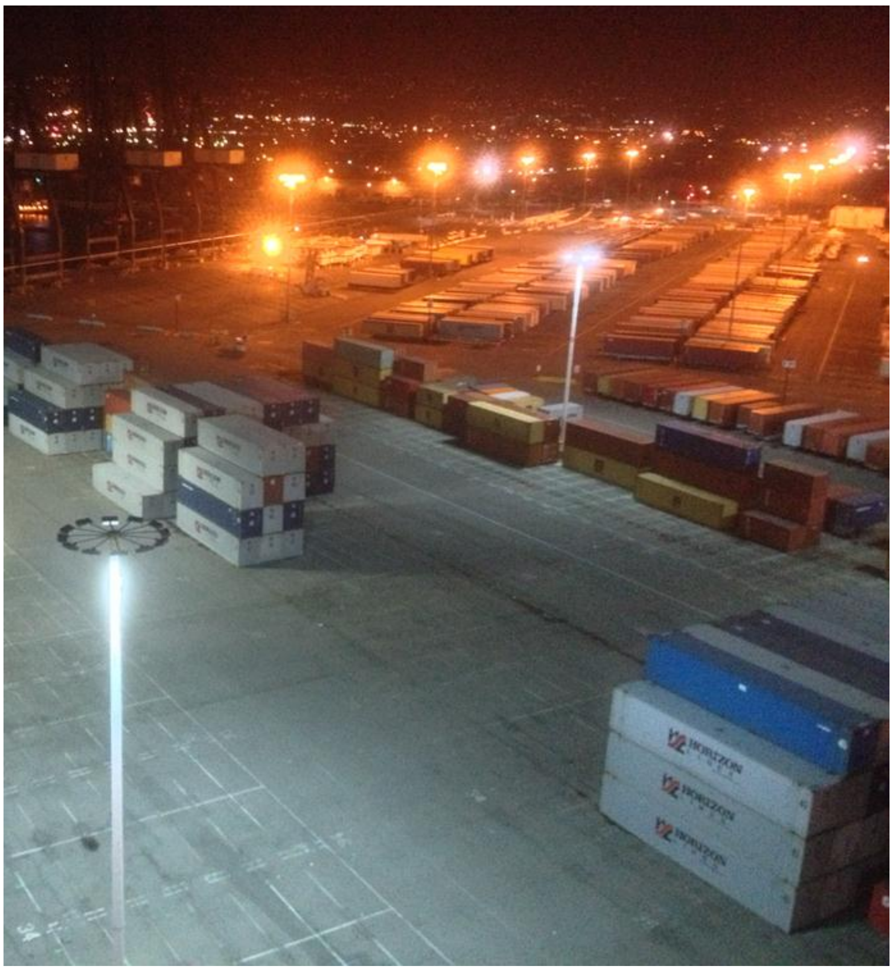

FIGURE 1: VIEW OF STUDY SITE FROM ABOVE, LEP STUDY AREA IN FOREGROUND, EXISTING HPS LIGHTING IN BACKGROUND

BACKGROUND

High-mast lighting presents a unique and specific challenge. Typically used in industrial or infrastructural applications, such as large parking areas, major highways and interchanges, airports, and port facilities, high-mast lighting is required to provide relatively uniform illumination across very large areas from a limited number of locations. High-mast lighting also has the advantage of limiting glare, by placing the light source very high and out of the typical field of view.

Because of the specific requirements of high-mast lighting, this segment has been dominated by HPS sources, like those currently in use at the study site for this study. HPS lighting can provide very large amounts of light relatively efficiently compared to other light sources. However, HPS lighting presents several important problems.

First of all, the color and visual quality of HPS light is relatively poor. The orange-yellow color is poorly suited to nighttime conditions, and renders colors poorly. Metal halide sources can provide better visual quality than HPS, but also typically require more energy to produce comparable light levels.

The other problem of high-mast lighting is that even with relatively efficient HPS sources, it uses large amounts of energy. High-mast HPS fixtures can use as much as 1280 W each, and typical high-mast poles use between two and twelve fixtures each.

While LED technology has been replacing HPS lighting in many applications, high-mast lighting remains somewhat out of reach for LEDs. Typical LED luminaires use large arrays of small LED chips to equal the light output of comparable single-lamp sources such as linear fluorescent or HPS. In a high-mast application, the LED array would have to be prohibitively large to match the output of an HID source, and even then the relatively low intensity of the individual LED chips may not be capable of reaching the long distances required by high mast lighting.

By contrast, LEP technology seems better suited to high-mast applications. The LEP modules used in this study provide a high-intensity white light from a single small source, using significantly less energy than a comparable HPS luminaire. The small size of the LEP source allows for more precise optical control, and the high intensity of the light ensures that it can be effectively delivered to the large areas common to high-mast applications.

Similarly, high-mast lighting typically uses very simple or basic controls. High-mast lighting is most often controlled with either photocells that turn individual fixtures on or off depending on daylight conditions, or with timers that control large groups of poles, turning fixtures on and off based on a predetermined schedule, as is the case with the HPS lighting at the study site. These control options provide little flexibility for operators of high-mast lighting. Lights are either on at full power or off, and lights stay on at full power all night, regardless of variations in activities or traffic.

Wireless lighting controls, on the other hand, provide more control flexibility to provide lighting only when and where necessary. Wireless control systems like the one examined in this study allow individual control of every fixture. Individual fixture control allows for lower light levels, and energy savings, at times of low traffic or activity by dimming fixtures or by turning off some of the fixtures on a multi-fixture pole. In a situation like the port facility study site, facility managers could establish multiple lighting zones, allowing full lighting power in zones with nighttime activity, while dimming or turning off some lighting in other zones without activity. Control scenarios can be set and changed remotely through PC-based software interfaces.

EMERGING TECHNOLOGY/PRODUCT

LIGHT EMITTING PLASMA (LEP)

The first electrode-less plasma lamps were invented by Nikola Tesla is the 1890s, but subsequent iterations of plasma lighting encountered a variety of challenges and limitations, such as limited lamp life, high heat, and high power requirements.[3]

A new system used in the LEP products in this study was first developed in 2000. The LEP lamp itself is a small quartz electrode-less capsule, the size of a large pill. The key to the system is the ceramic resonator in which the lamp capsule is embedded . This ceramic resonator concentrates a radio frequency (RF) field, energizing the capsule without electrodes. The concentrated radio frequency creates a plasma state inside the capsule, which emits a high-intensity white light.

Figure 2, below, shows a diagram of this process. The diagram was developed by Luxim, the manufacturer of the LEP modules used in this study.

FIGURE 2. DIAGRAM OF HOW LIGHT EMITTING PLASMA WORKS (IMAGE SOURCE: LUXIM)

The process shown in Figure 2, as described by Luxim is as follows:

Step 1

An RF circuit is established by connecting an RF power amplifier to a ceramic resonator known as the "puck". In the center of the puck is a sealed quartz lamp that contains metal halide materials and other gases.

Step 2

The puck, driven by the power amplifier, creates a standing wave confined within its walls. The electric field is strongest at the center of the lamp, which causes ionization of the gases, creating a glow.

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[3] http://en.wikipedia.org/wiki/Plasma_lamp, accessed November 28, 2012

Step 3

The ionized gas in turn heats up and evaporates the metal halide materials forming an intense plasma column within the lamp. This plasma column is centered within the quartz envelope and radiates light very efficiently.

(Source: http://www.luxim.com/technology/how-lep-works)

The high intensity white light that LEP produces makes it competitive with HID sources, such as HPS and Metal Halide, in a variety of applications, such as exterior roadway and parking lot, industrial high bay, and high-mast applications. Because of its small size and high light output, LEP is also an alternative to LED for high intensity scenarios that require precise optical control, or a concentrated beam, which cannot be delivered as successfully by large arrays of LED chips.

Because this form of LEP lighting is so new, it is relatively untested in real world scenarios, and it is not well known in a lighting market heavily saturated with LED products. In addition, there has been some concern that the radio frequencies used to energize the lamp may interfere with the wireless control systems that are sometimes used to control large outdoor lighting installations to which LEP lighting is well suited.

IMPROVED FIXTURE VERSIONS

Over the course of the study, several improved versions of the LEP fixtures were installed at the site. The three fixture versions assessed in the study were referred to as "Version A," "Version B," and "Version D" ("Version C" fixtures were rejected by the study site management, and were not studied).

Table 4 shows performance details for each version as reported by the LEP supplier and fixture manufacturer. Note that each fixture contains two lamps.

TABLE 4: FIXTURE VERSION SPECIFICATIONS

	LAMP LUMENS	LAMP POWER (W)	FIXTURE EFFICIENCY	NOTES
Version A	21,000	280	64%	
Version B	22,000	270	69%	
Version D	23,000	270	75%	Improved reflector and glass lens

WIRELESS CONTROLS

The wireless control system examined in this study consists of three main elements: wireless "controllers" connected to each fixture, a "gateway" that communicates to up to 250 controllers, and a PC-based user interface "host" that communicates to one or more gateways.

Each wireless controller communicates an on/off or dimming signal to the fixture, similar to the way a fixture-mounted photosensor communicates to a street light fixture. Control signals are relayed from the host through a wired or wireless internet connection to the gateway, where the control signal is sent on the individual fixtures.

The host allows users to set up zones of individual fixtures, and establish control programs to accommodate the lighting needs of the application. The ability to establish zones using individual fixtures allows for much greater flexibility than traditional exterior lighting control protocols. The host also provides the ability to establish more precise settings, such as timer controls that update daily to reflect changing sunrise and sunset times.

This study specifically examined the use of the wireless controls to reduce light levels at the study site during low activity periods. Because of the inconsistent nature of the schedule at the study site, the wireless control system requires manual user inputs to change the lighting control settings when the schedule allows, rather than using a pre-programmed control schedule.

ASSESSMENT OBJECTIVES

The objective of this report is to present findings on the performance of a high-mast installation of LEP lighting with wireless controls, as compared to the existing HPS lighting in use at the study site. This report evaluates three factors in relation to the new lighting system installed at the study site:

- Energy Use
  An evaluation of the power consumption and energy use of LEP lighting and wireless control system, as compared to the incumbent HPS lighting system.
- Illuminance
  An evaluation of the light levels provided by the LEP lighting at full power, and at various dimmed and control settings, as compared to the incumbent HPS lighting system, and long term performance, such as lumen depreciation, over approximately 10 months of operation.
- Light Quality
  A discussion of comparative light quality issues such as color rendering, glare, and visibility between LEP and HPS lighting. The discussion includes results of a survey of port employees.

TECHNOLOGY/PRODUCT EVALUATION

This report compares the performance of an existing HPS pole to several poles retrofitted with LEP fixtures and wireless controls. Each pole is 80 feet tall, and has 12 fixtures.

The existing fixtures use 1000 W HPS lamps. In the interest of providing a direct comparison, the baseline HPS pole that was monitored for this study had a full lamp and ballast replacement prior to the start of the study to ensure that it was fully functional and the power consumption was close to manufacturer specifications. In addition, light level measurements at the HPS pole were not taken until after a sufficient burn-in period of at least 100 hours to allow the gases in the lamps to stabilize.

The LEP fixtures are manufactured by Bright Light Systems, using LEP modules from Luxim, and wireless controls from Vasona Labs. The manufacturer's specification sheet states that the LEP fixtures use two LEP modules, for a total of 550 W per fixture[4]. Over the course of the study, three successive versions of the LEP fixtures were installed in the test area with each fixture providing improved light output over previous versions.

An early installation of LEP lighting at the study site (prior to this study) experienced multiple fixture failures that were believed to be caused by power quality issues at the site. The power at the study site experiences voltage spikes which may have overloaded the electronics in the LEP fixtures, causing them to fail. In order to avoid future problems, a power filter was installed on subsequent LEP poles, including the test pole monitored in this study. The filter[5], essentially a kind of transformer, absorbs the voltage spikes and prevents them from reaching the LEP fixtures.

Figure 3, below, shows a typical LEP fixture from Bright Light Systems, similar to those installed at the study site.

[4] http://www.brightlightsystems.com/support/datasheets/BLP1000.pdf

[5] Input Line Reactor, manufactured by TCI (Trans-Coil International), model number KDRULA4H

FIGURE 3. TYPICAL LEP FIXTURE INSTALLED AT THE SITE (IMAGE SOURCE: BRIGHT LIGHT SYSTEMS)

The LEP fixtures were controlled using the VasonaLink wireless control system from Vasona Labs. Each fixture included a wireless controller that communicates through a wireless gateway to a PC-based host interface.

In order to evaluate the performance of the LEP lighting and the wireless controls, the study examined three factors, described in detail below: energy use, illuminance levels, and visual quality.

ENERGY USE MONITORING

Energy use was monitored at both a baseline HPS pole and four test LEP poles, as described in detail in the

Technical Approach/Test Methodology section.

The monitored energy use data presented in this report compares the energy use of 12 LEP fixtures, as well as various control scenarios, to 12 HPS fixtures. Note that each existing HPS lighting pole at the site has 10 fixtures that are powered by a primary power source and controlled using a timer, and two fixtures that are powered by a separate power source and controlled by a photosensor. These two separately powered fixtures are considered "emergency fixtures" and are typically only turned on if the other 10 fixtures fail. Because the LEP fixtures are controlled by a separate wireless control system, the photocell and timer were bypassed on the LEP pole, allowing all 12 LEP fixtures to turn on each night. The energy monitoring equipment monitored all 12 fixtures on the LEP pole, but only monitored the primary power source for the 10 main HPS fixtures. However, results in this report are presented by extrapolating data from the 10 fixtures to all 12 fixtures on the HPS pole to provide a direct comparison to the LEP pole.

This study compares both power (W) and energy use (kWh) of the LEP and HPS lighting. In addition to these key parameters, other variables provided by the data logging system are discussed in the assessment of the LEP lighting technology. The variables available for review are discussed in more detail in the

Technical Approach/Test Methodology section, below.

ILLUMINANCE LEVELS

Illuminance is the measurement of the quantity of light incident on a surface. For this study, TRC measured illuminance levels from the test LEP poles and the baseline HPS pole. Illuminance levels were measured with all 12 HPS fixtures turned on, in order to provide an equal comparison to the LEP pole with 12 fixtures. Details of the measurement process are described below in the

Technical Approach/Test Methodology section.

The study site is required to meet the Occupational Safety and Health Administration (OSHA) requirements for light levels. The relevant OSHA light level requirements are as follows:

- Minimum average of 5 footcandles in work areas (54 lux)
- Minimum average of 1 footcandle in non-work areas (11 lux)

The OSHA requirements are specified in footcandles, but the study measurements were taken in lux (the metric unit of illuminance), so lux values are shown above for reference as well. In addition to comparing the illuminance of the LEP and HPS lighting, the study seeks to confirm that the LEP lighting meets the OSHA light level requirements.

One complication of measuring illuminance under nighttime conditions is the visual adaptation of the human eye in low light conditions. In order to provide the most complete understanding of the illuminance conditions at the site the study measured both photopic and scotopic illuminance, and then calculated mesopic illuminance to most accurately reflect nighttime visual conditions.

Although it is not explicitly stated, it is assumed that the OSHA requirements are based on photopic illuminance levels, since all illuminance standards are currently based on photopic footcandles. While TRC believes that mesopic illuminance levels are a better representation of human visual performance under nighttime conditions at the study site, final determination of the acceptability of using mesopic illuminance levels to confirm compliance resides with OSHA.

The issue of photopic, scotopic, and mesopic vision is discussed in detail below.

Photopic, Scotopic, and Mesopic Vision

The human eye behaves differently under different lighting conditions. Under typical interior and daylight brightness conditions, the visual response is dominated by the cone photoreceptors in the eye, which perceive colors and fine details. This is called photopic vision. Photopic illuminance describes light levels under these conditions, based on the photopic action spectrum adopted by the CIE (International Commission on Illumination) in 1924. Standard illuminance meters use the photopic action spectrum to determine light levels.

However, under very low brightness conditions, the visual response is dominated by the rod photoreceptors, which do not perceive color, and are more sensitive to peripheral vision. This is called scotopic vision. Under scotopic vision, the eye is more sensitive to the green and blue spectrum of light, causing these portions of the spectrum to appear brighter than normal. Scotopic illuminance describes the visual perception of light levels under these conditions, based on the scotopic action spectrum adopted by the CIE in 1951.

Completely scotopic or rod-dominated vision is limited to very low brightness conditions where little or no ambient light is present. It is almost impossible for vision to be fully scotopic under any artificially lit conditions. However, in typical exterior nighttime environments, the eye transitions between photopic and scotopic vision. The spectral sensitivity shift towards the blue end of the spectrum of light begins to occur under these conditions. This transitional state is called mesopic vision, and neither photopic illuminance nor scotopic illuminance can adequately describe perceived light levels under mesopic vision, as the eye transitions between cone-dominated and rod-dominated vision.

In 2012, the Illuminating Engineering Society (IES) developed a methodology to calculate mesopic light levels based on photopic and scotopic measurements ("IES TM-12-12: Spectral Effects of Lighting on Visual Performance at Mesopic Lighting Levels"). TRC used the strategy outlined in the IES document to calculate mesopic light levels at the study site based on measured photopic and scotopic illuminance data.

VISUAL QUALITY

Illuminance is only one of many aspects of light quality and performance. Other visual quality aspects, such as color rendering, can also impact perceived brightness, visual comfort, and user satisfaction. For example, the LEP manufacturer reports a color rendering index (CRI) of up to 75 (out of 100), whereas typical HPS lamps have CRIs in the low 20s.

In order to explore these issues of visual comfort and user satisfaction, TRC conducted a survey of port employees to determine how occupants at the site have responded to the new LEP lighting. In addition, TRC had informal discussions with employees at the study site as well as the electricians who installed the fixtures.

TECHNICAL APPROACH/TEST METHODOLOGY

FIELD TESTING OF TECHNOLOGY

This study compares a test installation of LEP high mast lighting with the existing HPS lighting at the study site. The diagram in Figure 4, below, shows the initial test area for the study, where the red dot indicates the LEP study pole, the blue dot indicates the baseline HPS study pole used in the study.

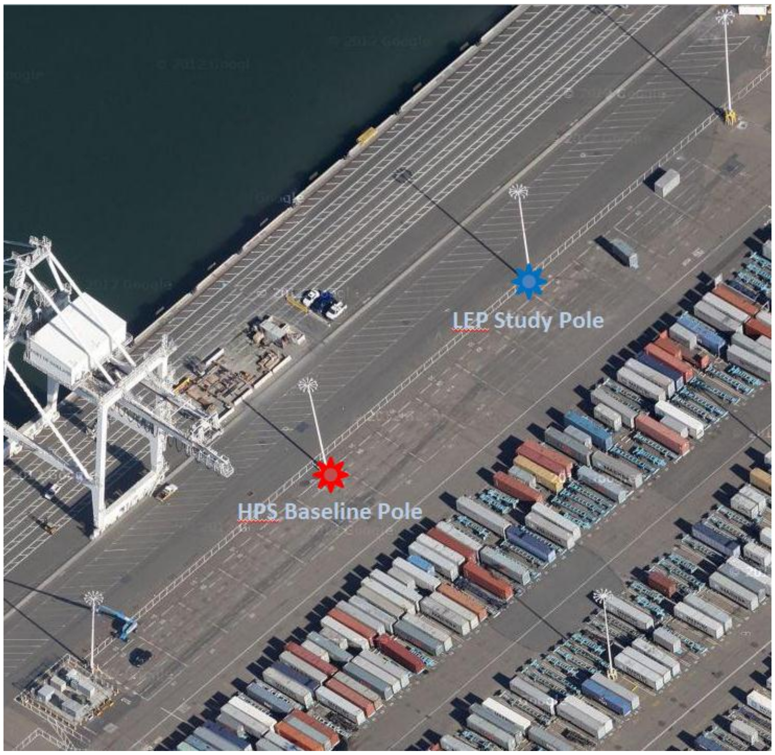

FIGURE 4. DIAGRAM OF INITIAL STUDY LOCATION, BLUE DOT INDICATES LEP TEST POLE, RED DOT INDICATES BASELINE HPS POLE

Following the completion of the initial study comparing a single HPS pole and a single LEP pole, the study was expanded to include four poles retrofitted to LEP, in an area of a total of nine retrofitted poles. Figure 5 shows a diagram of the expanded study area, where the blue dots indicate the four poles monitored and measured as part of the expanded study including the original test HPS pole which was retrofitted to LEP, and the yellow dots indicate additional poles in the area that were retrofitted to LEP. Additional lighting poles in the area surrounding the study site remained HPS.

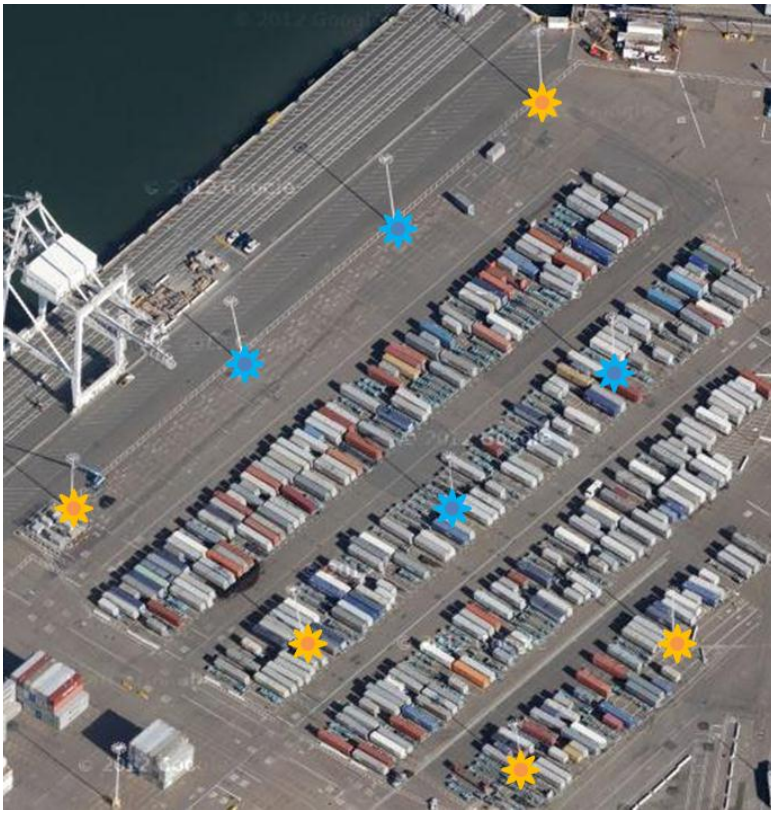

FIGURE 5: EXPANDED STUDY SITE, BLUE DOTS INDICATE LEP TEST POLES, YELLOW DOTS INDICATE ADDITIONAL LEP POLES NOT INCLUDED IN THE STUDY

Each lighting pole is 80 feet tall, and contains 12 fixtures. Existing HPS lighting is controlled by an automatic time-clock control system that turns the lights on at night, and off again in the morning. Ten of the 12 fixtures on the HPS pole were controlled by this time-clock system, while the other two fixtures are controlled by a photocell, and only turn on if the other ten fixtures are not functioning properly.

On the test LEP poles, all 12 HPS fixtures were replaced with new LEP fixtures. The LEP fixtures are controlled wirelessly using a digital control system. Each fixture is capable of being controlled individually. Initially, the LEP fixtures were programmed to turn on 30 minutes after sunset, and to turn off 30 minutes before sunrise. Later in the study, the LEP fixture programming was adjusted to turn on 10 minutes after sunset, and turn off 10 minutes before sunrise each day in order to ensure sufficient illumination at all times. Following the completion of the initial study, the expanded study examined two different control scenarios for nights when there was no activity in the study site area. The first control scenario involved dimming all 12 fixtures on each pole to a 50% dimming signal on low activity nights. The second control scenario involved turning off half of the fixtures on each pole during low activity nights. In this second scenario, alternating fixtures on the twelve-fixture pole were turned off to maintain uniform lighting at the lower light level.

The study measured energy use at both the baseline HPS pole and the test LEP poles, as well as illuminance levels in the area between the two initial study poles and the site edge, and in the area between the four expanded study light poles.

INSTRUMENTATION PLAN

The instrumentation plan for this project involves two distinct aspects: the energy monitoring equipment, and the illuminance measurement equipment. The equipment used in this project is described in the sections below.

POWER METERS AND DATA LOGGERS

Energy monitoring is carried out using a HOBO U-30 data logger system from Onset (http://www.onsetcomp.com/products/data-loggers/u30-gsm), which uses a cellular network to transmit data to Onset's online server, "Hobolink," where the data can be accessed in real time. The system uses E50B2 power and energy meters (http://www.onsetcomp.com/products/sensors/t-ver-e50b2) to measure electricity use and power quality.

FIGURE 6. HOBO U30 REMOTE MONITORING SYSTEM FROM ONSET

FIGURE 7. E50B2 POWER AND ENERGY METER FROM ONSET

The E50B2 power meters use current transformers (CTs), and directly connected voltage leads to measure energy use. The power meters measure the following variables:

- Volt-ampere reactive hours (VARh)
- Watt hours (Wh)
- Amp hours (Ah)

Those measurements recorded by the power meter are then transmitted to the U30 logger using pulse-input adapters. The pulse-input adapter transmits the values measured by the power meter to the logger in a series of pulses. The pulses are scaled depending on the variable being measured.

For example, for each Wh used by one of the LEP fixtures, the power meter sends a pulse to the data logger. In a typical one minute logging interval for an LEP fixture, the power meter will send 9 pulses to the data logger. In other words, the LEP fixture uses 9 Wh per minute. This Wh value can be converted to Watts (W) using the following equation:

EQUATION 1. WH TO W CONVERSION

W = Wh/h

Therefore in this example, the conversion is as follows:

EQUATION 2. WH TO W CONVERSION

W = 9 Wh / (60 seconds / 3600 seconds) = 540 W

As shown in Equation 2, the 9 Wh is divided by the length of the measurement interval, in hours, to determine that the Wattage for that one minute interval is 540W. However, it should be noted that this example reveals the relatively low precision of the pulse-input adapter at single measurement points. Using this conversion, each Wh pulse recorded in a one-minute interval translates to 60 W. In other words, a minute with 8 pulses would represent 480 W, and a minute interval with 10 pulses would represent 600 W. A longer time interval would provide more precision. Although the pulse data is relatively imprecise at the individual reading level, individual values can be averaged over longer periods of time to create more precise data. In addition, the pulse data is an effective way to measure cumulative energy use data over time (kWh, etc.).

Similar to the Wattage example above, the values measured by the power meter, and recorded by the data logger can be converted to the following variables:

- Volt-ampere reactive (VAR)
- Volt-amps (VA)
- Volts (V)
- Power factor (PF)
- Watts (W)
- Kilowatt hours (kWh)
- Kilowatts (kW)

The study used two logger systems to allow simultaneous monitoring on both the baseline HPS pole, and the LEP study pole.

The baseline HPS pole was monitored at the power mains to the pole, because all fixtures on the HPS pole are operated together. Energy use at the LEP study pole was monitored at the mains and at a sample of two individual circuits to provide additional information on the performance of the LEP fixtures.

Illuminance Meter

Illuminance measurements were taken using a Solar Light SL-3101 Scotopic/Photopic illuminance meter.

A new meter was purchased for the project, and was calibrated by the manufacturer on February 16, 2012.

FIGURE 8. SOLAR LIGHT SL-3101 SCOTOPIC/PHOTOPIC ILLUMINANCE METER

TEST PLAN

Monitoring and measurement plans for the study are outlined in the sections below.

BASELINE ENERGY MONITORING

Power meters and data loggers were installed on the baseline HPS pole on July 27, 2012. On the baseline HPS pole, one power meter was used to monitor energy use at the power mains in the electrical panel at the base of the pole. These power mains control 10 of the 12 fixtures on the pole. Energy monitoring equipment is described in detail above, in the Power Meters and Data Loggers section.

In order to provide the most equal comparison to the test LEP pole, all lamps and ballasts were replaced on the baseline HPS pole so that all 12 fixtures on the pole were fully functional (see Technology/Product Evaluation, above). Following these repairs, the baseline HPS pole was fully functional starting the night of August 24.

Monitoring at the baseline HPS pole continued until November 15, 2012, when the baseline pole was retrofitted to LEP.

LEP PRODUCT ENERGY MONITORING

As with the baseline HPS pole, power meters and data loggers were installed on the test LEP pole on July 27, 2012. On the test LEP pole, three power meters were used. One power meter monitored energy use at the power mains in the electrical panel which controls all 12 LEP fixtures on the pole. Two additional power meters were used to monitor energy use at two individual circuits, which each control a single LEP fixture.

Immediately following the initial LEP installation two of the LEP fixtures were not functioning properly and had to be replaced. Several weeks later, another LEP fixture was not functioning properly, with only one of the two LEP modules working, and had to be replaced. The malfunctioning LEP fixture was replaced on September 24, and the LEP pole was fully functional starting that night. These fixture issues are reflected in the monitored data for the full pole, but did not affect either of the two individual fixtures that were monitored for the study.

Following the retrofit of the baseline pole to LEP, monitoring continued using the same monitoring setup as described in the "Baseline Energy Monitoring" section. Following the installation of additional LEP poles at the study site, energy use monitoring was expanded to four LEP poles. Starting on January 11, two twelve-fixture poles were monitored using three power meters per pole, with one at the power mains for the pole, and two on individual circuits to measure single fixtures. In addition, one power meter was installed on each of two eight-fixture poles.

Energy monitoring continued on all four LEP poles until June 30, 2013, and all monitoring equipment was removed from the study site on July 15, 2013.

ENERGY MONITORING CONDITIONS

During the initial study, the test LEP lighting and the baseline HPS lighting were monitored simultaneously from the installation of the loggers in July 2012. However, it took several weeks to replace lamps and ballasts on the baseline HPS pole so that all fixtures were functioning for the comparison. As described above, the energy monitoring equipment measured the energy use of 12 fixtures on the LEP pole, and 10 fixtures on the HPS pole. In order to provide an equal comparison, the energy use data for the HPS presented here was extrapolated to represent 12 fixtures as follows:

EQUATION 3. EXTRAPOLATED HPS WATTS

Extrapolated HPS Watts = Measured HPS Watts / (10/12)

Analysis of the comparative energy use for the study began on August 24, once all the HPS fixtures on the baseline pole were fully functional.

In addition, the control schedule on the LEP fixtures was adjusted on September 22. Up until that point, the LEP lighting was turning on 30 minutes after sunset, and turning off 30 minutes before sunrise. However, after observing conditions at the site, TRC and management at the study site asked for the schedule to be adjusted to turn the lighting on earlier to ensure adequate illumination at the site. Starting on September 22, the LEP lighting turned on 10 minutes after sunset and turned off 10 minutes before sunrise.

Energy monitoring data collected between August 24 and October 22, 2012 was recorded at 60-second intervals. Later in the study, starting on October 23, the monitoring interval was extended to every 120 seconds, in order to provide more precise results (see pulse-input adapter discussion in the "Power Meters and Data Loggers" section). Energy use data recorded by the data logger was transmitted via cellular signal to the Hobolink online server every 15 minutes. TRC and PG&E staff had access to the data on the Hobolink server over the duration of the study.

Simultaneous monitoring continued until October 1, when the logging system on the test LEP pole malfunctioned and stopped logging data, as discussed in detail below. Energy use data for the initial study is primarily from the monitoring period from August 24 to October 1. The malfunctioning logger was repaired and reinstalled, and continued to monitor energy use for the expanded study. Monitoring for the expanded study continued from October 23, 2012 to June 30, 2013.

ILLUMINANCE MEASUREMENTS

For the initial study horizontal illuminance measurements were taken at ground level at pre-determined points defined by a 20' x 20' grid layout that extended throughout the rectangular area between the baseline HPS pole and the test LEP pole, and between those two light poles and the edge of the site as shown in Figure 9.

In addition to the horizontal measurements, vertical measurements were taken at heights of 20' and 40' above the ground, at pre-determined points at 40' intervals between each pole and the site edge. This illuminance measurement area was chosen to minimize influence from any surrounding light sources.

Both photopic and scotopic illuminance levels were measured using a Solar Light scotopic/photopic illuminance meter, as described in the Instrumentation Plan section, above. Photopic and scotopic illuminance values were used to calculate mesopic illuminance values according to the methodology described in "IES TM-12-12: Spectral Effects of Lighting on Visual Performance at Mesopic Lighting Levels."

Although footcandles is the familiar unit of illuminance measurement in the United States, the IES has transitioned to using the metric unit of "lux." As such, this study recorded illuminance measurements in lux rather than footcandles. The conversion of footcandles to lux is as follows:

EQUATION 4. FOOTCANDLE TO LUX CONVERSION

1 footcandle = 10.76 lux

Or, as a simple rule of thumb, 1 footcandle is approximately 10 lux.

During a site visit on August 30, 2012, the illuminance measurement grid was marked out at the site. Measurement points were marked on the ground with spray paint. Each point was marked with two perpendicular lines, where the intersection of the two lines indicates the measurement point. Vertical measurement points were also indicated by a "V" next to the measurement point markings. Figure 9, below, shows a diagram of illuminance measurement locations at the site. The "H" markings in the diagram indicate points where only horizontal measurements were taken; "V" indicates points where both horizontal and vertical measurements were taken.

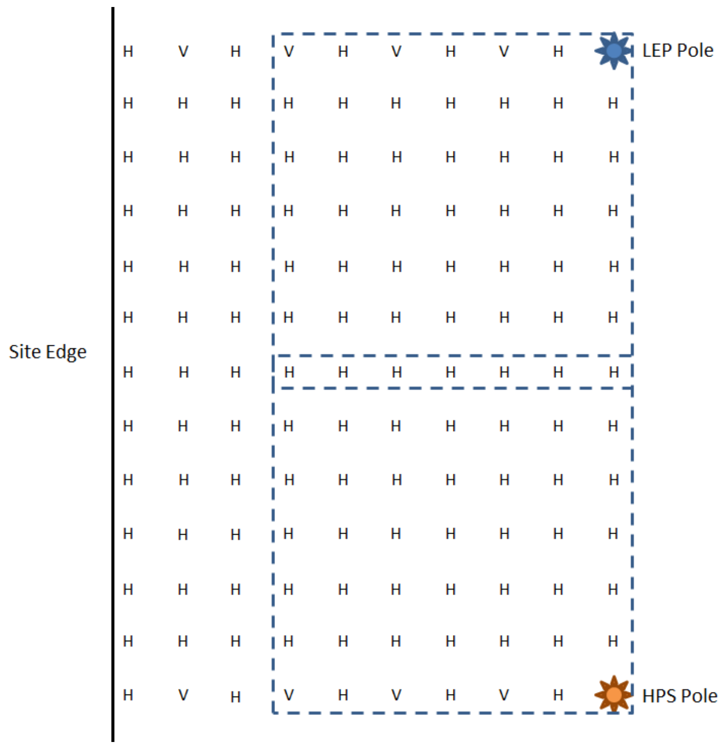

FIGURE 9. DIAGRAM OF ILLUMINANCE MEASUREMENT LOCATIONS

In order to provide an equal illuminance comparison between the LEP and HPS poles, the photocell controlling the emergency fixtures on the HPS pole was taped over during illuminance measurements, forcing the two additional fixtures to turn ON.

In order to provide a direct comparison, the values recorded at all measurement points up to 120' between the poles, and up to 120' toward the water line were used to evaluate the individual LEP and HPS poles. This adjusted area was chosen because 120' represents the typical midpoint between two poles in the broader site area, and therefore this area represents all the points that are most directly influenced by each respective pole. In addition, under typical working conditions, equipment along the site edge provides supplemental illumination in the working area beyond 120'. These adjusted measurement areas are indicated in Figure 9 with dashed lines. Using this adjusted measurement area provides a comparison of the influence of the two poles, while still allowing for the influence of surrounding light sources that are present under real-world conditions. Following the retrofit of the baseline HPS pole to new LEP fixtures, these same areas were used to compare the performance of different versions of the LEP fixtures.

For the expanded study, an additional measurement grid was created between the four poles in the expanded study. Figure 10 shows a diagram of the expanded illuminance measurement grid, indicating the four light poles in the expanded study, and the "H" markings indicate the measurement points in the grid. Poles 2 and 3 both had 12 LEP fixtures, and poles 6 and 7 had eight LEP fixtures each. The dashed rectangle on the right side of the diagram indicates the area used to assess the illuminance of the eight-fixture poles, the two dashed rectangles on the left indicate the areas used to assess the performance of the two twelve-fixture poles.

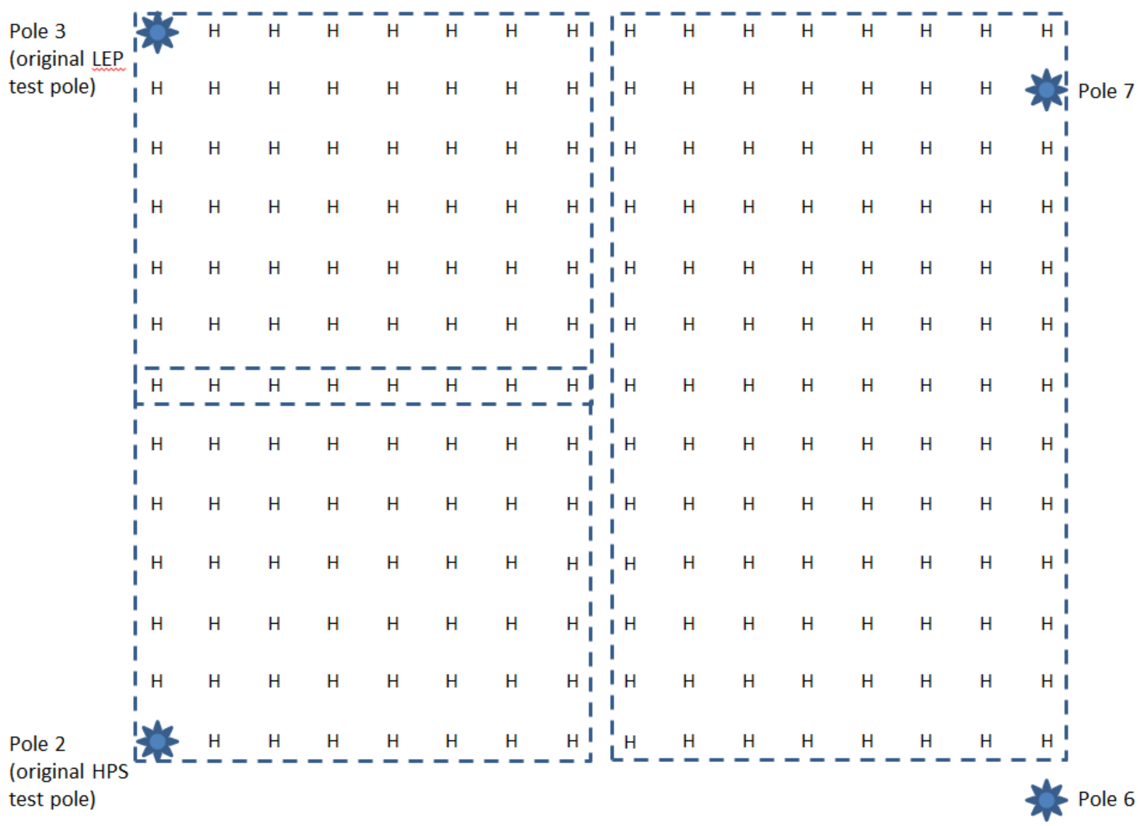

FIGURE 10: EXPANDED ILLUMINANCE MEASUREMENT GRID

As the diagram shows, the test poles were not located in a perfect grid pattern, so Pole 6 is slightly outside of the measurement grid, while Pole 7 is inside the grid rather than at the corner.

The original LEP test pole, Pole 3 in Figure 10, used Version A fixtures for the duration of the study. The eight-fixture test poles, Poles 6 and 7 in Figure 10, used Version B fixtures for the duration of the expanded study. The original HPS study pole, Pole 2 in Figure 10, was initially retrofitted to Version B LEP fixtures, and then was upgraded to Version D fixtures on April 29, 2013.

Illuminance measurements were taken on the original grid on September 20, October 18, and November 15, 2012, and January 10, March 21, May 1, May 20, June 10, and June 20, 2013. Illuminance measurements were taken on the expanded measurement grid on March 11 and June 3, 2013.

RESULTS

The results of the study indicate that the LEP lighting represents a significant reduction in energy use compared to the existing HPS lighting. However, the illuminance measurements taken at the site tell a less clear story. The LEP lighting has lower illuminance levels than the HPS, under both the photopic illuminance measurements, and calculated mesopic illuminance values. On the other hand, port staff surveys and informal conversations indicate that occupants at the site find the LEP lighting to be brighter than the HPS.

The sections below outline the results of various scenarios tested at the study site.

INITIAL STUDY RESULTS

The initial study provided a direct comparison of the new LEP lighting at full output to the existing HPS lighting at the site.

INITIAL STUDY: ENERGY USE RESULTS

Overall, the test LEP lighting represents a significant energy savings compared to the existing baseline HPS lighting. The energy savings results from both the lower wattage of the LEP lighting, and the increased precision of the wireless control system.

Table 5, below, summarizes the total energy use for the initial monitoring period from noon on August 24 to noon on October 1.

TABLE 5. TOTAL ENERGY USE, AUGUST 24 – OCTOBER 1

	TOTAL ENERGY USE, AUGUST 24 TO OCTOBER 1 (KWH)	AVERAGE POWER AT FULL OUTPUT (W)
HPS - extrapolated	6634	12934
LEP	2535	6145
Difference	-4099 (-62%)	-6789 (-52%)

An important detail shown in Table 5 is that the typical power used by the LEP pole at full output is only 52% less than the HPS pole, but the total energy use savings of 62% is much greater. The additional energy savings comes from two main sources. First, as discussed above, one of the LEP fixtures was not fully functional for most of the initial monitoring period resulting in less energy use on the LEP pole. This individual non-functioning LEP module, out of a total of 24 on the LEP pole, only accounts for about 4% of the typical LEP pole energy use. The other source of added energy savings is the more precise schedule allowed by the wireless control system on the LEP lighting.

Table 6, below, shows two examples of the schedules for the HPS and LEP lighting. The first example, the night of August 24 and 25, was during the more aggressive control schedule period, where the lighting was programmed to turn on 30 minutes after sunset, and turn off 30 minutes before sunrise. The second example, the night of September 24 and 25, is after the schedule was reprogrammed to turn lighting on 10 minutes after sunset, and turn off 10 minutes before sunrise.

TABLE 6. EXAMPLE LIGHTING SCHEDULES

	TIME ON	TIME OFF	TOTAL ON TIME
HPS 8/24-25	4:54pm	6:16am	13 hours, 22 minutes
LEP 8/24-25	7:31pm	5:30am	9 hours, 59 minutes
Difference	-2 hours, 37 minutes	-46 minutes	-3 hours, 23 minutes
HPS 9/24-25	4:53pm	6:44am	13 hours, 51 minutes
LEP 9/24-25	7:11pm	6:49am	11 hours, 22 minutes
Difference	-2 hours, 18 minutes	+5 minutes	-2 hours, 29 minutes

In both cases the LEP lighting is on for a significantly shorter amount of time than the HPS lighting. However, it should be noted that after the LEP schedule was adjusted, the LEP lighting turned off 5 minutes later than the HPS lighting. In addition to potential energy savings, the more precise schedule ensures that proper illumination is provided at the site at all times.

If the energy use comparison is isolated to the period where all LEP fixtures were fully functional and after the control schedule had been changed the savings is slightly reduced, but still substantial. Table 7 shows the energy use for this period, from September 24 through October 1.

TABLE 7. TOTAL ENERGY USE, SEPTEMBER 24 – OCTOBER 1

	TOTAL ENERGY USE, SEPTEMBER 24 TO OCTOBER 1 (KWH)	AVERAGE POWER AT FULL OUTPUT (W)
HPS - extrapolated	1257	12944
LEP	529	6347
Difference	-728 (-58%)	-6597 (-51%)

As shown in Table 7, even when all LEP fixtures are fully functional, and the control schedule was adjusted to more conservative timing, the LEP lighting still provides a 58% energy saving over the existing HPS lighting.

INITIAL STUDY: DAILY ENERGY USE EXAMPLES

In order to provide more detailed analysis of the energy use comparison, data for several individual days is presented below. These examples will help to clarify the energy characteristics of the HPS and LEP lighting.

Figure 11, below, shows the power consumption of the HPS and LEP poles on August 26. The HPS pole is shown in red, while the LEP pole is shown in green.

FIGURE 11. DAILY POWER CONSUMPTION, AUGUST 26, HPS POLE (RED) VS. LEP POLE (GREEN)

The aggressive scheduling for the LEP pole that was in place until September 22 is clearly evident in the graph in Figure 11. The LEP lighting turns off more than half an hour before the HPS lighting in the morning, and turns on two and a half hours after the HPS lighting in the evening.

Table 8, below, shows the performance characteristics for this day in more detail. The full output value for the LEP pole reflects the fact that one of the lamps in one of the fixtures was not functioning at this time. This adds to savings from the control schedule to result in an overall 63% energy savings from the LEP lighting compared to the baseline HPS lighting.

TABLE 8. DAILY OPERATION DETAILS, AUGUST 26

	OFF TIME	ON TIME	AVERAGE POWER AT FULL OUTPUT (W)	AVERAGE POWER WHEN OFF (W)	TOTAL ENERGY USE, 8/26 (KWH)
HPS Pole	6:17am	4:54pm	12845	0	172
LEP Pole	5:30am	7:31pm	6082	142	63
Difference	-43 minutes	-2 hours, 37 minutes	-6763 (-53%)	+142	-109 (-63%)

Although the LEP pole uses approximately 53% less energy than the HPS pole at full power, the LEP pole continues to use power when the lights are turned off because the control system, drivers, and power supplies in each fixture are constantly drawing a small amount of power. Even so, because of the aggressive schedule of the control system, the LEP pole uses 63% less energy than the HPS pole over the course of the day.

Figure 12, below, shows the power consumption of the HPS and LEP poles on September 29. The HPS pole is shown in red, while the LEP pole is shown in green. The data in Figure 12 shows the typical LEP pattern after the schedule was adjusted.

FIGURE 12. DAILY POWER CONSUMPTION, SEPTEMBER 29, HPS POLE (RED) VS. LEP POLE (GREEN)

When the lighting is on at full power, the LEP pole uses approximately 50% of the power than the HPS pole uses. The added precision of the wireless control system on the LEP fixtures generates additional savings, although not as much as the data shown in Figure 11 and Table 8, above. In the data shown in Figure 12, the LEP lighting still turns on over two hours after the HPS lighting. This time difference will change depending on the season and the length of the day, but this increased precision represents a substantial energy savings opportunity.

Table 9, below, shows the operational characteristics for September 29 in more detail.

TABLE 9. DAILY OPERATION DETAILS, SEPTEMBER 29

	OFF TIME	ON TIME	AVERAGE POWER AT FULL OUTPUT (W)	AVERAGE POWER WHEN OFF (W)	TOTAL ENERGY USE, 9/29 (KWH)
HPS Pole	6:50am	4:53pm	12935	0	180
LEP Pole	6:53am	7:05pm	6352	106	76
Difference	+3 minutes	-2 hours, 13 minutes	-6583 (-51%)	+106	-104 (-58%)

Although total energy savings will vary depending on the day, and the differences in the control schedule, it is clear that the LEP lighting system provides substantial energy savings over the existing HPS lighting. Again, the LEP lighting uses some energy even when the lighting is turned off, but that extra energy is almost negligible compared to the overall energy savings provided by the LEP lighting compared to the HPS lighting. Figure 13 shows the daily power consumption pattern for a more recent day when the LEP lighting schedule more closely matches that of the HPS lighting. In this example, the data is shown from noon to noon, instead of midnight to midnight.

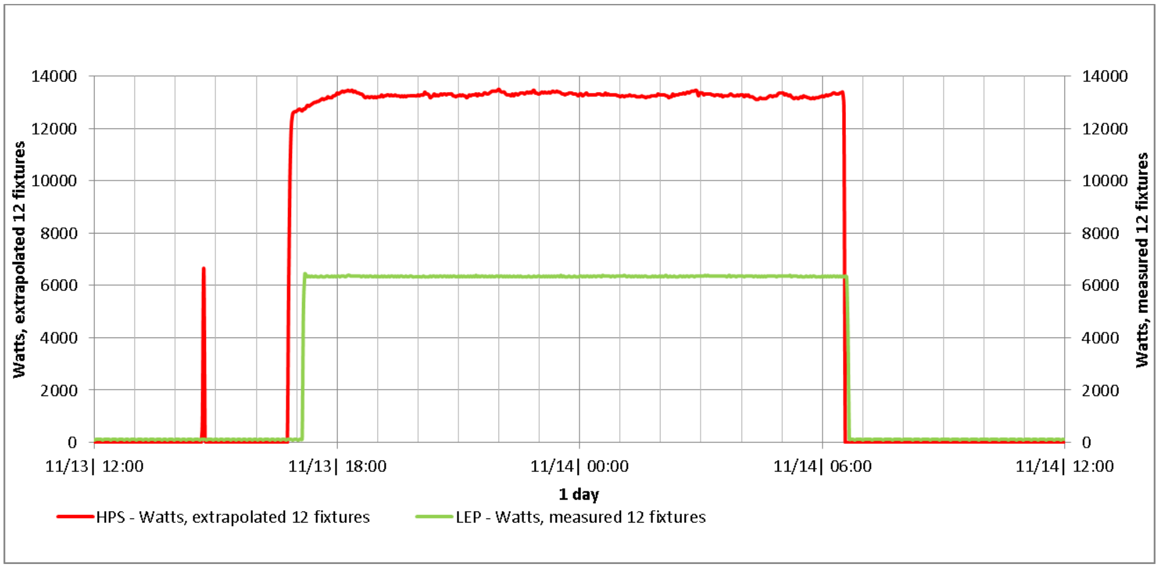

FIGURE 13. DAILY POWER CONSUMPTION, NOVEMBER 13-14, HPS POLE (RED) VS. LEP POLE (GREEN)

Although the magnitude of the power consumption is similar to the examples shown above, the advantage of the control schedule is nearly eliminated.

Table 10, below, shows the operation details for the night of November 13 to 14.

TABLE 10. DAILY OPERATION DETAILS, NOVEMBER 13-14

	ON TIME	OFF TIME	AVERAGE POWER AT FULL OUTPUT (W)	AVERAGE POWER WHEN OFF (W)	TOTAL ENERGY USE, 11/13–11/14 (KWH)
HPS Pole	4:48pm	6:32am	13248	0	182
LEP Pole	5:10pm	6:38am	6348	114	87
Difference	-18 minutes	+6 minutes	-6900 (-52%)	+114	-95 (-52%)

Now that the schedule for the LEP and HPS are almost equal, the energy use savings is also nearly equal to the demand savings. On a similar control schedule, the LEP lighting results in a 52% energy savings, as compared to the HPS lighting. As the data shows, the relatively small load that the controls system, drivers, and power supplies draw even when the lighting is turned off, is practically negligible in the overall energy use.

Initial Study: Direct Comparison of LEP and HPS Fixtures

Although the actual conditions at the study site varied over the course of the study, it is possible to estimate a direct energy use comparison between the LEP lighting and the HPS lighting, if all other conditions are equal.

This direct comparison of a 12-fixture HPS pole and a 12-fixture LEP pole uses the assumptions outlined below. All power assumptions are taken from measured data during the period between September 24 and October 1 when both poles were fully functional.

- HPS pole power at full: 12944W (extrapolated)
- LEP pole power at full: 6347W
- HPS pole power with lights off: 0W
- LEP pole power with lights off: 106W
- Average daily ON time: 12 hours
- Average daily OFF time: 12 hours

Average daily energy use for each pole is calculated as follows:

Equation 5. Estimated Average Daily Energy Use

*Average Daily kWh = ((power at full * 12 hours)/1000) + ((power at OFF * 12 hours)/1000)*

Annual energy use is calculated as follows:

Equation 6. Estimated Annual Energy Use

*Annual energy use (kWh) = Average Daily kWh * 365 days*

Table 11 summarizes the results of this direct comparison.

Table 11. Direct Comparison Estimate

	Power at Full Output (W)	Power when OFF (W)	Average Daily Energy Use (kWh)	Annual Energy Use (kWh/year)
HPS Pole	12944	0	155	56,575
LEP Pole	6347	106	77	28,105
Difference	-6597 (-51%)	+106	-78 (-50%)	-28,470 (-50%)

Although the LEP pole uses 51% less power at full output than the HPS pole, when the energy use is estimated over a day or a year, using equal schedules on both poles, the LEP lighting is estimated to use 50% less energy than the HPS lighting due to the energy that the LEP lighting uses even when turned off.

Initial Study: Illuminance Results

The study site is required to meet OSHA requirements for illuminance levels. For work areas at maritime facilities OSHA requires a minimum average of five footcandles (54 lux).

Figure 14, below, shows a three dimensional plot of photopic horizontal illuminance levels measured on the established measurement grid between the two study poles and the site edge. The LEP pole is at the top left corner of the graph, and the HPS pole is at the top right corner of the graph.

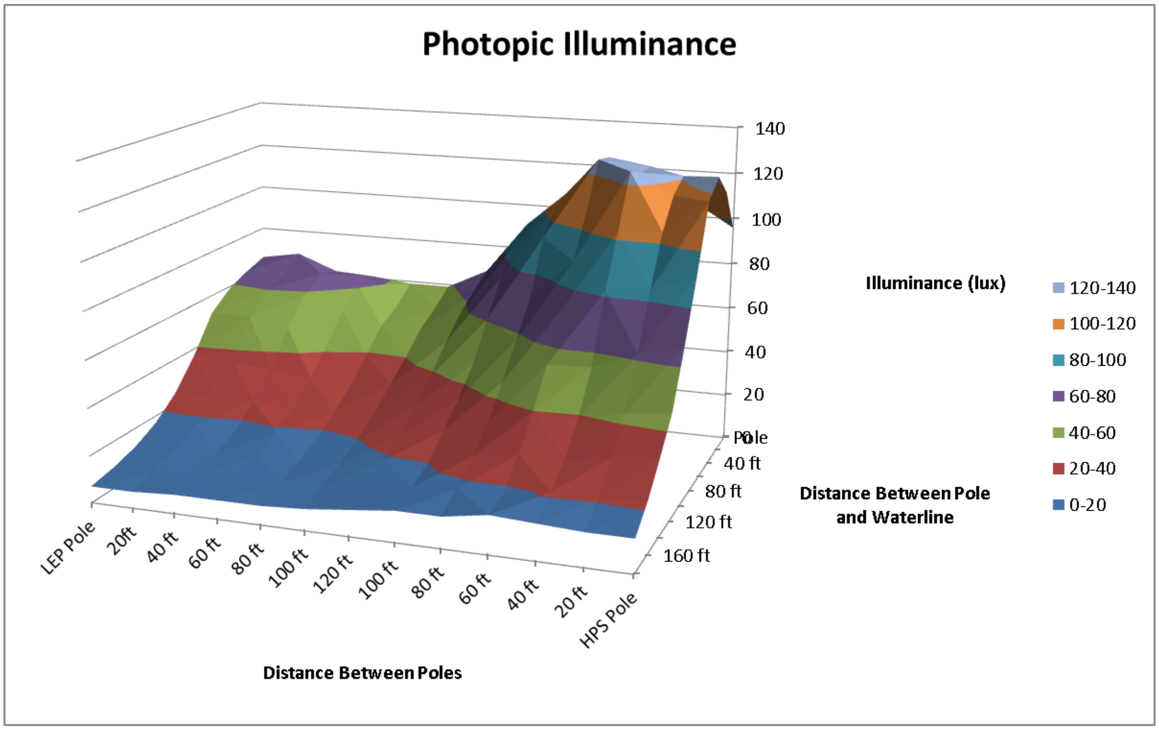

FIGURE 14. PHOTOPIC HORIZONTAL ILLUMINANCE MEASUREMENTS – LEP AND HPS

Because of the yellow-orange color of the HPS lighting, it performs much better than the LEP lighting using photopic illuminance measurements. According to the graph in Figure 14, the maximum illuminance near the HPS pole is nearly twice that of the maximum illuminance near the LEP pole.

Another way to look at this data is presented below in Table 12. The table presents common metrics for evaluating lighting performance.

Using the adjusted measurement area described above (see Illuminance Measurements), Table 12 shows the average, maximum and minimum illuminance for each pole, as well as two common uniformity ratios that are used in IES standards to evaluate outdoor lighting. The lower the uniformity ratio, the less variation in light levels within a given area. Generally, for working conditions such as the study site, low uniformity ratios are preferred, as they require less adaptation by the eye. For reference, typical IES recommendations for parking lot lighting suggest that uniformity ratios should be no more than 4:1 (average:minimum).[6]

TABLE 12. PHOTOPIC ILLUMINANCE DATA (ADJUSTED AREA) – LEP AND HPS

	Adjusted Average (lux)	Maximum (lux)	Minimum (lux)	Max:Min	Avg:Min
HPS	78	126	24	5.25:1	3.25:1
LEP	43	69	17	4.06:1	2.55:1

[6] ANSI/IESNA RP-8-00, American National Standard Practice for Roadway Lighting

As the data in Table 12 shows, the HPS lighting provides higher overall photopic light levels, but the LEP lighting is more uniform. However, the lighting from both poles is well within the 4:1 uniformity recommendation (average:maximum).

The primary concern with the data shown in Table 12 is that the adjusted average for the LEP lighting does not meet the minimum average illuminance level required by OSHA for maritime work areas (54 lux).

However, the photopic illuminance levels may not fully describe the visual conditions at the site. As described above, for each set of illuminance measurements, the study also conducted an analysis to determine mesopic illuminance, based on a methodology established by the IES. The mesopic illuminance levels are a better indicator of visual performance under nighttime lighting conditions that the photopic levels. Figure 15 shows a three-dimensional plot of the calculated mesopic illuminance levels.

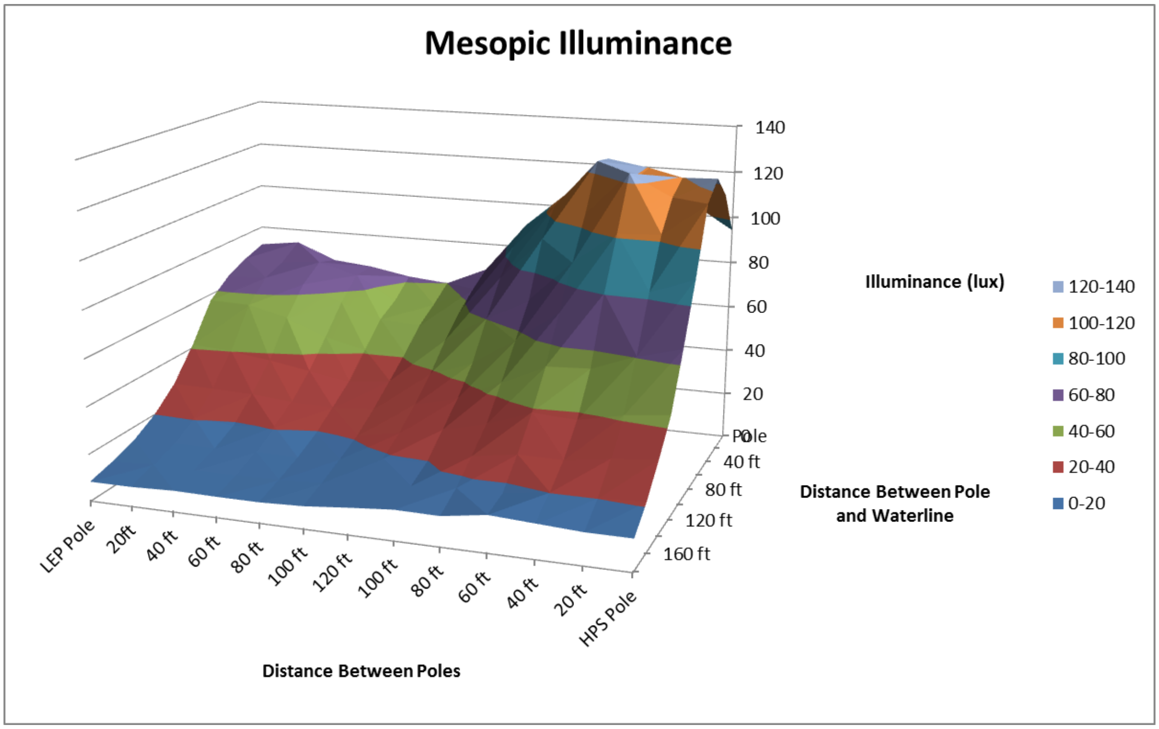

FIGURE 15: CALCULATED MESOPIC HORIZONTAL ILLUMINANCE – LEP AND HPS

Although the overall trends in Figure 14 and Figure 15 are similar, the mesopic illuminance levels in Figure 15 show slightly higher values for the LEP pole, and slightly lower values for the HPS pole. These results are shown in detail in Table 13. Using the calculated mesopic illuminance, the average HPS light level reduces slightly to 77 lux, and the LEP average increases slightly to 46 lux.

TABLE 13: CALCULATED MESOPIC ILLUMINANCE DATA (ADJUSTED AREA) – LEP AND HPS

	Adjusted Average (lux)	Maximum (lux)	Minimum (lux)	Max:Min	Avg:Min
HPS	77	125	24	5.20	3.20
LEP	46	74	19	3.85	2.40

Although the calculated mesopic light levels shown in Table 13 indicate an increase for the LEP over the measured photopic light levels, the average illuminance from the LEP in this case is still below the 54 lux minimum average.

The expanded study, described in detail in the sections below, tested improved versions of the LEP fixture, as well as an expanded study area and wireless controls options.

In addition to horizontal illuminance levels at the ground, the study also measured vertical illuminance levels at 20′ and 40′ above the ground. These measurements were intended to represent the light levels on the sides of shipping containers stacked at the study site.

Photopic vertical illuminance measurements are shown below in Figure 16. The figure shows LEP and HPS illuminance values at 20′ above the ground, and 40′ above the ground, as well as the difference between the LEP and HPS values for each height.

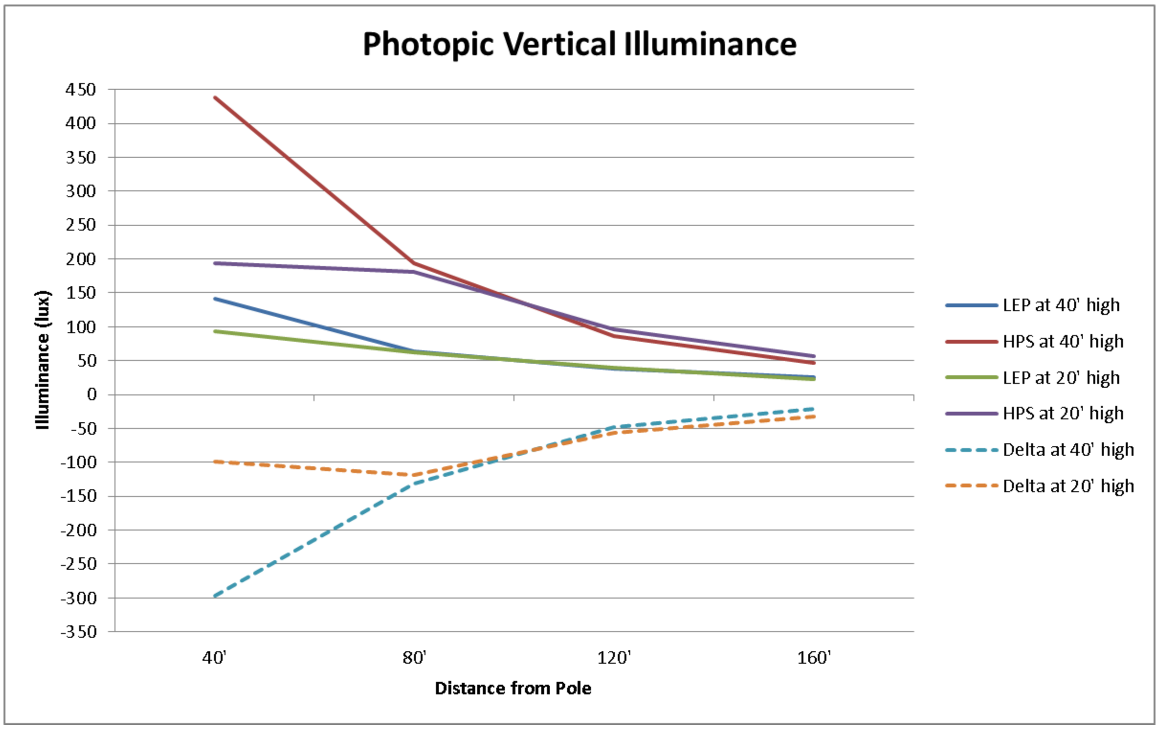

FIGURE 16. PHOTOPIC VERTICAL ILLUMINANCE – LEP AND HPS

The vertical illuminance measurements indicate that the vertical illuminance values under the HPS lighting are much higher than corresponding horizontal values, while the vertical illuminance measurements under the LEP lighting are more consistent with corresponding horizontal illuminance measurements. Although the LEP values are lower than the HPS values, the measurements suggest that the LEP lighting will provide sufficient illumination to maintain legibility of shipping container markings.

EXPANDED STUDY RESULTS

Following the initial study comparing a single LEP pole with the incumbent HPS lighting, the study was expanded with additional poles at the study site retrofitted to LEP. The expanded study had no baseline HPS pole to compare the performance of the LEP fixtures – rather the expanded study evaluated the performance of the LEP fixtures when installed in a larger area and not influenced by output from the HPS fixtures.

With additional LEP poles at the study site, as well as an extended study period, the expanded study considered the following issues:

- LEP performance in an additional area at the study site
- Energy and light output of improved LEP fixture versions
- Energy and light output for various control scenarios using the wireless control system
- Light output for the LEP fixtures over time

Results from the expanded study are presented in the following sections. Note that some of the additional LEP poles installed during the expanded study had eight (8) fixtures per pole as opposed to twelve (12) fixtures per pole. The study site and the fixture manufacturer had expected that eight fixtures would be sufficient to provide adequate illumination.

The energy analysis and illuminance levels discussed below are based on the twelve-fixture poles unless otherwise noted.

For ease of comparison, all illuminance results in this section will be presented as the calculated mesopic illuminance levels. TRC believes that the mesopic illuminance levels are most representative of the nighttime visual conditions at the site.

The expanded study included installing LEP fixtures on additional poles in and around the study area, replacing the existing HPS lighting. Three additional LEP poles were included in the expanded study, and a total of nine poles in and around the study area were retrofitted to LEP.

The additional poles in the expanded study area served several purposes. One main goal was to study the results of a more complete LEP installation than the scenario in the initial study. Another goal was to study the effectiveness of reducing the number of fixtures on each pole from twelve to eight.

LEP ILLUMINANCE EFFECTIVENESS – WITHOUT HPS INFLUENCE

The ability to measure a larger installation of LEP lighting revealed that the illuminance measurements in the initial study were heavily influenced by the presence of the HPS lighting. Although the initial study found that the average photopic illuminance level under the LEP lighting was 43 lux, when the HPS lighting in the area was replaced with LEP lighting, the photopic illuminance level in that same area dropped to an average of 30 lux (averaged across five site visits).

Figure 17 shows a three-dimensional plot of calculated mesopic illuminance levels based on measurements taken at the site on March 21, 2013. The plot shows illuminance levels after all nine poles in and around the study area were retrofitted to LEP. This plot also shows the slightly improved "Version B" of the LEP fixture replacing the HPS pole from the initial study (see "Energy and Illuminance Impacts from Improved Fixture Versions" below for more information). The illuminance values shown in this plot are noticeably lower than those shown above in Figure 15 for the initial study.

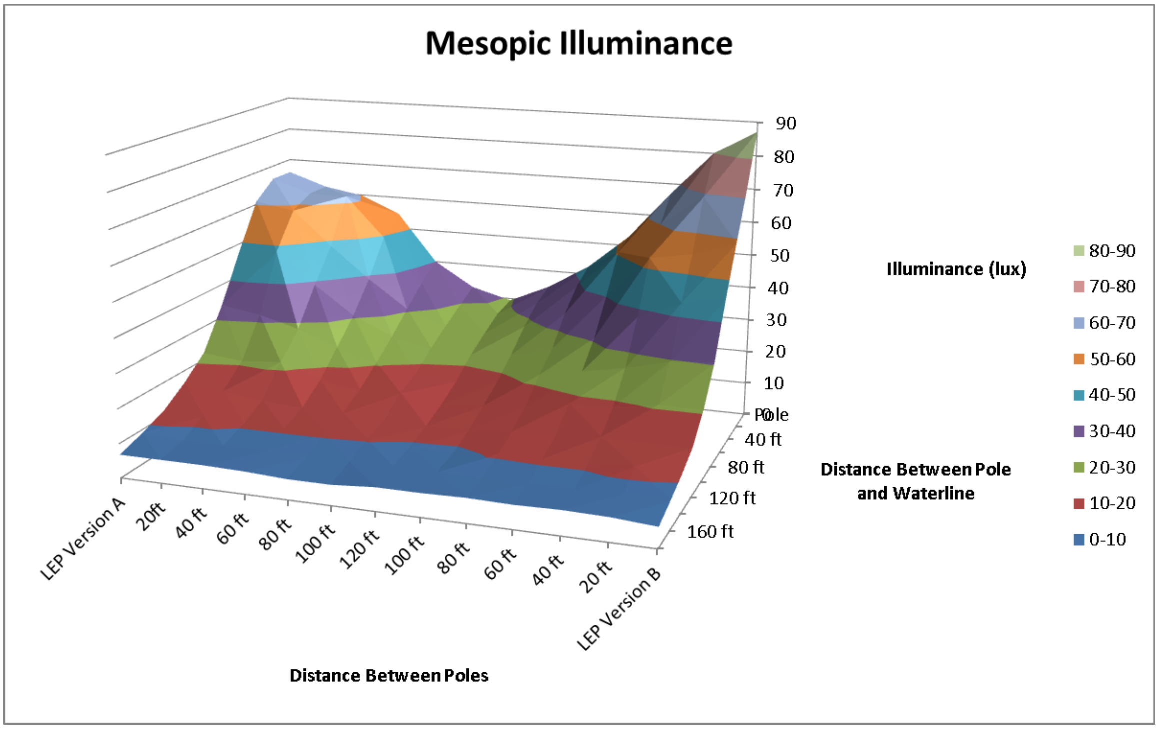

FIGURE 17: CALCULATED MESOPIC HORIZONTAL ILLUMINANCE – LEP ONLY, MARCH 21, 2013

Table 14 shows the calculated mesopic illuminance data in more detail. The average mesopic illuminance for the two LEP poles was 34 lux, significantly less than the 46 lux calculated for the LEP pole in the initial study. Although the maximum illuminance level increased with the Version B fixtures (87 lux instead of 74 lux), eliminating the influence of the HPS lighting reduced the overall average illuminance.

TABLE 14: CALCULATED MESOPIC HORIZONTAL ILLUMINANCE

	ADJUSTED AVERAGE (LUX)	MAXIMUM (LUX)	MINIMUM (LUX)	MAX:MIN	AVG:MIN
LEP (version A) with HPS influence	46	74	19	3.85	2.40
LEP only (average of one each of version A and B), March 21, 2013	34	87	12	7.53	2.95

These results indicate that the initial versions of the LEP fixtures provided about one half of the illuminance provided by the HPS lighting (see Table 13). However, further improvements to the LEP fixtures provided significant improvements in the light output, as described below in "Energy and Illuminance Impacts from Improved Fixture Versions."

IMPACT OF THE NEW EIGHT-FIXTURE POLES VS ORIGINAL TWELVE-FIXTURE POLES

In addition to the ability to isolate performance of the LEP fixtures, the expanded study provided the opportunity to evaluate the impact of the decision to use eight fixtures per pole instead of the existing twelve fixtures.

Figure 18 shows a three-dimensional plot of illuminance levels in the expanded study area. Values at the top and left side of the plot are nearest the twelve-fixture poles, while values near the bottom and right side of the plot are closest to the eight-fixture poles. The plot shows that the influence of additional poles in the study area slightly increases the values near the twelve-fixture poles, as compared to the values shown in Figure 17 between two poles and the waterline. In addition, the values near the eight-fixture poles are proportionally lower, as expected.

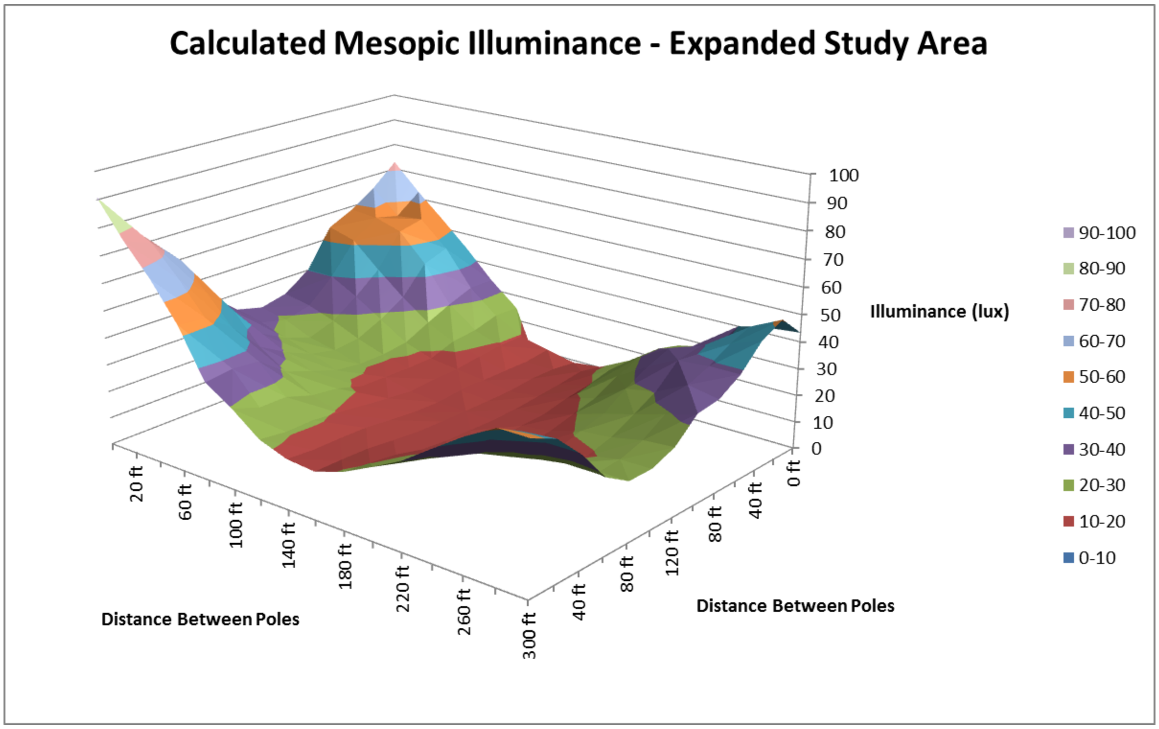

FIGURE 18: CALCULATED MESOPIC HORIZONTAL ILLUMINANCE LEVELS – EXPANDED STUDY AREA, MARCH 11, 2013

Table 15 shows the calculated mesopic illuminance levels in more detail. As the table shows, the average illuminance for the eight-fixture poles is approximately 74% of the illuminance for the twelve-fixture pole, but both averages were still well below the 54 lux minimum.

TABLE 15: CALCULATED MESOPIC HORIZONTAL ILLUMINANCE LEVELS – EXPANDED STUDY AREA, MARCH 11, 2013

	ADJUSTED AVERAGE (LUX)	MAXIMUM (LUX)	MINIMUM (LUX)	MAX:MIN	AVG:MIN
LEP 12-fixture poles	35	91	15	6.03	2.31
LEP, 8-fixture poles	26	52	15	3.56	1.79

Although reducing the number of fixtures on the pole allows for additional energy savings, the illuminance levels from the eight-fixture pole are well below the minimum required light levels, and therefore do not represent a viable solution for this study site.

ENERGY AND ILLUMINANCE IMPACTS FROM IMPROVED FIXTURE VERSIONS

Over the course of the expanded study, the fixture manufacturer provided a series of improved LEP fixtures to the test site in an attempt to achieve minimum illuminance requirements. Two additional LEP fixture versions were installed at the site following the initial study period. Each new version provided an incremental increase in light output without significantly changing the power consumption of the fixtures. In the following discussion, the original fixture version from the initial study is referred to as "Version A" and the subsequent versions are referred to as "Version B" and "Version D."

Figure 19 shows the average power for a 12-fixture pole for each fixture version. As the chart shows, each fixture improvement resulted in slightly reduced power consumption. The Version D fixtures also had lower power consumption when the fixtures were turned off, using an average of 43W per pole, compared to the average power consumption of 106W when the Version A fixtures are turned off, further increasing power savings.

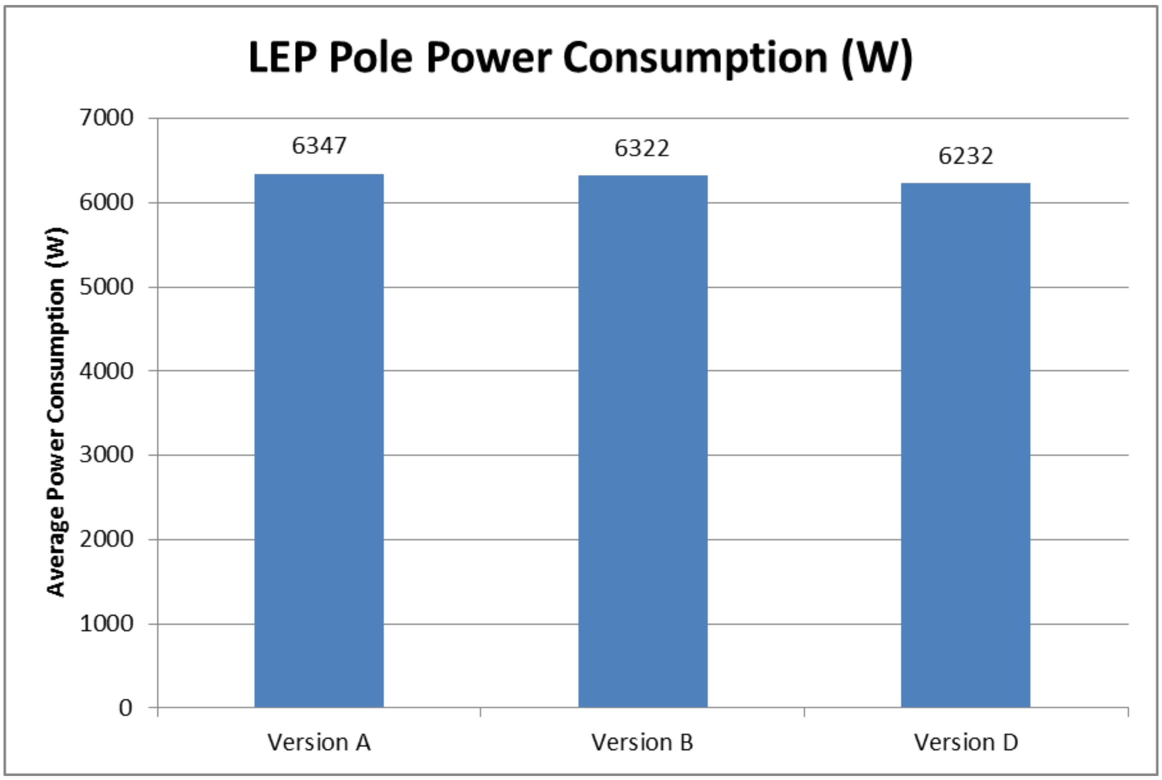

FIGURE 19: AVERAGE LEP POLE POWER CONSUMPTION FOR IMPROVED FIXTURE VERSIONS

Despite reducing power consumption, each improved fixture version also increased light output. Figure 20 shows the average illuminance for each fixture as measured in the initial study measurement area.

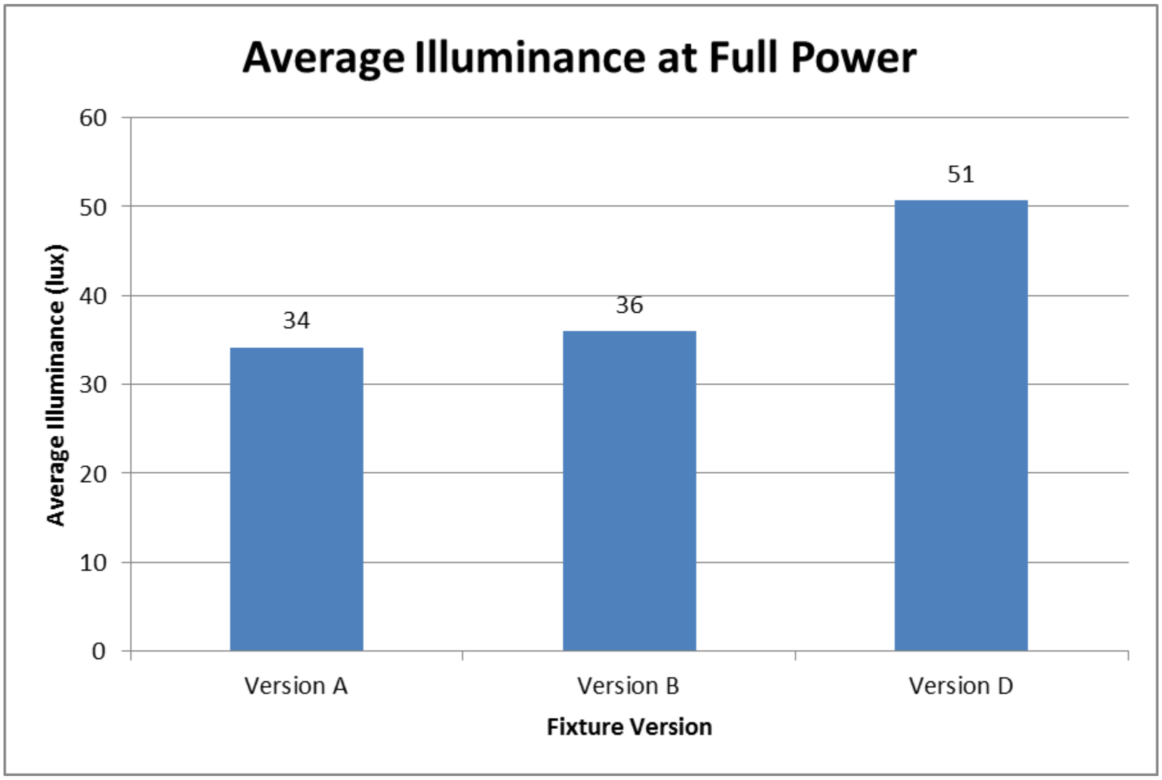

FIGURE 20: AVERAGE MESOPIC ILLUMINANCE AT FULL POWER FOR IMPROVED FIXTURE VERSIONS

Although Version B provided only a slight increase in light output, increasing the average illuminance from 34 to 36 lux, Version D provided a significant increase in illuminance, increasing the average mesopic illuminance to 51 lux.

The Version D average illuminance remains slightly lower than the required minimum average illuminance level of 54 lux. However, this may be due in part to the fact that there was only one Version D pole at the study site, surrounded by older fixture versions with slightly lower light output. In addition, the measurement area for these calculations is at the edge of the grid, without another row of poles to contribute to the average. TRC believes that a full installation of Version D fixtures at the study site would likely meet the minimum light level requirements.

Table 16 shows an updated energy use comparison between the incumbent HPS technology, and the upgraded Version D LEP fixtures. All assumptions in this table are the same as those described above in "Initial Study: Direct Comparison of LEP and HPS Fixtures." As the table shows, the Version D LEP pole at full output uses 52% less power and energy than the HPS pole.

TABLE 16: ENERGY USE COMPARISON - VERSION D

	POWER AT FULL OUTPUT (W)	POWER WHEN OFF (W)	AVERAGE DAILY ENERGY USE (KWH)	ANNUAL ENERGY USE (KWH/YEAR)
HPS Pole	12944	0	155	56,575
LEP Pole, v.D	6232	43	75	27,485
Difference	-6712 (-52%)	+43	-80 (-52%)	-29,090 (-52%)

ENERGY SAVINGS FROM CONTROL STRATEGIES

The expanded study also considered the energy savings potential of the use of the wireless controls installed in the LEP fixtures at the study site. The wireless control system allows for the individual control of each LEP fixture, including dimming, providing for a wide range of control strategies.

Nighttime activity at the study site varies depending on the day, and the area of facility. This variation provides the opportunity to reduce light levels and energy use in areas and nights without activity. The study considered two main control strategies. The first strategy involved dimming the fixtures to a 50% control signal during low activity times. The second strategy involved turning off half of the fixtures on the pole during low activity times. The sections below discuss each of these strategies in more detail.

Results of the control scenarios shown use values from the Version D fixtures because those fixtures represent the most current technology.

CONTROL SCENARIO: DIMMING

The first control strategy tested was dimming all fixtures to 50% control signal on all twelve fixtures on each pole. Although the control setting was set at 50%, dimming control settings do not necessarily directly correspond to the light output of the fixture, or the power consumption. As the results of this study found, a dimming control signal of 50% resulted in greater than 50% power consumption, but less than 50% light output.

Figure 21 shows the results of the 50% dimming signal tests with the Version D fixtures. The blue bars in the chart represent calculated average mesopic illuminance in lux, and the red diamonds represent the average pole power consumption in Watts. As the chart shows, the average illuminance at 50% dimming signal is less than 50% of the full output value, but the power consumption is more than 50% of the full output value.

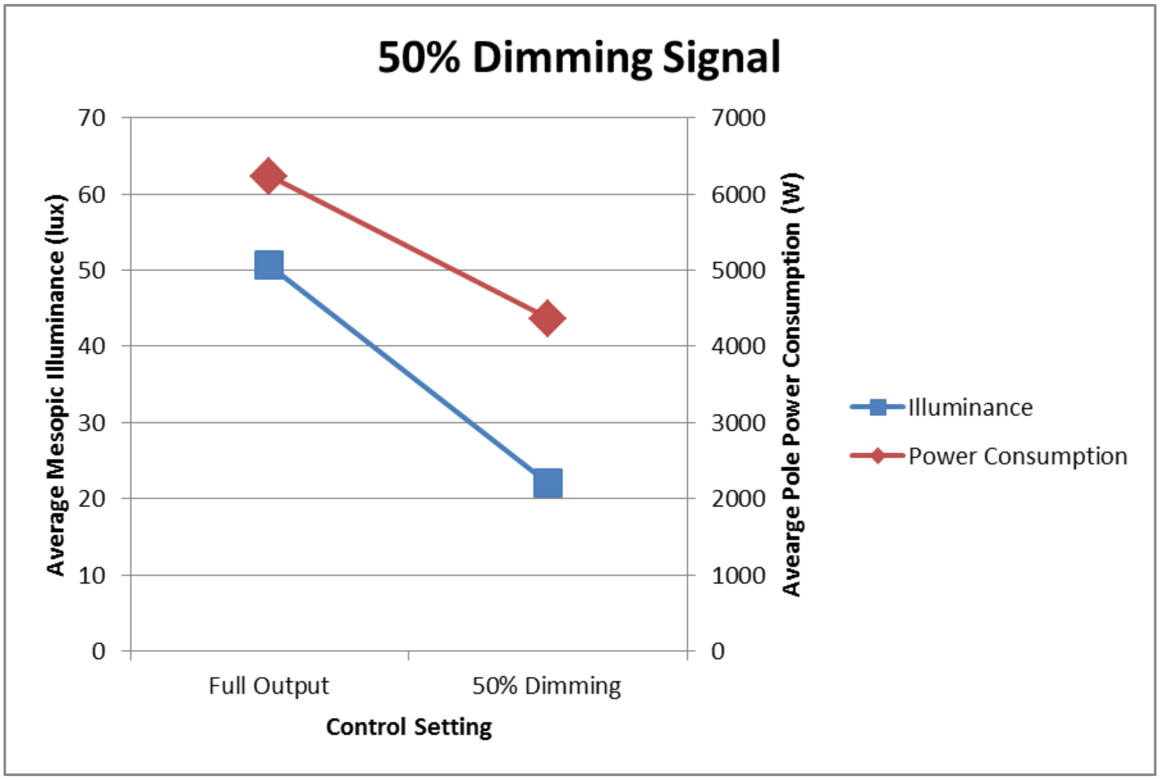

FIGURE 21: 50% DIMMING SIGNAL RESULTS

Table 17 shows these results in more detail. As the table shows, the light output at 50% dimming signal was 57% less than full power, but the power consumption was only 30% less than the full output value.

TABLE 17: 50% DIMMING SIGNAL RESULTS

	AVERAGE MESOPIC ILLUMINANCE (LUX)	AVERAGE POLE POWER CONSUMPTION (W)
Full Output	51	6232
50% Dimming Signal	22	4367
Percent Reduction	57%	30%

In order to better understand the dimming properties of the LEP fixtures, TRC tested the fixtures at two additional dimming signal values, 25% and 75%. Although the fixtures are technically dimmable to 20% control signal, the manufacturer of the LEP modules does not recommend dimming below 40% due to the color shift in the fixtures at low dimming levels. Below 40% dimming signal the light becomes very blue, and would not be useful for most applications.

Figure 22 shows the changes in power consumption and average illuminance through three dimming control signal levels, 75%, 50% and 25%. As the chart shows, in all three cases, the illuminance is less than the dimming signal, while the power consumption is significantly higher.

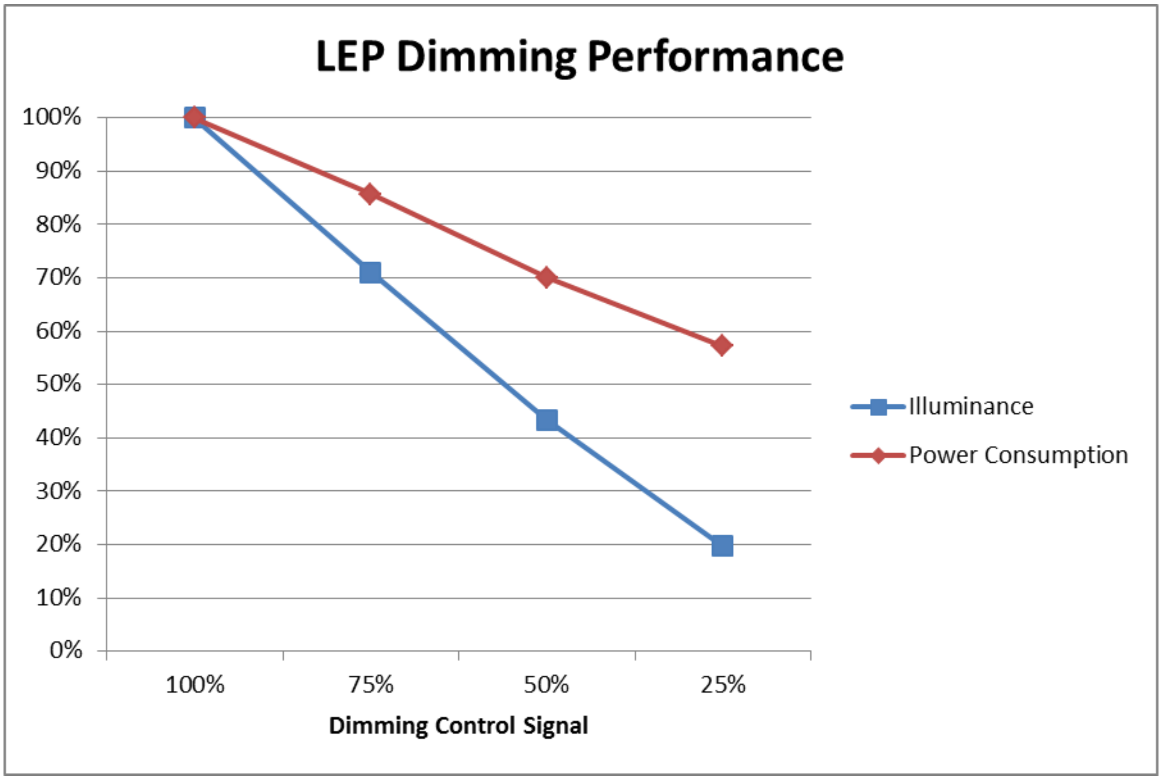

FIGURE 22: LEP DIMMING PERFORMANCE

Table 18 shows these results in more detail. As the table shows, in all cases, the illuminance level is below the dimming control signal level, while the power consumption is significantly higher than the dimming control signal level. As noted above, the 25% dimming control is unlikely to be used in typical applications, but the data shown in the table reinforces this trend.

TABLE 18: LEP DIMMING PERFORMANCE

DIMMING CONTROL SIGNAL	ILLUMINANCE	POWER CONSUMPTION
100%	100%	100%
75%	71%	86%
50%	43%	70%
25%	20%	57%

Despite the disconnect between dimming signal, illuminance and power consumption, dimming control may be useful in scenarios where LEP fixtures are configured with one or two fixtures per pole, and where uniformity is a high priority. However, in scenarios like the study site where each pole has twelve fixtures, multiple fixtures can be turned off entirely when less light is needed without sacrificing uniformity. This consideration led to the second control strategy discussed in the following section.

CONTROL SCENARIO: HALF-ON, HALF-OFF

In addition to the dimming scenarios considered above, this study examined a control strategy where half of the fixtures on each pole are turned off entirely during low activity times. Because each of the poles has twelve fixtures, turning off half of the fixtures reduces the power consumption by approximately half, and provides about half of the light, without sacrificing uniformity.

Figure 23 shows the results of the half-on, half-off control tests for the Version D fixtures. The blue bars in the chart represent calculated average mesopic illuminance in lux, and the red diamonds represent the average pole power consumption in Watts. As the chart shows, both the illuminance and the power consumption of the half-on, half-off control scenario are approximately half of the full output values.

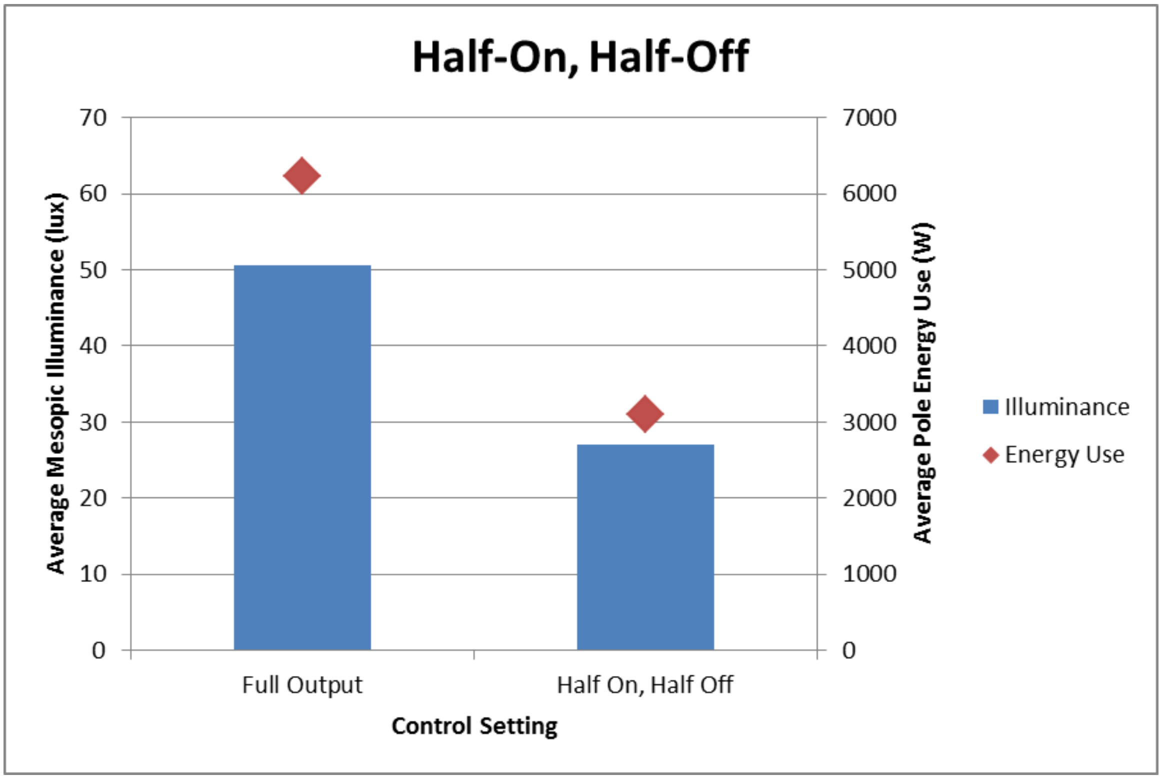

FIGURE 23: HALF-ON, HALF-OFF CONTROL RESULTS

Table 19 shows these results in more detail. As the table shows, turning off half of the fixtures during low activity periods provides slightly more than 50% of full output illuminance while consuming only about 50% of the power.

TABLE 19: HALF-ON, HALF-OFF CONTROL RESULTS

	AVERAGE MESOPIC ILLUMINANCE (LUX)	AVERAGE POLE POWER (W)
Full Output	51	6232
Half-On, Half-Off control	27	3099
Percent Reduction	47%	50%

As these results show, in situations like the study site where there are multiple LEP fixtures on each pole, turning off some of the fixtures entirely is a better control option than dimming in terms of both light output and power savings. This partial fixture control strategy also has the added benefit of avoiding the color shift issues that dimming the LEP fixtures causes.

Furthermore, applications like the study site, with twelve fixtures per pole have several options for partial fixture control, using eight, six or four fixtures to achieve the desired light level without significantly impacting uniformity.

CONTROL ENERGY SAVINGS OVER TIME

Active lighting control for low activity periods presents a significant opportunity for energy savings. As part of the wireless control study, the facility engineer actively controlled the lighting for a 125 day period from October 23, 2012 to February 24, 2013. During this period, any time there was activity in the area around the test site, the lights were kept on a full power. If there was no activity scheduled in the area, the lighting was reduced, either by dimming or by turning off half of the fixtures. Over the course of the control scenario study, 80 of the 125 nights, or 64% of the nights had a reduced light level. Table 20 compares the power consumption of the incumbent HPS, the study LEP lighting without controls, and the LEP with half-on half-off controls at low activity times. The table also shows the average daily and annual energy use comparison for all three conditions, assuming that the active control scenario uses a reduced light level on 64% of the nights, as recorded in the study.

TABLE 20: POWER CONSUMPTION SUMMARY

	POWER AT FULL OUTPUT, W	POWER AT LOW ACTIVITY TIMES, W	STANDBY POWER, W	AVERAGE DAILY ENERGY USE, KWH	AVERAGE ANNUAL ENERGY USE, KWH
HPS Pole	12944	12944	0	155	56,575
LEP Pole, no controls	6232	6232	43	75	27,375
LEP Pole, half-on half-off control for low activity times	6232	3099	43	51	18,615

Table 21 shows the energy savings for three different conditions. First, the table shows the energy savings of using LEP without active controls compared to the incumbent HPS. Second, the table shows the energy savings of using LEP with active controls compared to the incumbent HPS. Finally, the table shows the energy savings of LEP with controls compared to LEP without controls. Energy savings calculations are based on the power and energy use values shown above in Table 20, and assuming that the active control scenario allows reduced light levels on 64% of the nights, as recorded at the study site. As Table 21 shows, using the half-on, half-off control scenario, this active lighting control for low activity nights would result in a 67% energy savings compared to the incumbent HPS lighting, and a 32% savings over the LEP without active controls.

TABLE 21: ENERGY SAVINGS SUMMARY

	SAVINGS AT FULL OUTPUT, W (%)	SAVINGS AT LOW ACTIVITY TIMES, W (%)	STANDBY POWER, W	AVERAGE DAILY ENERGY SAVINGS KWH (%)	ANNUAL ENERGY SAVINGS, KWH
Savings, LEP without controls vs. HPS	6712 (52%)	6712 (52%)	+43	80 (52%)	29,200
Savings, LEP with controls vs HPS	6712 (52%)	9845 (76%)	+43	104 (67%)	37,960
Savings, LEP with controls vs LEP without controls	0	3133 (50%)	0	24 (32%)	8,760

As the table shows, the addition of the active controls results in significant energy savings compared to the LEP lighting without controls. In the case of the study site, including the active control could result in an additional annual savings of 8,760 kWh per pole as shown in Table 21. Actual control savings will vary depending on site conditions, but other applications of wireless controls may be able to save even more energy if they are able to reduce light levels more often, or reduce to lower light levels.

ILLUMINANCE OVER TIME

The length of the expanded study also provided the opportunity to study the performance of the LEP fixtures over time in order to determine if there is any significant degradation of light output, or lumen depreciation.

As described above, the Version A fixtures installed for the initial study were kept in place for the 10-month duration of the study in order to measure any lumen depreciation over time. To assess lumen depreciation, TRC compared the illuminance measurements in the straight line between the base of the pole and the waterline from the various illuminance measurement dates over the course of the study.

Figure 24 shows a selection of photopic illuminance measurements between the base of the pole and the waterline over the course of the study period. Unfortunately, because of the changing lighting conditions surrounding the study site, early measurements were heavily influenced by the presence of nearby HPS lighting, resulting in higher illuminance levels measured around the initial LEP test pole.

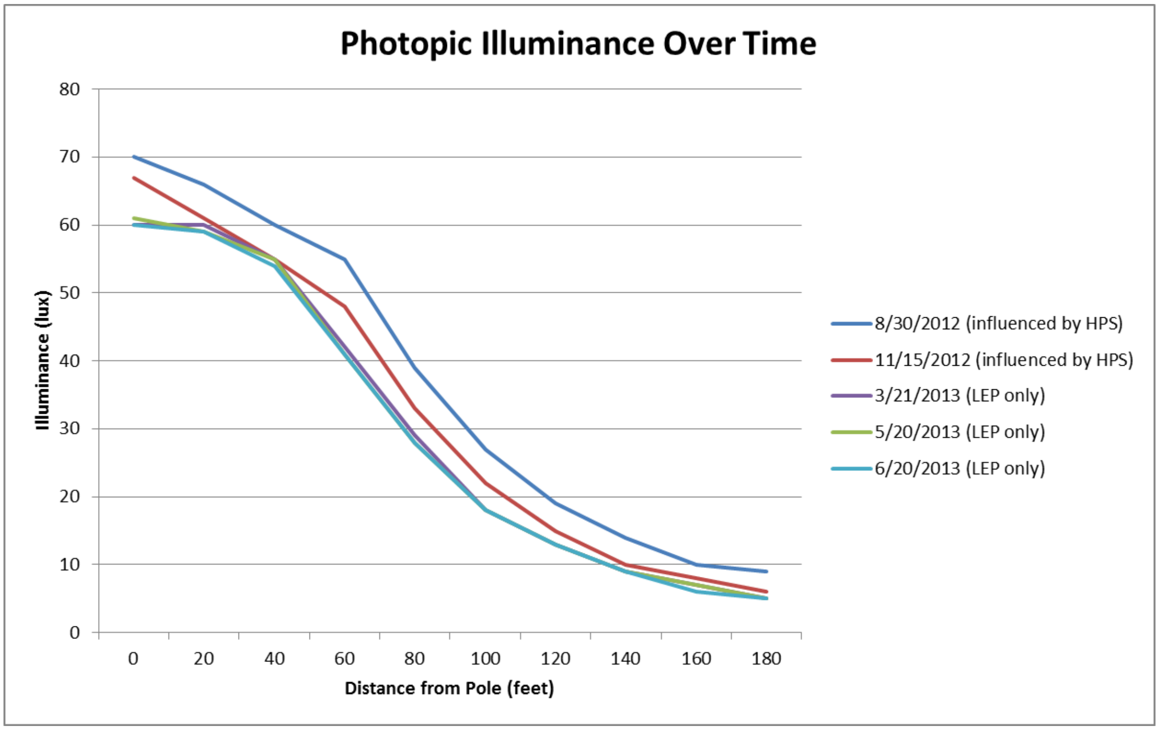

FIGURE 24: LEP PHOTOPIC ILLUMINANCE MEASUREMENTS OVER TIME

Although the data in the chart suggests that the LEP illuminance dropped between measurements taken on August 30, 2012, and those take on November 15, these reductions are likely the result of HPS lighting in the area being replaced with LEP fixtures. Further reductions between November 15, 2012 and March 21, 2013 are also likely explained by additional lighting retrofits at the site. Measurements taken from March 21, 2013 and after are virtually indistinguishable.

Although the results, as shown in Figure 24, are difficult to interpret, TRC expects that the differences in the measurements were due primarily to the removal of nearby HPS lighting, and that the LEP lighting did not have any significant lumen depreciation over the ten months of the study period.

VISUAL QUALITY AND OCCUPANT SURVEYS

In addition to the quantitative data discussed in the previous sections, TRC conducted an online survey of facility managers at the study site to get a sense of what working conditions are like under the LEP lighting. Although seven people responded to the survey, only six of the respondents were familiar with the LEP lighting installation, so all results shown here are based on a sample size of six respondents – which is a very small sample size rendering the results not significant from a statistical perspective. Further, the responses from the small sample show a significant variation in the responses. Thus it is hard to extrapolate any general trends from the survey data except the overall perception of illuminance from LEP. Detailed survey results are shown in the Appendix.

Overall, the survey responses were mostly positive, with most respondents indicating that the new LEP lighting appeared brighter than the incumbent HPS lighting. Some respondents indicated that the LEP lighting provided improved visibility as compared to the incumbent HPS lighting, but some respondents reported that visibility of workers on foot and markings on containers is actually reduced under the LEP lighting.

RETURN ON INVESTMENT

TRC conducted a simple-payback return on investment calculation to determine how quickly the value of the energy savings exceeded the initial cost of retrofitting to LEP lighting.

This calculation makes a number of assumptions based on the nature and location of this study. Calculations were based on retrofitting an existing 12-fixture pole, similar to the poles at the study site. Fixture costs range from $2500 to $2900 depending on the inclusion of wireless controls, and the volume of the fixture order. The installation of the 12 fixtures is assumed to take two electricians eight hours each, for a total of 16 labor hours. The calculations use a labor rate of $110.44 per hour for the San Francisco area, based on data from Means CostWorks (RS Means 2010). According to data from PG&E, industrial customers pay between $0.12 and $0.17 per kWh of electricity, with an average rate of $0.15 per kWh. Finally, the calculations assume that the lighting is used for a total of 4100 hours in a typical year, as established in the Database for Energy Efficient Resources (DEER) for exterior lighting applications. These simple payback calculations did not consider the potential for increased energy rates in the future, the difference in maintenance costs over time, differential costs of other retrofit options, or the time-value of money.

Table 22 shows a range of simple payback times in years assuming that the LEP lighting is turned on at full power every day, depending on the cost of the fixtures, and the electricity rate. Payback times range between 6.8 years and 11.1 years, although the average industrial electricity rate of $0.15 per kWh would provide payback times in the seven to nine year range.

TABLE 22: SIMPLE PAYBACK (IN YEARS) ASSUMING LEP LIGHTING AT FULL POWER AT ALL TIMES

	Fixture Price	
Electricity Rate (per kWh)	$2500	$2900
12 cents	9.6	11.1
15 cents	7.7	8.9
17 cents	6.8	7.8

However, the values shown above do not include the additional potential energy savings from the control scenarios made possible by the wireless controls used at the study site.

Actively controlling LEP lighting during low activity time periods has the potential to significantly reduce the payback periods. Exact payback periods with active controls will vary depending on the control strategy, and how often the light level can be reduced. For example, based on the results at the study site if half of the lights are turned off 64% of the time, typical payback periods could be reduced by about 23%.

Table 23 shows simple payback based on the active control results at the study site. By actively controlling fixtures at the site, payback periods could be as low as 5.2 years.

TABLE 23: SIMPLE PAYBACK (IN YEARS) ASSUMING ACTIVE CONTROL OF LEP FIXTURES

	FIXTURE PRICE	
ELECTRICITY RATE (PER KWH)	$2500	$2900
12 cents	7.4	8.5
15 cents	5.9	6.8
17 cents	5.2	6.0

As noted above, these simple payback calculations do not consider a number of other factors, including the comparative cost of other retrofit options or the time value of money. The actual payback for a retrofit LEP installation is likely to be shorter than the values listed here.

RESULTS SUMMARY

The results discussed in the sections above can be summarized into the following key findings:

- **LEP fixtures provide less light than the incumbent HPS, but new LEP fixture versions are likely to meet minimum light level requirements** – Although the new LEP light fixtures do not match the illuminance levels of the incumbent HPS lighting, TRC expects that a full installation of twelve-fixture LEP poles at the study site is likely to meet the minimum average illuminance requirement of 5 footcandles (54 lux) when calculated as mesopic illuminance.
- **LEP fixtures provide significant power savings over HPS** – The LEP fixtures provided a 52% power savings compared to the incumbent HPS lighting at the study site.
- **Dimmed LEP fixture power reductions are not proportional to light output reductions –** Dimming the LEP fixtures resulted in light levels slightly lower than the proportional control signal, while the power consumption of dimmed LEP fixtures is notably higher than the proportional control signal.
- **Active use of wireless controls for low activity periods provides significant energy use savings –** Actively controlling LEP fixtures using the half-on half-off control scenario at the study sight results in 67% energy savings compared to the incumbent HPS, and a 32% savings compared to the LEP fixtures without controls.
- **LEP fixtures did not experience significant lumen depreciation** – Although the results were complicated by the changing lighting environment over the course of the study period, measurements indicate that the LEP lighting maintained a consistent light output over the ten month course of the study.
- **Most workers report brighter lighting conditions**– Results of the port staff survey indicate that most people report that the new LEP lighting is brighter than the incumbent HPS lighting. However, some respondents reported that visibility of workers on foot and markings on containers is actually reduced under the LEP lighting.

EVALUATIONS

All factors being equal (schedule, number of fixtures, etc.), the latest version of the LEP lighting is estimated to provide a 52% power savings over the existing HPS lighting. The ability to lower lighting levels through the wireless controls provides an opportunity for up 67% energy savings compared to the incumbent HPS lighting. However, the light level measurements present a concern for the test LEP lighting. The calculated average mesopic illuminance from the Version D LEP fixture was 51 lux, slightly less than the 54 lux (5 footcandle) minimum average required by OSHA. TRC believes that a complete installation of Version D fixtures at the study site would meet the minimum light level requirements, but further testing may be needed to better understand the light output characteristics of the LEP fixtures. Furthermore, the LEP fixtures do not match the light output of the technology they are replacing in this scenario, causing concern for whether the LEP fixtures are an adequate retrofit solution for high-mast lighting.

It should be noted that most exterior lighting applications have much lower minimum lighting requirements than this study site, and the LEP fixtures should easily achieve typical street or parking lot lighting requirements.

In addition, despite lower measured light levels, survey results of staff at the study site indicated that most people felt that the LEP lighting was brighter than the HPS and provided improved visibility. However, one response indicated that visibility of workers on foot was actually reduced under the new LEP lighting.

The testing of control scenarios at the study site provided mixed results. In general, the ability to reduce light levels during low activity times presents a significant energy savings opportunities. The most successful scenario tested at the study site results in a 32% savings compared to the LEP lighting at full power. The wireless controls also provide the opportunity to create multiple zones in large areas, providing higher light levels only where they are needed, and reducing light levels in other areas. However, the tests of the dimming control scenarios with the LEP fixtures resulted in lower than expected light output and higher than expected power consumption. As an alternative, turning off half of the fixtures on each pole during low activity times resulted in higher light levels with less power consumption than dimming the fixtures.

In addition, both the LEP lighting and the wireless control system experienced problems over the course of the study. Over the course of the initial study, three of the twelve version A fixtures failed and had to be replaced. During the expanded study, four of the 84 version B fixtures experienced full or partial failure. Additionally, two of the twelve version D fixtures failed shortly following installation and had to be replaced. The first of these two failures was due to a cross-threading of the driver to the emitter, and was likely the result of human error in a rushed effort to retrofit existing version B fixtures to the version D specification on site, rather than in a controlled manufacturing setting. It is unlikely that this failure would be repeated under typical conditions. The second of these failures was the result of an old power supply left in a fixture that was retrofitted from version B to version D, and eventually led to the failure. The wireless control system also experienced several challenges over the course of the study. In several instances the control system was unable to communicate with one or all of the fixtures, resulting in an inability to adjust the LEP lighting as needed. In another case, the software was not updating the sunrise and sunset times correctly, resulting in some of the fixtures not following the established schedule.

Overall, the LEP lighting represents a significant energy savings opportunity for the study site, especially in conjunction with the wireless control functionality to reduce light levels and energy use during low activity periods. The port staff surveyed for the study also indicate a general preference for the LEP lighting over the existing HPS. However, the relatively low measured illuminance levels and the overall reliability of the new technologies remain causes for concern.

RECOMMENDATIONS

Based on the results of this study, TRC presents the following strengths and weaknesses of the LEP lighting and wireless lighting controls assessed in this study. TRC recommends that PG&E consider these strengths and weaknesses in deciding whether to adopt LEP lighting and wireless lighting controls into the Energy Efficiency ("EE") program.

Strengths:

- **LEP lighting provides significant power consumption savings compared to HPS** – At full output the LEP lighting resulted in a 52% power consumption savings compared to the incumbent HPS lighting at the study site.
- **LEP lighting provides greatly improved visual quality compared to HPS** – Surveys of port staff indicated that most respondents found the LEP lighting to appear brighter and improve visibility compared to the HPS lighting at the study site.
- **LEP fixtures did not experience significant lumen depreciation** – The results of the study indicate that the LEP fixtures did not experience any significant lumen depreciation over the ten month duration of the study.
- **Wireless lighting controls provide significant energy savings** – The wireless control system installed with the LEP lighting at the site has the potential to provide a combined 67% energy savings compared to the incumbent HPS lighting at the study site, and up 32% energy savings compared to the LEP lighting without active controls.
- **Wireless lighting controls provide greatly improved control flexibility** – In addition to the energy savings, the wireless lighting controls allow for much greater flexibility that existing timer controls. Improved flexibility includes the ability to establish multiple zones, the ability to specify control zoning down to the individual fixture level, and the ability to change zones and control scenarios as the needs of the site change.

Weaknesses:

- **LEP light levels were significantly lower than HPS** – At full output, the Version D fixtures provided an average mesopic illuminance of 51 lux, compared to 77 lux from the incumbent HPS lighting.
- **LEP dimming results in low light output with high power consumption –** The results of the control scenario tests found that dimming the LEP fixtures to a control signal of 50% provided only 43% of the illuminance compared to full output, but with 70% power consumption compared to full output settings. Other dimming levels exhibited similar results. These results indicated that dimming the LEP fixtures provide only minimal power savings compared to the reduction in light levels.

- **LEP fixtures had high failure rate –** A total of eight LEP fixtures experienced failures over the course of the study (7% of the fixtures installed for the study, not including the fixture failure attributed to human error). Failures occurred across all three fixture versions studied. Some of this failure could be partly due to the fact that the product was actively under development though quality control and failure issues need to be addressed if LEP is to scale in the market.
- **Wireless lighting controls experienced functionality problems** – Over the course of the study the wireless control system experience several problems. Problems included failures communicating with fixtures, and problems automatically updating the schedules to match changes in sunrise and sunset times. Similar to the recommendation above, these control system glitches need to be evaluated and fixed in order for a more robust installation and operation of future LEP fixtures.

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APPENDIX: DETAILED SURVEY RESULTS

This appendix presents the detailed findings of the port staff survey.

The first question asked respondents about the brightness of the new LEP lighting. As Figure 25 shows, despite lower measured light levels, all six respondents reported that the new lighting is at least somewhat more bright than the existing HPS lighting, and two respondents reported that the LEP lighting is much more bright.

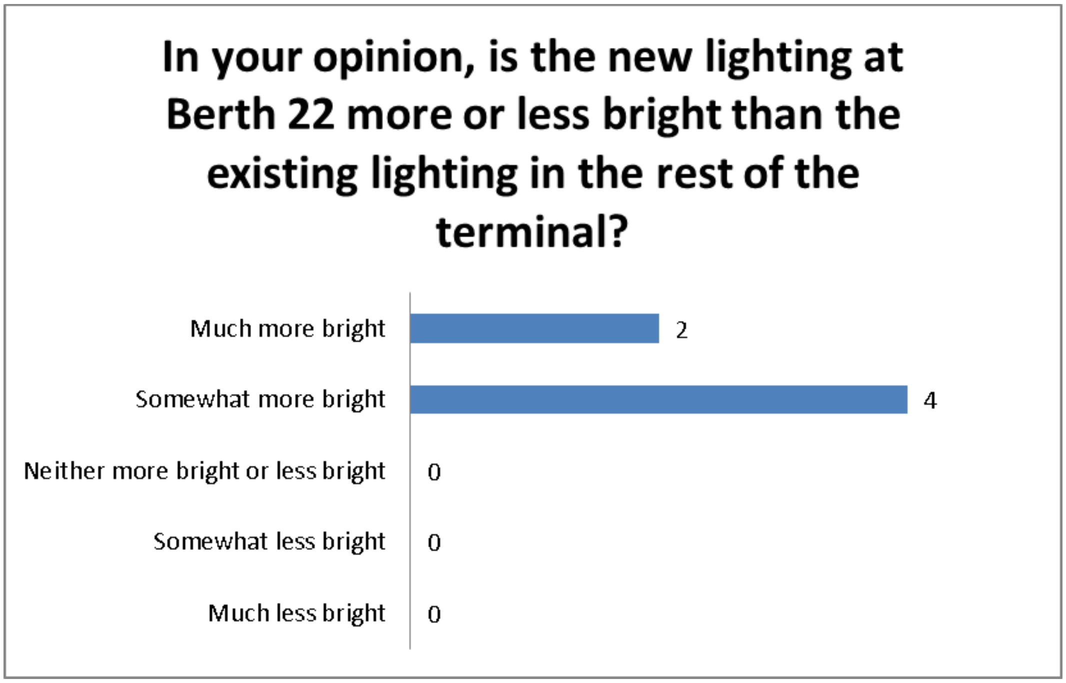

FIGURE 25: SURVEY RESULTS – OVERALL BRIGHTNESS

The second question asked respondents about uniformity. As Figure 26 shows, five respondents reported that the new LEP lighting is at least somewhat more uniform than the existing HPS lighting, while one reported that the uniformity is about the same.

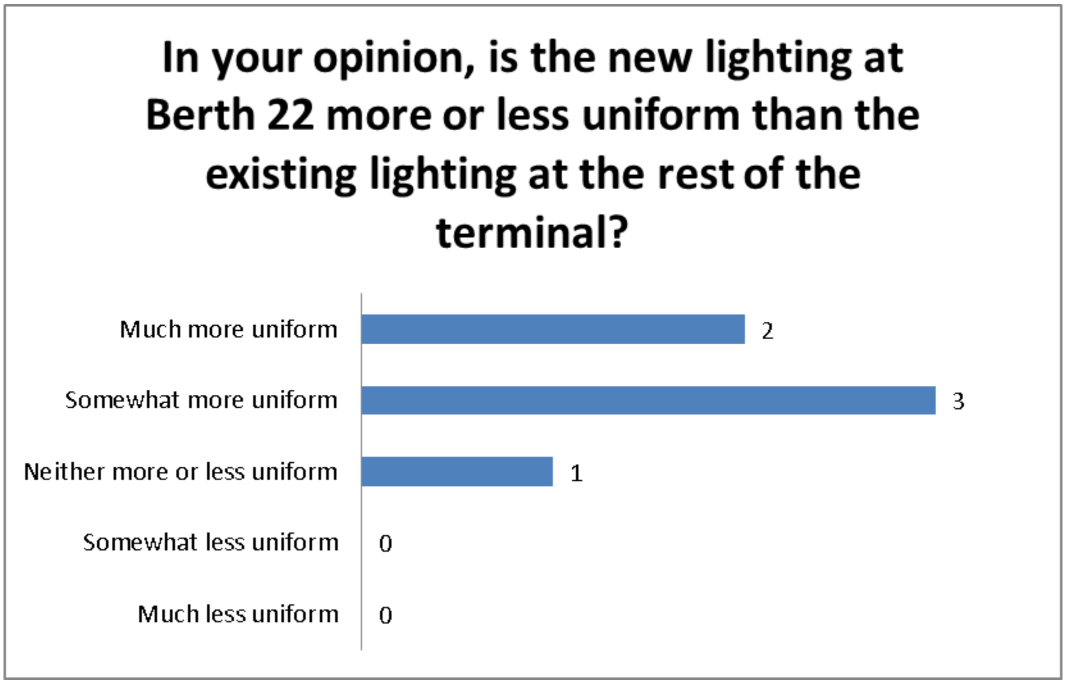

FIGURE 26: SURVEY RESULTS – UNIFORMITY

The next series of questions asked about the visibility of specific features of the study site environment under the new LEP lighting as compared to the existing HPS lighting. Figure 27 shows that four of the six respondents reported that the visibility of the "bull rail" at the water line is somewhat better under the LEP lighting, while two report that it is about the same.

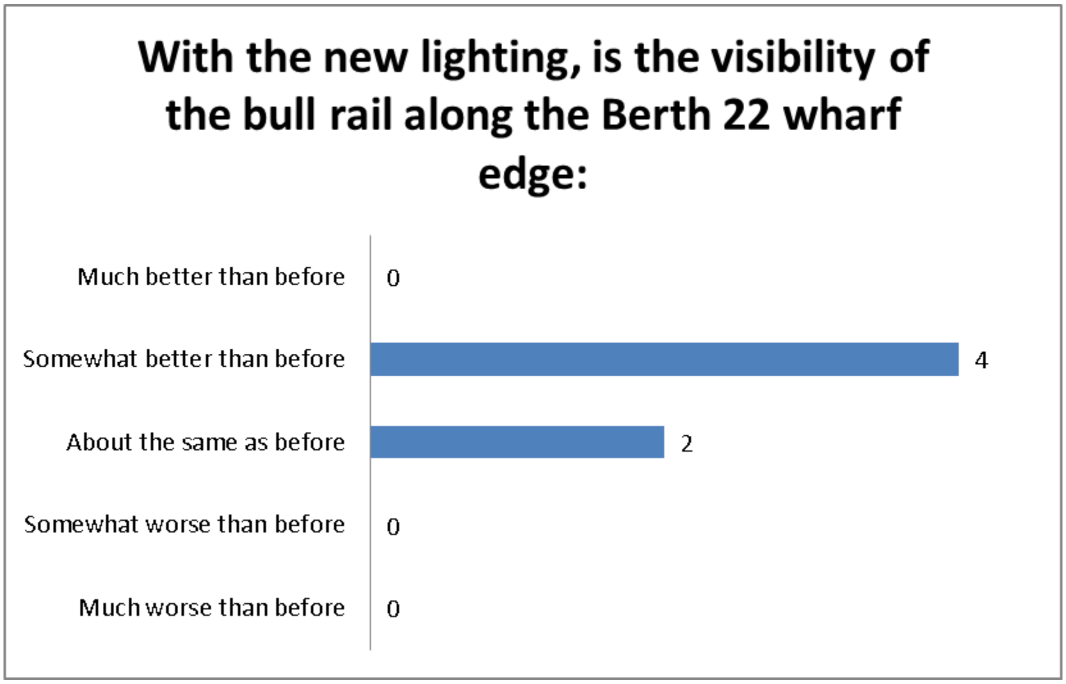

FIGURE 27: SURVEY RESULTS – VISIBILITY OF THE BULL RAIL AT THE WHARF EDGE

As Figure 28 shows, five of the six respondents reported that visibility of the ground striping in the study area was at least somewhat better than before. However, one respondent reported that the visibility of the ground striping was somewhat worse.

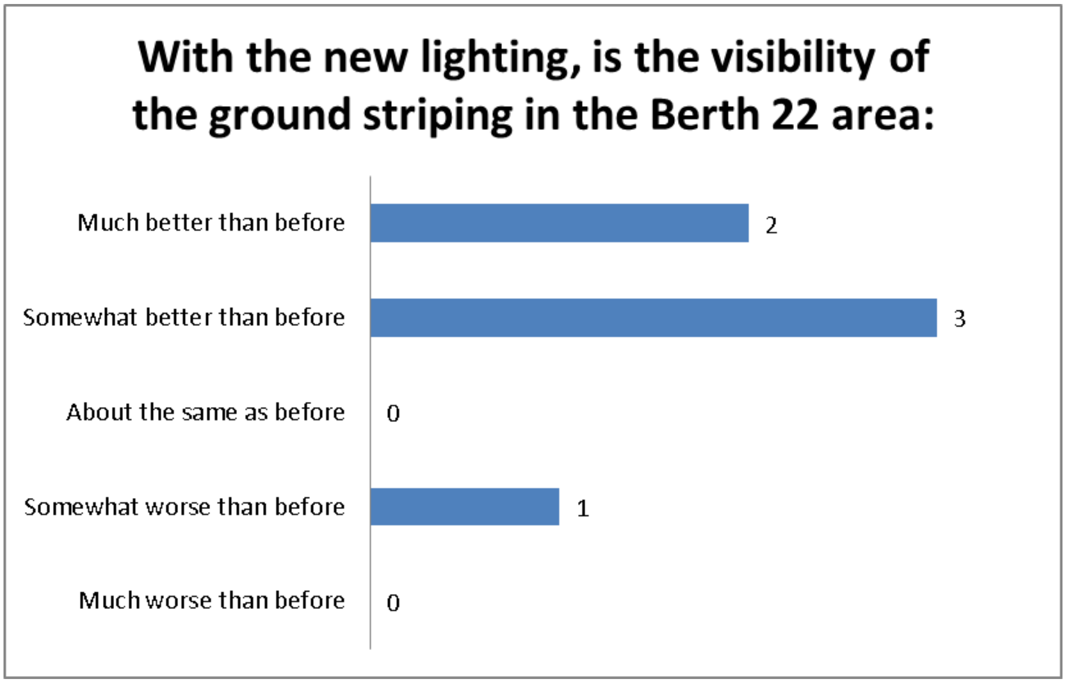

FIGURE 28: SURVEY RESULTS – VISIBILITY OF GROUND STRIPING

The results shown in Figure 28 may also have been influenced by the fact that the ground striping in the study area was in the process of being repainted during the period when this study was conducted. This may partially explain the broad variation in responses to this question.

Figure 29 shows that four of the six respondents reported that visibility of workers on foot in the study area is at least somewhat better than before, although one respondent reported that visibility of other workers was about the same, and one reported that visibility of workers on foot was actually somewhat worse than before.

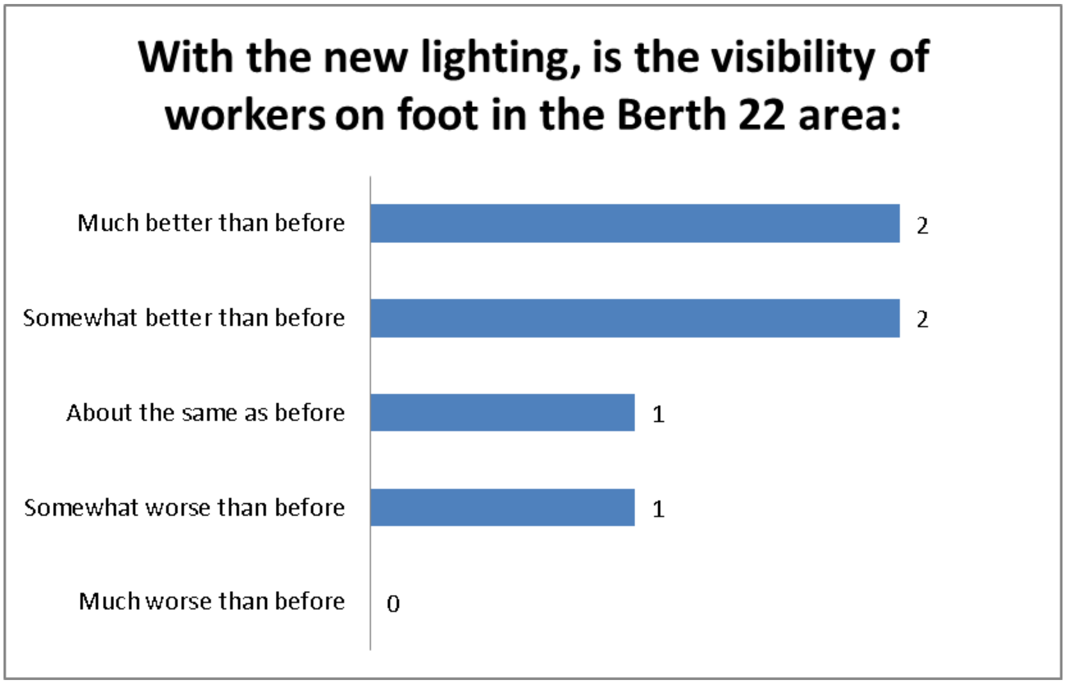

FIGURE 29: SURVEY RESULTS – VISIBILITY OF WORKERS ON FOOT

As Figure 30 shows, five of the six respondents reported that the visibility of other vehicles in the study area was at least somewhat better than before. One respondent reported that visibility of other vehicles was about the same.

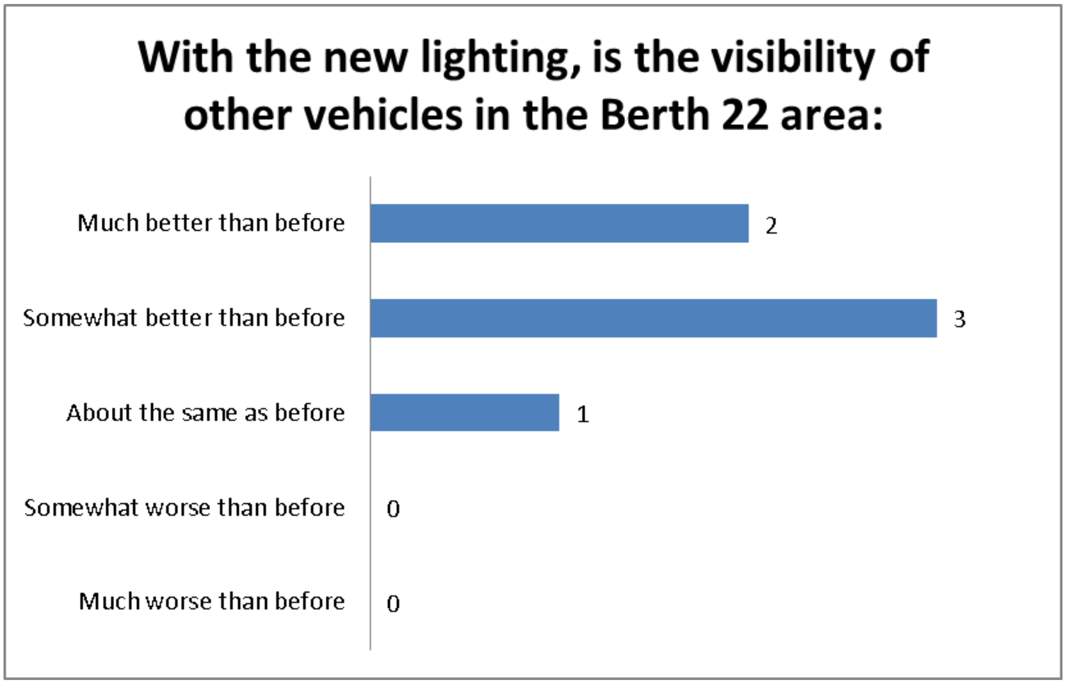

FIGURE 30: SURVEY RESULTS – VISIBILITY OF OTHER VEHICLES

Similarly, Figure 31 shows that four of the six respondents reported that visibility of shipping containers and container marking is at least somewhat better under the LEP lighting. One respondent reported that visibility was about the same, and one reported that visibility of containers and container numbers was somewhat worse under the LEP lighting.

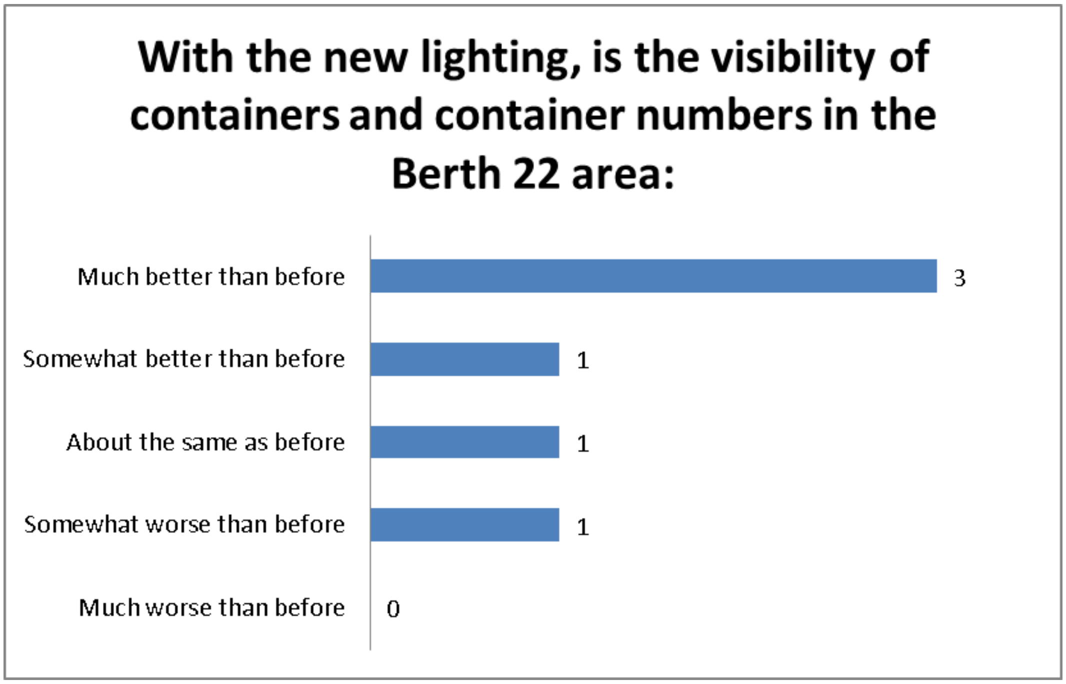

FIGURE 31: SURVEY RESULTS – VISIBILITY OF CONTAINERS AND CONTAINER NUMBERS

The survey also asked respondents to identify any aspects about the new LEP lighting they felt reduced their safety or effectiveness. Only two of the six respondents provided answers to this open ended question:

- One respondent noted that during fog, the new LEP lighting actually makes visibility worse in the study area
- Another respondent noted that shadows under the new LEP lighting are sharper than those under the HPS lighting, increasing contrast

Finally, the survey asked respondents to note any other aspects of the new lighting that they wanted to share. Again only two respondents provided answers for this open ended question:

- One respondent reported that the new lighting provides a "more natural sense of light." This respondent also noted that the new lighting causes less glare and reflections off the windshields of other vehicles.
- Another respondent noted that there is less glare over the top of the terminal (i.e., less light pollution into the night sky), but that when looking directly at the new fixtures directly they are very bright.